**MIXED SILICICLASTIC-CARBONATE RAMP SEDIMENTS AND
CORAL BIOHERMS OF THE LATE ORDOVICIAN
LOURDES FORMATION, WESTERN NEWFOUNDLAND:
SEDIMENTOLOGY, STRATIGRAPHY, AND TECTONIC SIGNIFICANCE**

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Abstract

The Late Ordovician Lourdes Formation (Long Point Group) of the Port au Port Peninsula, western Newfoundland, preserves a record of short-lived (~5-7 m.y.), mixed siliciclastic-carbonate sedimentation on a narrow, high-energy ramp. The ca. 75 m-thick formation is divided into three members. In ascending order, they are; the dominantly peritidal Shore Point Member, the mostly shallow subtidal, carbonate Black Duck Member, and the more argillaceous Beach Point Member. The lower two members are capped by prominent paleokarst surfaces. Deposition of the Lourdes Formation post-dates a 6-8 m.y. hiatus; renewed deposition overlapped allochthonous strata on the orogen side of the local Taconic foreland basin. Facies across the platform range from peritidal carbonates and sandstones and shallow-ramp bioherms and skeletal shoals, to deeper calcareous shales. Cyclicity is evident on at least three scales, including m-scale shallowing-upward cycles, decameter-scale depositional sequences, and larger-scale sequences. An overall deepening trend is identified, culminating with the deeper-water siliciclastic sediments of the overlying Winterhouse Formation. The demise of the carbonate ramp was likely caused by increased influx of sand and mud linked to tectonism along the basin margin. Coral bioherms within the uppermost Black Duck Member exhibit complex internal structures, including framework, boundstone, and suspension deposit elements. The bioherms exhibit classic stages of reef growth, including stabilization, colonization, and diversification. With rigid frameworks built mostly by the stacking and intergrowth of large corals, bioherms of the Lourdes Formation are some of the oldest known reefs to show true dominance of a framework construction strategy over binding and baffling strategies that predominate in younger

reefs.

This is the first detailed study of the Lourdes Formation, characterizing the initiation, development and demise of the mixed siliciclastic-carbonate ramp system. The unique depositional setting in a post-collisional Taconic remnant basin allows comparison of the Lourdes carbonate ramp with equivalent Late Ordovician epicontinental foreland platforms in eastern North America and offers a unique opportunity to explore the influence and timing of sea-level change related to ongoing local and regional tectonism and eustasy on patterns of platform development relative to patterns defined within epicontinental platform successions across the foredeep in eastern Laurentia.

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Statement of Original Contribution

This research is focused on understanding the depositional history of the only Ordovician carbonate succession in western Newfoundland that post-dates the Taconic orogenic event, through a detailed study of the stratigraphy and sedimentology of the Lourdes Formation. Research involved two six-week field seasons in 2003 and 2004, in which I carried out bed-by-bed measurement and description of stratigraphic sections and detailed investigation of the internal architecture of coral bioherms. The stratigraphic data is summarized in the stratigraphic sections included in Appendix A, and examples of the detailed mapping of bioherms are presented in figures of Chapter 4. Samples were collected for fossil identification, stable isotope and elemental geochemistry, and petrographic studies. Fossil identification was conducted or confirmed by several paleontologists who are acknowledged in Chapter 4.

For the sedimentological portion of the study, I carried out detailed petrographic descriptions, including cathodoluminescence microscopy, of selected samples to establish lithology and characterize facies. I also undertook scanning electron microscopy and Microprobe analysis for identification of detrital grains and diagenetic components, under the supervision of Lewis Ling and Peter Jones at Carleton University. Stable isotope (C and O) analysis was undertaken at the G.G. Hatch Isotope Laboratory at the University of Ottawa. I performed all stages of sample preparation, including grinding, weighing, acid reaction, and calibration of the mass spectrometer.

In an investigation of sandstone provenance, I point-counted eighteen stained thin-sections, and incorporated whole-rock elemental analysis by ICP-AES and XRF of sandstones and shales. I selected and ground the samples for the geochemical analysis,

which was carried out by GeoLabs in Sudbury.

From the data produced in this study, I established one of the first facies models for the origin of the Lourdes Formation, and developed an initial sequence stratigraphic interpretation which will be further refined by future studies of the subsurface and the overlying formations. The provenance data allows better understanding of basin paleogeography and tectonic history. Detailed study of fossils, facies, and orientation of coral bioherms has allowed the first interpretation of the paleoecology and depositional setting of these previously well known but poorly documented structures, and additionally, some further insight into Paleozoic reef evolution.

Method of Presentation

This thesis is presented as two manuscripts (Chapter 2 and 4) and an unpublished chapter (Chapter 3), each with a different focus to highlight themes and topics of the research. This format was intended to facilitate the publication of this research; however, it introduces some unavoidable repetition. Chapters 2 and 4 have been published, both with K.L. Batten Hender as first author, in co-authorship with Dr. George R. Dix. They have been edited slightly from the published manuscripts to reflect corrections requested by the Examining Board and to meet the requirements of thesis formatting. Chapter 5 is a summary of the conclusions from this research.

CHAPTER 1:
INTRODUCTION

Ordovician sedimentary rocks of western Newfoundland contain an important record of the closure of the Iapetus Ocean and the formation of the Appalachian mountain belt (Williams 1979). The evolution of the edge of the Laurentian continent from a broad passive margin, to a compressional tectonic regime with ophiolite obduction is well documented from this region (James et al. 1989). Collision during the Taconic orogenic event was a prolonged process; an irregularly-shaped continental margin with promontories and embayments allowed for diachronous collision of the oncoming microcontinent and development of remnant basins, and the earliest indications of the oncoming collision are recorded in western Newfoundland (Knight et al. 1991).

The Caradocian Lourdes Formation, the focus of this dissertation, post-dates the main phase of the Taconic orogeny in western Newfoundland, whereas well-documented time-equivalent carbonate platforms from the remainder of eastern Canada and the United States occur in still ongoing convergent tectonic settings. The unique location of the Lourdes platform in time and space along a foredeep remnant basin allows an excellent opportunity to compare the sedimentary response to a likely still active tectonically active setting (Knight et al., 1995), and the possibility of separating the respective influences of eustasy and tectonics on carbonate sedimentation.

Much of the body of existing research on the Lourdes Formation, following its initial description by Schuchert and Dunbar (1934), consists of paleontological studies with an aim toward biostratigraphic characterization (Bergström et al. 1974; Fåhræus 1974; Stait 1988). Early studies of the stratigraphy and sedimentology by Rogers (1965), and Stait and Barnes (1991), and of coral bioherms within the Lourdes Formation (James and Cuffey 1989) offer a general framework for details presented in this dissertation.

The research project encompasses the first bed-by-bed detailed stratigraphy and

sedimentology of the Lourdes Formation. Interpretation of this data has resulted in the development of a dynamic facies model for Lourdes Formation deposition, and improved understanding of sequence stratigraphy, provenance of siliciclastic sediment, and the tectonic history of the basin. Detailed study of the coral bioherms has allowed an improved interpretation of their development, paleoecology, depositional environment, and importance to the evolutionary history of reefs.

Subsequent chapters of this thesis address these topics sequentially: sedimentology, facies model, and depositional/tectonic setting for the Lourdes Formation (Chapter 2, presented as a published manuscript); a framework for sequence stratigraphic interpretation of the Long Point Group (Chapter 3); and an in-depth investigation of the structure, facies, and paleoecology of small coral bioherms of the Lourdes Formation, some of the earliest known coral reefs (Chapter 4, also a published manuscript).

CHAPTER 2:
FACIES DEVELOPMENT, DEPOSITIONAL MODEL, AND IMPLICATIONS FOR
REGIONAL TECTONICS

Published as:

Batten Hender and Dix, *in press (accepted September, 2007)*, Facies development of a Late Ordovician mixed carbonate-siliciclastic ramp proximal to the developing Taconic orogen: Lourdes Formation, Newfoundland, Canada, *Facies*.

ABSTRACT

The Upper Ordovician (upper Whiterockian to Mohawkian) Lourdes Formation represents a narrow (tens of kilometers), short-lived (~5-7 m.y.), high energy, mixed siliciclastic-carbonate ramp that onlapped allochthonous strata along the orogen side of the local Taconic foreland basin. Ramp development followed a 6-8 m.y. hiatus during which weathering had concentrated chemically-mature siliciclastics that were admixed with initial carbonate sediments. A facies gradient across the platform contains paleokarst and peritidal carbonates and sandstones, shallow-ramp carbonate bioherms and skeletal shoals, and deeper ramp calcareous shales. Transgressive systems tracts are marked by ramp-wide sheets and shoals of skeletal grainstone and low accumulation rates, and highstand systems tracts are marked by significant admixture and interbedding of siliciclastics with cross-ramp carbonate facies. Platform demise coincides with increased siliciclastic input, likely tectonically influenced. The Lourdes ramp is equivalent to epicontinental foreland ramps along eastern Laurentia, but its narrower width precluded formation of oceanographically restricted platform-interior facies.

INTRODUCTION

The Lourdes Formation (Long Point Group) of western Newfoundland, eastern Canada, contains a detailed record of the birth, life, and demise of a Late Ordovician mixed siliciclastic-carbonate ramp following westward overthrusting of basinal sedimentary and ophiolitic allochthons within a Taconic foreland basin. The platform represents a short-lived (5-7 m.y.) re-establishment of the carbonate factory, once a dominant sedimentary component of the older passive-margin and foreland successions in the region (James et al. 1989).

Understanding facies development of the Lourdes Formation is important because it lay on the opposite side of the foreland basin relative to well studied epicontinental platforms elsewhere in eastern North America (e.g., Holland and Patzkowsky 1998; Pope and Read 1997a); the platform developed in a still tectonically active setting; and environmental conditions may have created ecological pressure influencing emergence of the dominance of a reef constructor guild more typical of post-Ordovician buildups (Chapter 4). Continuous (15 km) outcrop exposure along Long Point Peninsula (Fig. 2-1) provides the opportunity for assessment. This paper details the ramp's sedimentology, facies, and depositional history; presents a dynamic facies model; and underscores the depositional interplay of siliciclastic and carbonate sediments.

GEOLOGICAL SETTING

The Humber Zone (Williams 1979) comprises the western Newfoundland portion of the Appalachian orogen. Its geologic history documents five prominent tectonostratigraphic stages associated with opening and closing of the Iapetus Ocean basin (Cooper et al. 2001): (1) synrift sedimentation associated with Late Precambrian

Fig. 2-1: A) Location of study area: western Newfoundland (upper inset), Port au Port Peninsula (lower inset), and study site locations. B) General stratigraphy of the Humber zone in western Newfoundland, modified from Williams et al. (1998).

ocean basin formation; (2) Cambrian through Early Ordovician passive-margin carbonate platform development; (3) Middle Ordovician foreland carbonate platform development coincident with the basin's gradual destruction; (4) formation of the Taconic Unconformity linked to Middle Ordovician tectonic emplacement of deep-water sedimentary (Humber Arm, Hare Bay) and ophiolitic (Bay of Islands) allochthons and to Taconic collisional tectonics and accretion of the oceanic Dunnage Zone east of the Humber Zone (Cawood et al. 1995; James et al. 1989); and (5) resumption of sedimentation (including the Lourdes Formation) following the Taconic Unconformity (Cooper et al. 2001) within the post-collisional Taconic foreland. The record of overthrusting in western Newfoundland predates culmination of orogenesis in more southerly parts of the Appalachian orogen (Knight et al. 1995).

On Long Point (Fig. 2-1), an outcrop exposure (Loc. 1, 2, Fig. 2-1A) of the Lourdes Formation resting on allochthonous Humber Arm strata has historically represented evidence for post-Taconic disconformity (James et al. 1989; Knight et al. 1991; Rodgers 1965). A revised structural model for the local and regional geology reinterprets the contact as a thrust marking the roof of a Late Devonian structural triangle zone (Stockmal and Waldron 1993; Waldron and Stockmal 1991). In the Hunt-Pan Canadian Port au Port Well #1 (Fig. 2-1A), the equivalent Lourdes interval is ~170 m thick, and rests disconformably on the underlying Goose Tickle Group which underlies the Taconic Unconformity (Figs. 2-2, 2-3; Burden and Williams 1995; Cooper et al. 2001). The added thickness is represented by a graptolitic shale and a limestone unit not exposed along Long Point (Fig. 2-2; Burden and Williams 1995). Regional stratigraphic reconstructions based on offshore seismic data propose that the thicker subsurface

Fig. 2-2: Model for the depositional setting of the Lourdes Formation, based on Cooper et al. (2001) and interpretations from the current study. Units denoted A and B represent subsurface limestone (A) and graptolitic shale (B) that are interpreted to lie stratigraphically below, but southwest of the current outcrop belt of the Lourdes Formation (Burden and Williams 1995). The Lourdes Formation overlies the Taconic Unconformity and onlapped the Goose Tickle Group, and possibly the Humber Arm allochthon. The current Lourdes-Humber Arm contact (bold line) illustrates an interpreted Acadian thrust fault (Waldron et al. 1993) that creates the present-day structural juxtaposition of Lourdes on Humber Arm strata.

Fig. 2-3: A) Stratigraphic nomenclature for the Long Point Group. Subdivisions of members (e.g., BP2) represent depositional units. B) Biostratigraphic summary, Lourdes and Winterhouse formations based on: **1** Fåhræus 1973 (conodonts), **2** Bergström et al. 1974 (conodonts, graptolites), **3** Stait 1988 (nautiloids), **4** Quinn et al. 1999 (graptolites), **5** Gillespie 1998 (acritarchs). Dark numbered circles indicate Winterhouse Formation ages, white numbered circles indicate Lourdes Formation ages. Dotted lines indicate estimated age ranges. Absolute dates on column are based on Webby et al. (2004) North American stages. Alternate stage names (denoted “Holland”) are based on usage by Holland and Patzkowsky (1996), and are correlated to biostratigraphic zones, but not to absolute age.

Lourdes succession thins easterly (toward the orogen) due to progressive onlap across the underlying Taconic Unconformity (Cooper et al. 2001). The seismic data clearly shows an unconformable contact between the Long Point Group and the underlying Goose Tickle Group (Stockmal et al. 2004; Waldron and Stockmal 1991). This geometry may have allowed the formation to have onlapped the edge of the Humber Arm Allochthon. Subsequent Acadian tectonism transposed the now exposed portion of the Lourdes Formation eastward by ~30-40 km to its present location (Stockmal and Waldron 1993; Waldron and Stockmal 1991), making the current Humber Arm-Lourdes boundary, where exposed in outcrop, a thrust fault (Fig. 2-2; Waldron et al. 1993).

METHODS

Coastal cliff sections were measured on Long Point Peninsula and at Three Rock Point (Fig. 2-1; Appendix A) during two six-week field seasons in 2003 and 2004. Facies descriptions are based on field observations, photographs, lithological samples, and 197 thin sections. Point counting of sandstones follows Dickinson and Suczek (1979), using 300 grains from each of eighteen thin sections of sandstone stained for feldspar. Standard cathodoluminescence microscopy was used with polished thin sections, with working conditions of 50 mA, 12 kV and ~40 mTorr. Electron microprobe analysis (Carleton University), following standard methods, qualitatively identified heavy mineral grains. Sandstone and shale samples were powdered for major, trace, and rare-earth element (REE) analysis by Geoscience Laboratories (GeoLabs), Ontario Geological Survey, Sudbury, Ontario. Geochemical data are included in Appendix C. Major elements were determined using standard X-ray fluorescence procedure (XRF) and ICP-AES, while

trace and REE analysis used conventional ICP-MS procedures.

STRATIGRAPHIC FRAMEWORK

The Lourdes Formation forms the lowermost unit of the Long Point Group (Schuchert and Dunbar 1934); the Long Point Group is ~1300 m in thickness in outcrop. It contains three formations (Quinn et al. 1999; Stait and Barnes 1991); in ascending order, Lourdes Formation, Winterhouse Formation, and Misty Point Formation (Fig. 2-3A). The Lourdes Formation is a ~70-m thick interval consisting of fossiliferous marine limestone, calcareous sandstone, and shale. The Winterhouse and Misty Point formations (~860 and ~400 m thick, respectively; Quinn et al. 1999) are mostly siliciclastic in composition and identify progradation of marginal marine and deltaic deposits over the Lourdes platform (Quinn et al. 1999).

The Lourdes Formation contains three unconformity-bounded members; in ascending order, Shore Point Member, Black Duck Member, and Beach Point Member (Figs. 2-3A, 2-4; Stait and Barnes 1991). Where exposed, the boundary between the Shore Point and Black Duck members is an interpreted paleokarst with small-scale (<10 cm) paleotopographic relief. The boundary between the Black Duck and Beach Point members is also an interpreted paleokarst, with more extensive development of rounded to sinuous dissolution karren and related galleries up to 1 m below the boundary. There is paleotopographic relief (~1 m) related to the erosional surface, and overlying siliciclastic beds of the Beach Point Member on-lap paleotopography created by the disconformity.

The duration of Long Point Group sediment accumulation represents a composite time interval, with deposition occurring during the latest Whiterockian and Mohawkian, and possibly Cincinnati, stages (Fig. 2-3B). The underlying Mainland Formation (upper

Fig. 2-4: Composite stratigraphic column of the Lourdes Formation on Long Point Peninsula. Paleocurrent data is presented in separate rose diagrams in units BD2 and BD3 for dual-sense (bi-directional or ambiguous) structures, and unidirectional structures.

Goose Tickle Group; Fig. 2-1B) is considered to be of Llanvirn age (Cooper et al. 2001; Quinn 1995). The Lourdes Formation likely spans the latest Whiterockian through early Mohawkian (or middle Caradocian) interval, a period of about 5-7 million years based on revised Ordovician biostratigraphy (Webby et al. 2004). Cooper et al. (2001) suggested a more restricted, 2-3 my, period. Uncertainty arises because the middle Black Duck Member contains most of the biostratigraphically significant fossils, including middle Caradocian conodonts (*gerdae* zone; Bergström et al. 1974; Fåhræus 1973) and graptolites (*multidens* biozone – equivalent to North American *bicornis* and *americanus* biozones; Bergström et al. 1974). Nautiloids support a latest Whiterockian (early Caradocian) age (Stait 1988). The underlying Shore Point Member contains no biostratigraphically diagnostic fossils, thereby precluding assignment of a precise maximum age. Graptolites and shelly macrofossils from the Winterhouse Formation indicate that at least part of this formation is of Cincinnati age (Bergström et al. 1974; Quinn et al. 1999).

LOURDES FACIES DESCRIPTIONS AND INTERPRETATIONS

Lithofacies (Tables 2-1 and 2-2) and their associations relative to each stratigraphic member (Table 2-3) are distinguished on the basis of lithology, physical and biogenic sedimentary structures, and fossils. Further elaboration of selected facies follows.

Table 2-1: Carbonate facies descriptions and interpretations.

	<u>Lithology and Components</u>	<u>Bioturbation</u>	<u>Physical Structures & Geometry</u>	<u>Interpretation</u>
C1: mudstone	<p>Light grey, variably sandy mudstone; micrite to microspar with rare, thin interbeds of green, argillaceous limestone.</p> <p>Components: ostracodes, gastropods, pelmatozoan ossicles, calcareous red algae, bryozoans, trilobite and molluscan debris, skeletal debris, peloids, flat-pebble mud intraclasts.</p> <p>Cement: voids rimmed by isopachous bladed calcite and filled with later equant ferroan calcite spar.</p> <p>Siliciclastics: 0-40%; very fine to medium, angular sand.</p>	<p>Mostly horizontal burrows, locally dolomitized; microborings in bioclasts. Some beds thoroughly bioturbated.</p>	<p>Laminated (rare) to thickly bedded; tabular, laterally continuous beds; locally truncated by channels; irregular fenestral cavities, partially filled with calcite crystal silt; desiccation cracks (1-5 cm diam. polygons); graded beds defined by concentration of sand; microkarst at top of some beds, filled with Facies S5.</p>	<p>Intertidal to supratidal shallowing-up cycles with tidal channels; low-energy tidal flat.</p> <p>References: 6, 7, 10, 11, 13.</p>
C2a: skeletal grainstone	<p>White to light grey, fine to very coarse grainstone; grains locally abraded and/or with thin micritic coatings; well sorted.</p> <p>Components: pelmatozoan ossicles (up to 90%), brachiopods, bryozoans, gastropods, cephalopods, trilobites, bioclastic debris, rare <i>Labyrinthites</i>, rare pisoids and oncoids.</p> <p>Cement: epitaxial calcite on echinoderm fragments, isopachous rims of bladed calcite, fine to coarse pore-occluding equant calcite spar.</p> <p>Siliciclastics: silt to medium sand is rare to absent.</p>	<p>Unbioturbated or locally burrowed.</p>	<p>Thin to thick beds with sharp to erosive bases; tabular and trough cross-bedding; wave and current ripples; scour-and-fill structures; gutter casts.</p>	<p>Open marine, moderate- to high-energy shoals or barrier bars; highly winnowed, TST.</p> <p>References: 1, 2, 7, 8, 13.</p>

C2b: oncoïd-bearing cortoid grainstone	Light grey, fine to coarse grainstone to (rare) packstone; all grains have micrite envelopes and/or <i>Girvanella</i> coatings; > 50% of skeletal grains are of unidentifiable origin due to micritization. Cement: epitaxial calcite on echinoderm fragments, isopachous rims of bladed calcite, fine to coarse pore-occluding equant calcite spar. Components: micritized grains (cortoids), peloids, intraclasts, coated skeletal fragments, aggregate grains, large <i>Girvanella</i> oncoïds concentrated in beds (see oncoïd description in text). Siliciclastics: very fine to medium sand is rare to absent.	Unbioturbated or locally burrowed; ubiquitous microboring in bioclasts.	Thin to thick beds with sharp to erosive bases; tabular cross-bedding; wave and current ripples; HCS.	Moderate to high energy; wide range of depths in a ramp system; early cementation and re-working; highly winnowed; TST. References: 4, 7, 9, 12.
C3a: oncoïd-intraclast grainstone	Pink to grey, medium to very coarse-grained grainstone, rudstone and minor wackestone; diagenetic chert nodules; iron oxide (after pyrite?) staining of grains. Components: pelmatozoan ossicles and articulated stems, coral fragments, brachiopods, bryozoans, bioclastic fragments, <i>Girvanella</i> oncoïds (lobate to irregular in form; see description in text), superficial ooids, peloids, intraclasts. Cement: isopachous rims of bladed calcite, fine to coarse pore-occluding equant calcite spar, small scattered dolomite rhombs. Siliciclastics: rare, fine to very coarse quartz sand.	Rare <i>Skolithos</i> ; abundant <i>Thalassinoides</i> preserved along carbonate-shale boundaries.	Thin to very thick, tabular to irregular beds; thickest beds are continuous over >1 km; erosive bases and sharp tops; internal scour-and-fill structures; stacked and amalgamated beds; HCS.	High to moderate energy; shallow subtidal to emergent; shallowing-up cycles; hardground development; TST. References: 4, 7, 9.
C3b: highly fragmented intraclast grainstone	As Facies C3a, except highly reworked breccia, with an argillaceous to silty matrix. Orientation of fragments ranges from random to only slightly rotated.	No bioturbation evident.	Irregular, discontinuous beds; commonly interbedded with or passing laterally into intact beds of Facies C3a.	Emergent paleosol (?) Reference: 5

C4: fine peloidal-skeletal grainstone	Light grey, fine to very fine, calcite-cemented grainstone to packstone. Components: trilobite and ostracode fragments; echinoderm ossicles; round to irregular peloids. Cement: epitaxial calcite on echinoderm grains, equant calcite spar (locally inclusion-rich), small dolomite rhombs concentrated in burrows. Siliciclastics: angular silt to fine sand (1-5%); siliciclastic clays, fine to medium-grained phosphatic fragments.	Very small horizontal burrows; <i>Skolithos</i> common; "Lam-scam" style bioturbation (sensu Bromley 1990: p.203).	Thin to medium beds; sharp, erosive bases and irregular, burrowed tops; planar lamination, low-angle cross-stratification, and HCS; locally amalgamated; beds continuous over > 15 m; forms widely spaced interbeds with C6	Inner to mid-ramp; proximal tempestite beds; TST. References: 5, 7.
C5: hardground and intracast rudstone	Erosional surfaces and rudstone composed of clasts derived from these surfaces; both have dark coatings of pyrite; rudstone matrix typically medium to coarse, bioclastic packstone to grainstone or calcareous arenite to calcareous siltstone and shale. Components: pelmatozoan ossicles, coral fragments, bryozoans, brachiopods, bioclastic debris, intraclasts. Cement: Epitaxial calcite on echinoderm grains, inclusion-rich equant calcite spar. Siliciclastics: quartz silt and sand common. Bimodal; silt and very fine sand are angular, coarse sand is rounded.	<i>Trypanites</i> borings along intraclasts and hardground surfaces.	Thin to thick beds; typically graded with intraclasts concentrated at base; clasts are flat, horizontally aligned, and rarely imbricated.	Early lithification in the shallow subsurface, followed by (possibly repeated) exhumation, erosion, boring, and re-burial; TST and HST. References: 5.
C6: nodular packstone	Light to medium grey, fine- to coarse-grained, skeletal packstone, grainstone, and rudstone; argillaceous laminae/drapes; diverse and abundant, robust biota; little evidence of fossil abrasion. Components: echinoderms, brachiopods, trilobites, ostracode fragments; bryozoans, coral fragments, corals, nautiloids, gastropods, molluscan debris. Siliciclastics: variably sandy (very fine to medium sand); thin interbeds of silty shale; locally argillaceous.	Highly bioturbated, obliterating most primary sedimentary structures; few individual traces are preserved; argillaceous laminae are	Dominantly thinly bedded, rarely medium; irregular to nodular; internal scoured surfaces. Sand occurs as burrow fill, in thin, discontinuous laminae, or disseminated; hard surfaces encrusted by bryozoans, <i>Solenopora</i> , rare crinoid holdfasts.	Subtidal open platform or shoreface; probable storm deposition reworked by bioturbation; HST. References: 7, 8, 12.

C7: coral bioherm facies association	<p>Coral bioherms, ranging in height from 1 to 8 m, with an average width of 1 to 2 m.</p> <p>Components: corals, including <i>Labyrinthites chidensis</i> (most abundant), <i>Eofletcheria</i> sp., and <i>Aulopora</i> sp., <i>Labechia</i> sp. stromatoporoids, sponges including lithistids, <i>Solenopora</i> sp., and <i>Epiplastospongia coactilis</i>, diverse bryozoans, and pelmatozoans, including hold-fasts; ostracodes, sponge spicules, crusts of <i>Girvanella</i>, <i>Wetheredella</i> sp., and <i>Sphaerocodium</i> sp.; lime mud.</p> <p>Siliciclastics: fine silt to sand in reef cavities.</p>	<p>locally reworked by bioturbation and incorporated into limestone; <i>Thalassinoides</i> common on bases of beds; large fossils bored by <i>Trypanites</i>.</p>	<p>Irregularly stacked framework; dome, bell, or hourglass-shaped in cross-section; internal cavities filled by microbial-stromatoporoid boundstone and laminated silty mudstone; reef flanks contain skeletal rudstone to very coarse grainstone.</p>	<p>Open ramp, below normal wave base, above storm wave base; HST. Reference: 3.</p>
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References:

1. Aigner (1985), 2. Ausich (1997), 3. Batten Hender and Dix (2006), 4. Dumas and Armott (2006), 5. Flügel (2004), 6. Ginsberg et al. (1977), 7. Holland (1993), 8. McLaughlin et al. (2004), 9. Read (1985), 10. Shinn (1983), 11. Shinn (1986), 12. Steinhilff and Walker (1996), 13. Tucker and Wright (1990)

Table 2-2: Mixed and siliciclastic facies descriptions and interpretations.

	<u>Lithology and Components</u>	<u>Bioturbation</u>	<u>Physical Structures & Geometry</u>	<u>Interpretation</u>
Mixed carbonate-siliciclastic facies				
M1: argillaceous nodular packstone	Light to medium grey, calcisiltite to coarse-grained, sandy packstone, wackestone, or rudstone, surrounded by dark grey, friable, silty shale (up to 75%); fossiliferous, occasional pyrite-coated hardgrounds. Components: diverse brachiopods, pelmatozoan ossicles, trilobites, ostracode fragments, rare, small <i>Labyrinthites</i> corals. Shale contains abundant whole strophomenid brachiopods and trilobites. More robust fossils concentrated in limestone beds.	Ubiquitous horizontal burrows and pervasive bioturbation in shale imparting a nodular fabric; some discrete <i>Planolites</i> burrows preserved in nodules.	Thin, nodular, tabular lenticular, or discontinuous beds of limestone, surrounded by laminated to bioturbated shale; punctuated by thicker, continuous, erosive-based, typically graded limestone beds; remnants of original bedding preserved in nodules; most primary structure obliterated by bioturbation; small scale shallowing-upward cycles.	Low energy (shale), punctuated by storm winnowing events (carbonate), reworked by bioturbation during quiet intervals. References: 1, 2, 3, 4.
Siliciclastic facies				
S1: tabular-bedded arenite	White to grey, angular to subrounded, fine to coarse quartz arenite and feldspathic arenite, and locally, wacke with lime mud matrix. Components: Quartz, microcline, plagioclase, biotite, muscovite, zircon, chromite, chamosite. Cement: typically equant to drusy calcite spar. Carbonate components: skeletal debris, lime mud intraclasts.	Locally abundant <i>Skolithos</i> , especially at tops of beds.	Thickly laminated to medium bedded; amalgamated beds; sharp to erosive bases; local tabular cross-bedding with paleoflow to N and E; planar lamination; interbedded with Facies C1 to form peritidal shallowing-upward cycles, and grading upward to Facies C1 within individual beds.	Peritidal deposits; <i>Skolithos</i> distribution indicates breaks in sedimentation. Reference: 5, 6.

S2: channel-fill wacke	White to grey, fine to coarse, poorly sorted, angular quartz wacke to feldspathic wacke with lime mud matrix. Components: Quartz, lithic fragments, chert, microcline, plagioclase. Carbonate components: micritic intraclasts similar to C1 lithology, rare skeletal fragments including <i>Labyrinthites</i> coral and gastropods.	Horizontal burrows on outermost edges of channel fill.	Medium beds fill small channels (0.5-1 m thick, 5-10 m wide); highly erosive/scoured bases; structureless, trough and tabular cross-bedding, lamination, and contorted bedding; abundant flat-pebble limestone intraclasts in bases of beds. Paleoflow to NW. Erosionally truncates beds of C1 and S1.	Tidal channels of the upper intertidal zone Reference: 5, 6.
S3: feldspathic arenite and conglomerate	Grey to green, fine to very coarse, poorly sorted, angular to subangular feldspathic arenite to feldspathic wacke. Locally contains: 1) well lithified, rounded cobbles of feldspathic arenite, 2) flat-pebble arenite intraclasts with pyrite coatings and borings (reworked hardground intraclasts) similar to C5, 3) granule to pebble limestone intraclasts of varying composition, and 4) rounded pebbles of hydrothermal dolomite. Components (sand sized): Quartz, microcline, plagioclase, rare chert, biotite, muscovite, zircon, chromite, chamosite. Cement: equant calcite spar. Carbonate components: echinoderm ossicles, brachiopods, skeletal debris, peloids, micritized grains, highly abraded corals.	Locally abundant horizontal burrows and <i>Skolithos</i> .	Laminae to medium beds; conspicuous directly above paleokarst surfaces, at base of Black Duck Mbr. and Beach Point Mbr, but also occurs as medium beds in the Beach Point Mbr.	Terrestrially-derived alluvial and/or shallow subtidal deposits that prograded out across the ramp during lowstand and earliest transgression. Reference: 2.

S4: green wacke	Green, poorly lithified, feldspathic wacke. Poorly sorted, fine to coarse, rounded grains. Matrix of siliciclastic silt and clay. Cement: where visible, is calcite or dolomite. Components: Quartz, microcline, plagioclase, lithic fragments. Carbonate components: peloids, micritized skeletal fragments.	None.	Thin to medium beds. No internal structure. Horizontal microfracturing of sand grains is common. Occurs only at base of Lourdes Fm., in Unit SP1; poorly exposed.	Subaerial or marine reworking of Mainland Fm. or Humber Arm siliciclastics?
S5: calcareous sandstone	Buff, grey, or green, variably argillaceous, angular to rounded, poorly to moderately sorted arenite and wacke, with micritic or clay matrix and/or carbonate cement. Components: Quartz, microcline, plagioclase, lithic fragments. Carbonate components: limestone intraclasts, skeletal debris, whole brachiopods, pelmatozoans.	Small vertical and horizontal burrows filled with lime mud or sandy lime mud.	Thin to medium beds; commonly laminated; +/- erosive bases; locally fills paleokarst depressions; punctuates limestone successions; local erosional surfaces colonized by high numbers of brachiopods.	Marine reworking of fluvial/longshore supplied sand.
S6: shale	Dark grey to green, variably calcareous, siltstone to sandy shale; friable and recessive, with occasional thin limestone beds. Components: Quartz, feldspar, muscovite, biotite, fine pyrite phosphatic fragments (inarticulate brachiopods?). Minor chlorite. Carbonate components: trilobites, ostracodes, brachiopods, and rugose corals. Fossils = 1-15%.	Small horizontal burrows; mild bioturbation.	Medium to thick lamination with occasional thin graded limestone beds.	Low energy, offshore, with distal storm beds; deposition via suspension. Reference: 3.

References:

1. Flügel (2004), 2. Handford and Loucks (1993), 3. Holland (1993), 4. McLaughlin et al. (2004), 5. Shinn (1986), 6. Tucker and Wright (1990).

Table 2-3: Distribution of facies within the Lourdes Formation. Bold text indicates facies is limited to a single unit.

Member	Unit	Major Facies	Minor Facies
Beach Point Member	BP3	C5 C6 M1 S6	C2a C3a C3b S5
	BP2	C2a C2b C3b	C5 M1 S5
	BP1	C2a C2b M1 S6	S3 S5
Black Duck Member	BD3	C7 C6	C4 C5
	BD2	C2a	C4
	BD1	M1 S6	C5 S5
Shore Point Member	SP4	C1 S1	S2
	SP3	C1 S1	S2
	SP2	S5	
	SP1	S4	

C1: Lime mudstone

This sandy, locally channelized facies (Fig. 2-5) with fenestral, desiccation and local microkarst features (Table 2-1) contains different interbedded biofacies: (a) a restricted assemblage consisting of ostracodes and gastropods accompanied by intense bioturbation; and b) a more diverse assemblage of fragmental pelmatozoan ossicles, calcareous red algae, bryozoans, and trilobite and molluscan debris. The overall lithology and inorganic sedimentary features are typical of low-energy prograding tidal flats, including tidal channels (Pratt et al. 1992; Shinn 1986). A typically low-diversity faunal assemblage marks overall restriction and/or environmental stress (Holland 1993), whereas beds containing a more diverse biofacies likely reflect normal marine sediments transported shoreward by storms.

C2: Skeletal/cortoid grainstone

Two subfacies (Table 2-1; Fig. 2-6) are recognized within this grainstone facies on the basis of allochem constituents. Subfacies C2a contains a diverse mixture of skeletal allochems and rare coated grains, whereas subfacies C2b is an oncoid-bearing cortoid grainstone with common non-skeletal components (Table 2-1).

The stenohaline pelmatozoans dominating subfacies C2a indicate an open marine environment, with bedding characteristics (Table 2-1) suggesting common transport and reworking due to either storms or strong currents. This largely encrinitic subfacies represents widespread pelmatozoan meadows, whose sediment was locally reworked into banks, bars, and blankets by currents and/or storm events (Aigner 1985; Ausich 1997). The subfacies may have formed extensive coastal shoals or fringing banks (Read 1985) or subtidal sand sheets during transgression (Holland 1993; McLaughlin and Brett 2004).

Fig. 2-5: Peritidal facies. A) Facies C1 and S1, Unit SP4, Section 3. Lowest bed contains planar cross-stratified calcareous sandstone (Facies S1) with thin overlying bed containing desiccation cracks (arrows). Uppermost bed is intensely bioturbated, sandy lime mudstone (Facies C1). B) Bedding-plane view of desiccation cracks in Facies C1; Unit SP4, Section 4. C) Stacked tabular beds, Facies C1 and S2, truncated by a small tidal channel. Erosional channel base is indicated by arrow. Unit SP4, north of Section 3; staff is 150 cm high. D) Thin section photomicrograph of lime mudstone, Facies C1. Micrite matrix surrounds an ostracode (o), and a fenestral pore (f), which each contains a thin layer of geopetal silt and blocky calcite cement. Smaller quartz sand and silt and very fine skeletal fragments are scattered throughout. Plane polarized light.

Fig. 2-6: Grainstone, Facies C2 and C3. A) Meter-scale skeletal grainstone beds of Facies C2a, mostly tabular and structureless near the base, with trough cross-beds (arrow) higher in the section. Unit BP1, Section 15; staff divisions are in 10-cm increments. B) High-angle cross-stratification (arrow) and scouring, Facies C3a; Unit BP2, Section 20. C) Grainstone, Facies C3a, with cross-stratification in lower bed and erosional scour (arrow) at base of overlying coarser bed. Unit BP2, Section 20.

In subfacies C2b, large (3-10 cm diameter), mostly sub-spherical oncoids are concentrated in discontinuous beds or along bedding planes (Fig. 2-7). Oncoids have smooth outer surfaces, and are composed of grains similar in composition to the surrounding grainstone matrix. Their centres are usually clumps of *Girvanella*, surrounded by faintly concentric grainstone laminae with an open meshwork of *Girvanella*. Grains are cemented by isopachous and luminescent, bladed to equant calcite and a later stage of non-luminescent equant to drusy mosaic spar.

The initial non-luminescent cement likely defines an oxidizing seafloor or near-surface diagenetic environment that allowed rapid cementation. Large patches of non-luminescent calcite cement and smaller local areas where grains appear to be floating in calcite spar (Fig. 2-7B) suggest that either matrix mud or some sort of binding agent (microbes?) has been dissolved and replaced by cement. Cortoid grains are linked to the destructive or constructive action of cyanobacteria, algae, and fungi, which is most intense in warm, shallow marine settings (Flügel 2004). Bedded grainstones containing a high percentage of grains with micrite envelopes, together with rounded bioclasts, are characteristic of current-washed sand shoals of inner-ramp settings or in winnowed platform-edge sands (Flügel 2004). Unlaminated or weakly laminated meshwork-fabric oncoids are usually indicative of quiet-water conditions (Flügel 2004), and *Girvanella* oncoids in particular may be diagnostic of slow sedimentation rates (Peryt 1981). This combination when associated with a cross-bedded grainstone suggests that oncoid growth occurred during inter-storm periods. As HCS is also characteristic of relatively shallow water and shoreface depositional environments (Dumas and Arnott 2006), subfacies C2b may have developed shoreward of subfacies C2a.

Fig. 2-7: Large oncoids of Facies C2b. A) Bedding-plane view showing variety of sizes and sub-spherical shapes of oncoids; Unit BP1, Section 19. B) Photomicrograph showing internal structure of a large oncoïd. Grains are rounded skeletal grains and cortoids, and dark micritic areas are mostly composed of *Girvanella*. Pore space is occluded by blocky calcite spar. Plane-polarized light.

C3: Oncoid intraclast grainstone

Facies C3 (Fig. 2-8) contains two subfacies best differentiated on the basis of bedding attributes (Table 2-1). Both contain a diverse faunal assemblage, with a high proportion of pelmatozoan material. In subfacies C3a, highly scoured bedding contacts (Fig. 2-6C) and hummocky cross-stratification (HCS) give an overall lenticular aspect to the bedding. This subfacies is usually underlain by Facies C6 and S6 to form rhythmic meter-scale, coarsening- and shallowing-upward intervals, and is interpreted as a high-energy, shallow subtidal to emergent deposit. Early lithification is defined on the basis of beds truncated at steep angles and small-scale erosional features visible in thin section (Fig. 2-8A).

The oncoids in this subfacies (Fig. 2-8B) rarely exceed 20 mm in size and display a range of shapes, with nuclei of particles (pelmatozoan, composite carbonate, terrigenous) encrusted with asymmetric sets of thinly and crinkly laminated micrite, or with slightly thicker layers of *Girvanella* filaments forming a laminated or meshwork fabric (Fig. 2-8B). Sets of laminae are frequently disconformable, likely indicating episodic rotation of oncoids.

Subfacies C3b differs by its fragmental bedding fabric of small blocks varying from highly disorganized to slightly rotated from normal bedding (Fig. 2-8E). Many intraclasts within this facies possess brownish iron oxide-stained margins encrusted by *Girvanella* (Fig. 2-8D). The fragmented bedding is evidence of early lithification. Association with black chert nodules (Table 2-1) may identify lithification as a product of subaerial exposure (Holland and Patzkowsky 1998), and iron staining may identify incipient paleopedogenesis (Flügel 2004).

Fig. 2-8: A-C: Photomicrographs of oncoid-intraclast grainstone, Facies C3a, in plane-polarized light. A) Small-scale erosional surface (arrow) identifying early lithification and erosion from truncation of grains and small composite grains/intraclasts. B) Small, dense oncoids formed of nuclei of skeletal grains and cortices of dense, irregularly laminated micrite. Laminae are asymmetric and contain multiple micro-unconformities. Matrix contains rounded skeletal grains with well-developed micrite envelopes. C) Cortoid grains showing evidence of both destructive micritization due to microboring (dark, inner rim) and constructive micritization due to encrustation likely related to cyanobacteria (lighter, outer rim). D-E: Highly fragmented intraclast grainstone, Facies C3b. D) Photomicrograph (plane polarized light) of an intraclast with iron-rich rim (dark arrow) and encrustation by *Girvanella* (white arrow). E) Field photo showing both *in situ* brecciated and bounding intact bedding of Facies C3a; Unit BP2, Section 20.

C4: Fine-grained peloidal-skeletal grainstone to packstone

This facies is well stratified with planar, low-angle and HCS fabrics (Fig. 2-9; Table 2-1). Stratification stands out in field exposures because it occurs within otherwise burrowed and nodular Facies C6, creating a “laminated to scrambled”, or “lam-scram” fabric (Bromley 1990). C4 beds likely represent rapid deposition related to storm transport, with bedding-top burrows developed between storms.

C5: Hardground and intraclast rudstone

Finely crystalline and framboidal replacement pyrite form discontinuous impregnation mineralization rims along erosional surfaces that possessed existing endolithic borings (Fig. 2-10; Table 2-1) identifying hardgrounds. Pyrite alteration also affects margins of intraclasts that form coarse-grained rudstone lenses to thin beds, commonly above an erosional surface or hardground. These pyritized surfaces and intraclast lags occur in the various grainstone and packstone facies, and are most prominent near the top of the Lourdes Formation.

Individual pyrite crystals and framboids occur disseminated throughout Lourdes Formation sediment and likely reflect bacterial sulfate reduction associated with oxidation of organic matter in the near subsurface. However, alteration of intraclasts and surfaces requires a longer-term or focused process of pyritization. One model that fits with lag deposit formation and hardground surfaces in the Lourdes Formation is that of Hallam (1969), wherein a given surface or lag deposit represents multiple episodes of shallow burial, reworking, and exhumation, with pyritization associated with stages of reburial. For the Newfoundland paleosurfaces, slow rates of sedimentation coupled with episodic storm current or wave erosion was a likely control on burial and exhumation.

Fig. 2-9: Fine peloidal-skeletal grainstone, Facies C4. A) Bed (between arrows) of Facies C4 with low-angle cross-stratification representing hummocky cross-stratification; Unit BP2, Section 20. B) Stacked beds of laminated fine grainstone with erosive contact (arrow). Beds become amalgamated toward the right. Unit BP2, Section 17. C) Thin section photomicrograph of fine peloidal grainstone, Facies C4. Plane polarized light. D) Detail of thin section shown in C. Dark grains (P) are mostly peloids and less common light-coloured grains (Q) are angular quartz silt to fine sand. Skeletal grains, such as the echinoderm fragment indicated (E) are typically highly fragmented and difficult to identify. Cement consists of epitaxial calcite overgrowths on echinoderm fragments and blocky equant calcite spar. Plane polarized light.

Fig. 2-10: A) Dark, pyrite-encrusted, bored hardground surface capping a bed of calcareous sandstone near base of Unit BP1, Section 12. B-D: Hardground-intraclast rudstone, Facies C5. B) Imbricated, pyrite rimmed flat intraclasts in a limestone bed, interbedded with recessive shale. Unit BP1, Section 8. C) Wave-washed outcrop surface showing darkened pyrite rims of intraclasts in a skeletal packstone matrix. Top of Unit BP3, Section 20. D) Photomicrograph (plane polarized light) of a small intraclast from C, showing endolithic boring and darkened rim composed of finely crystalline pyrite.

C6: Nodular packstone

This is the most common and characteristic facies of the Lourdes Formation. The variety of textures, inorganic sedimentary structures, and distribution of siliciclastics (Table 2-1) are often obscured by pervasive bioturbation (Fig. 2-11), yet few individual traces are preserved.

A normal marine, shallow subtidal environment is interpreted for this facies on the basis of diverse faunal assemblage (Table 2-1), relatively coarse grain size, limited abrasion of particles, abundance of siliciclastic sediment that may identify longshore transport, robust fossil morphologies, the frequency of boring and encrustation (Holland 1993), and the intensity of bioturbation (Holland 1993; Mángano and Droser 2004). This environment was affected by episodic storm transport as defined by interbedded C4 deposits (Table 2-1).

C7: Coral bioherm facies

Bioherms of this facies, described by James and Cuffey (1989), occur in the middle member of the Lourdes Formation, and are described in greater detail in Chapter 4. In general, bioherms consist of a framework of large, stacked colonies of *Labyrinthites chidlensis* along with other corals, stromatoporoids, and sponges. Spaces between framework elements are filled by detrital sediment or boundstone. The detrital sediment consists of graded laminae of skeletal wackestone with silt and fine sand. This material represents a combination of bioherm-derived debris and suspension fall-out of detrital material, probably related to storms. The boundstone component consists of micritic, microbial-stromatoporoid boundstone containing several microfossils representing

Fig. 2-11: Facies C6 and C7. A) Highly bioturbated, nodular packstone, Facies C6, near top of Unit BD3, Section 8. Poorly preserved thin bedding below the sharp bedding plane is mostly obscured by bioturbation whereas upper bed is thoroughly bioturbated. Hammer for scale. B) Thin section photomicrograph of Facies C6. Grains include fragments of echinoderms (E), bryozoans (B), and trilobites (T), a lithistid sponge encrusted by *Girvanella* (G), peloids (P), and intraclasts (I). Large intraclast in lower right exhibits an uneven coating of micrite and *Girvanella*. Cement is equant calcite spar. Plane polarized light. C) Small dome-shaped coral bioherm, Facies C7 at Locality 4. Bioherm is composed of stacked colonies of *Labyrinthites chidlensis* (some large examples labeled “L”), with lesser contributions from stromatoporoids, and micritic microbial boundstone. Rock hammer for scale (circled). D) Larger, wall-like coral bioherm, Facies C7, at Locality 10. Stratigraphic top is to the left, and total exposed stratigraphy is approximately 6 m. Surrounding sediments are thinly bedded, highly bioturbated packstone, Facies C6.

calcified cyanobacteria (*Girvanella*, *Wetheredella* sp., *Sphaerocodium* sp). This lithology also hosts silt-filled stromatactoid cavities similar to “polymud” fabric *sensu* Lees and Miller (1985). Lenses of skeletal grainstone formed bases upon which some of the bioherms nucleated, and reef debris forms horizontal grainstone beds and wedges adjacent to bioherms. The bioherms range in shape from small mound-shaped structures to tall (up to 15 m in stratigraphic height) narrow forms (Figs. 2-11C, D); however, the actual height above the seafloor during growth was probably never more than 1 m.

The primary strategy of reef growth was the formation of a rigid skeletal framework by the stacking and intergrowth of large corals and to a lesser extent, stromatoporoids; however, lesser contributions from microbial precipitation and boundstone growth show similarities with mud mounds which dominated pre-Devonian reefs elsewhere. The inter-bioherm level-bottom sediment is Facies C6 (nodular packstone). Thus, Facies C7 formed in a similar shallow subtidal, normal marine setting with good circulation, and subjected to intermittent periods of high energy.

M1: Argillaceous nodular packstone facies

This facies is a composite of thinly interbedded, fine- to coarse-grained, normally graded skeletal limestone (Table 2-1) interbedded with fossiliferous, bioturbated to laminated calcareous shale, locally defining small-scale shallowing-upward cycles. This facies is typically underlain by Facies S6 (shale), and contains local hardgrounds and intraclasts of Facies C5.

Environmental controls were likely similar to those defining the C4-C6 facies association. M1 limestones are interpreted to identify storm deposits whereas intervening shales and elevated bioturbation correspond to periods of quiescence. The substantially

higher shale content is interpreted to document a more seaward, deeper, and overall lower-energy setting.

S3: Feldspathic arenite/conglomerate

This poorly sorted facies is confined to a single, but stratigraphically important occurrence at the base of the Beach Point Member, filling small paleokarst fissures and galleries in the upper meter of the underlying platform. The range in texture and clast lithologies, including large, well abraded, and bored coral colonies (Fig. 2-12C), reveals a mixture of numerous siliciclastic, carbonate, and even hydrothermal dolomitic sources.

Stratigraphic and compositional attributes suggest that terrigenous clastic sediments prograded out across the exposed platform following a sea-level lowstand. These sediments were likely reworked and admixed with carbonate debris derived from the underlying platform during subsequent early transgression. The presence of detrital pebble clasts of saddle dolomite (which identifies an elevated, $>80^{\circ}\text{C}$, temperature of formation; Spötl and Pitman 1998) suggests that tectonic uplift coincident with the Lourdes interval, or possibly some earlier event, exhumed and reworked dolomite veins associated with older strata (T. Lane, pers. comm., 2005).

S4: Green wacke

This facies, restricted to the base of the Lourdes Formation (Fig. 2-12D), is thinly bedded, poorly lithified, and contains no obvious environmentally diagnostic features. Its stratigraphic position relative to the regional tectonic framework (Stockmal et al. 1995) suggests that the sediment may be reworked from upper Goose Tickle Group or Humber Arm sources.

Fig. 2-12: Mixed sediment (M1) and siliciclastic (S) facies. A) Discontinuous argillaceous nodular packstone and shale, Facies M1; Unit BD1, Section 5. B) Interbeds of friable shale, Facies S6, and graded limestone storm beds; Unit BP1, Section 9. C) Feldspathic arenite to conglomerate, Facies S3. Lobe of siliciclastic debris in bottom left of photo overlies highly burrowed limestone (Facies C6; marked) of Unit BD3. The paleokarst contact has about 10 cm of relief including a significant overhang (arrow). Pebble-sized clasts of well-lithified sandstone (S), and highly abraded and rounded corals (C) are indicated. Base of Beach Point Member, Section 12. D) Green wacke, Facies S4, forming the base of the Lourdes Formation, Section 1, directly overlying recessive friable argillite of the Humber Arm Allochthon. This surface has been recently interpreted as a major regional thrust fault. Scale card is 8.5 cm long.

S5: Calcareous sandstone

This facies locally fills paleokarst cavities, forms thin to medium beds punctuating limestone successions, and composes all of Unit SP2 (Table 2-3). Locally, irregular erosional surfaces are colonized by large numbers of whole, *in situ* brachiopods, and rare crinoid holdfasts suggesting that a firm to hard substrate had developed. This facies represents reworking of terrigenous sediment, admixed with carbonate components, and possibly transported by currents.

SILICICLASTIC PROVENANCE

Mineral and geochemical data

Three datasets identify a prominent change in sedimentary provenance across the Mainland-Lourdes formation boundary and the lower Lourdes Formation. Data are based on a representative stratigraphic coverage of sandstones from the Lourdes Formation (Fig. 2-4), as well as two random samples of the Mainland Formation (southwest of Long Point Peninsula), and one from the Humber Arm Allochthon exposed beneath the interpreted thrust fault underlying the Lourdes Formation at Locality 1 (Fig. 2-1).

Point-counting (Fig. 2-13) reveals that the mostly monocrystalline quartz and feldspathic (microcline) sandstones of the Lourdes Formation (Table 2-1) fall within the mature continental block provenance (Dickinson and Suczek 1979; Fig. 2-13). Zircon grains, counted as lithic fragments, make up most of the lithic component. Detrital opaque minerals, which were not included in point-counting totals (Dickinson and Suczek 1979), were examined by electron microscopy and include rounded grains of chromite and Ti-Fe oxides. Samples of the Mainland Formation and the Humber Arm strata, in contrast,

Fig. 2-13: Point counting data, sandstones. Provenance fields are from Dickinson and Suczek (1979), and minerals as indicated: Q=quartz, Q(m)=monocrystalline quartz, F=feldspar, L=lithic fragments. Long Point Group sandstones cluster in the “continental block provenance” field in contrast to older sediments from the Mainland Formation and the Humber Arm Supergroup that identify “recycled orogen” provenance.

contain greater amounts of lithic fragments, and fall within the recycled orogen provenance field (Fig. 2-13), fitting previous provenance interpretations for these units (Quinn 1995; Schwab 1991).

Geochemically-defined provenance divisions based on Sc, Th, La, and Zr/10 (Bhatia and Crook 1986) offer inconclusive results (Fig. 2-14A). However, comparison of Y/Ni to Cr/V ratios (McLennan et al. 2003), previously used to identify ophiolitic sources for the Goose Tickle Group in western Newfoundland (Hiscott 1984), shows that samples from the upper Long Point Group (Winterhouse and Misty Point formations) have ratio ranges similar to this older stratigraphic group, whereas the Lourdes samples with higher Y/Ni ratio (Fig. 2-14B) reflect greater felsic content (McLennan et al. 2003).

Rare earth element (REE) datasets (Fig. 2-15) normalized to the rock/chondrite standard of Nakamura (1974) illustrate a common profile geometry trend and relatively tight clustering of samples from the Misty Point, Winterhouse, and Humber Arm Allochthon sandstones (Fig. 2-15). The Lourdes samples have similar profile geometries, but identify an apparent upsection (Shore Point to Beach Point members) transposition to higher rock/chondrite ratios. This likely documents decreasing dilution by silica, identifying more quartzose and feldspathic siliciclastics in the Shore Point Member.

Paleocurrent data

Paleocurrent measurements (Fig. 2-4) from the Lourdes Formation identify a prominent northeasterly transport direction for unidirectional currents, and a smaller northwest component that includes tidal channel measurements. Paleocurrent directions for the Mainland Formation, in contrast, are largely southwesterly (Quinn 1988; Quinn 1995) indicating a pronounced change in orientation across the Mainland-Lourdes

Fig. 2-14: A) Inconclusive division of sedimentary provenance for the Lourdes Formation based on La, Sc, Th, and Zr/10, following Bhatia (1984). B) Y/Ni versus Cr/V with data from the current study compared to data from the Goose Tickle Group and the Mainland Formation (Hiscott 1984). Sample size for the Lourdes is small (3), but the formation shows higher Y/Ni values suggesting higher proportion of input from felsic sources.

Fig. 2-15: Rare Earth Element (REE) plots for sandstones of the Lourdes Formation (A), compared with (B) overlying siliciclastic rocks of the Winterhouse and Misty Point formations, (C) underlying siliciclastic of the Mainland Formation, and (D) allochthonous sandstones from the Humber Arm Supergroup. All samples are normalized to chondrite values (Nakamura 1974).

formation boundary coincident with a prominent change in sedimentary provenance.

DISCUSSION

Paleogeographic and climatic framework of the Lourdes platform

The Lourdes Formation is the only carbonate component of the Taconic foreland basin-fill succession that post-dates westward overthrusting of Taconic allochthons (Fig. 2-2; Cooper et al. 2001). It lay on the outboard orogen side of the foreland basin, part of regional onlap onto the underlying Taconic Unconformity and emplaced Humber Arm Allochthon strata (Fig. 2-2; Cooper et al. 2001). The change in prominent paleocurrent directions across the Goose Tickle Group-Lourdes Formation boundary reflects change in the region's oceanographic framework across the Taconic Unconformity. According to the reconstruction of Cooper et al. (2001), the Lourdes platform may have developed adjacent to an exposed portion of the Humber Arm Allochthon or a structural ridge of intercalated Goose Tickle and Humber Arm rocks. A previous interpretation of submarine ridge (James and Cuffey 1989) does not necessarily explain the abundance of siliciclastics within the formation. Stockmal et al. (1995) suggested that the platform formed along a flexural bulge, within a still tectonically active basin; it would form a *back-bulge* platform in the revised tectonostratigraphic framework of Cooper et al. (2001). It is likely that the platform once lay adjacent to a tectonically complex eastern hinterland, the probable source of reworked ophiolitic detritus during Goose Tickle through Long Point Group time (Quinn 1995).

In the Late Ordovician, the Lourdes platform lay at tropical (approximately 15-20° South) paleolatitudes (Dalziel 1997; Jurdy et al. 1995; Scotese and McKerrow 1991)

during the waning phase of greenhouse climate (Barnes 2004a; Wilde 1991). Climate cooling is recorded in the equivalent late Mohawkian to early Cincinnati succession of eastern North America (Lavoie and Asselin 1998; Patzkowsky and Holland 1993; Pope and Read 1997b). Fauna typical of tropical carbonate “photozoan” assemblages (e.g., tabulate corals, stromatoporoids) become smaller and less abundant moving upsection through the Beach Point Member, and disappear by the base of the overlying Winterhouse Formation. Calcareous green algae, once common in Middle Ordovician carbonate successions in the region (Klappa and James 1980), are absent from the Lourdes Formation. The biotic assemblage of the Winterhouse Formation (brachiopods, graptolites, trilobites, nautiloids, rugose corals, conodonts, and receptaculitids; Quinn et al. 1999; Stait and Barnes 1991) may represent a more temperate-water biota compared to the predominant tabulate coral and stromatoporoid assemblage of the Lourdes carbonate ramp.

According to regional climate maps (e.g., Boucot et al. 2004; Golonka et al. 1994; Pope and Read 1998), the study area lay in a latitudinal arid zone. However, locally it was likely more semi-humid as illustrated by minor development of paleokarst but lack of significant topography on exposure surfaces, by evidence of relatively abundant siliciclastics in the Lourdes Formation itself, and especially by the concentration of coarse-grained siliciclastics (Facies S3), that requires some fluvial network transporting sediments from the hinterland to the coastline for redistribution. The predominance of skeletal banks as opposed to ooid shoals may identify a meteorological influence on local ocean salinity (Read 1985); and, the absence of evaporites, evidence of dissolved evaporites, and dolostones within the peritidal facies of the Lourdes Formation suggests humid or semi-humid environmental conditions (Pope and Read 1998).

Facies development of the Lourdes platform

Distribution of facies in the Lourdes Formation, and their arrangement from peritidal to mid-ramp settings, suggest that the formation represents a relatively high-energy carbonate ramp (Fig. 2-16; Burchette and Wright 1992). The evidence for ramp morphology is circumstantial given that the outcrop exposures do not contain the entire spectrum of inner platform to deep basinal facies, nor is there a facies association marking a shelf-slope transition. Instead, the bioherm (C7) facies along with Facies C2, C3, C4, and C6 identify environments extending from peritidal to mid-ramp settings, and, most importantly, forming no obvious impediment to circulation. The presence of coarse-grained, cross-bedded sandstones in the subtidal portion of peritidal cycles indicates relatively high-energy, shoreline-proximal environmental conditions; there is no evidence for extensive low-energy shallow subtidal facies as one often finds protected from open-ocean energy by a prominent shelf-slope break, whether reef or shoal-rimmed or not (Jones and Desrochers 1992). The predominance of high-energy facies in the Lourdes Formation is not unlike the widespread coarse-grained facies extending across the high-energy, Holocene ramp that underlay the North West Shelf, Western Australia (James et al. 2004).

Outcrop exposures indicate a minimum 15 km (=length of Long Point exposures) breadth for the Lourdes platform (parallel to strike). The width of the carbonate portion of this platform was likely on the order of only a few tens of kilometers, with the low-energy, deeper water S6 shales and minor interbedded graded limestones (Table 2-1) documenting the outermost exposed ramp setting.

The proposed facies model (Fig. 2-16) illustrates interpreted facies arrangements

Fig. 2-16: Dynamic facies model, Lourdes Formation, showing distribution of facies and timing of siliciclastic flux relative to late transgression and highstand/stillstand of sea level (top), and transgression (bottom). Ramp subdivisions (inner and mid-ramp) are based in Burchette and Wright (1992). Facies characteristics of environments are shown in corresponding boxes, and interpreted extent of each stratigraphic member is illustrated by arrows. Other symbols: sl = sea level, fwwb = fair-weather wave base, SWB = storm wave base.

during periods of highstand and transgressive conditions. Sea-level variation clearly influenced not just facies distribution, but led to exposure and erosion of proximal portions of the ramp defining inter-member boundaries (Fig. 2-4). Further definition of controls by eustasy, tectonism and sediment supply on platform development is to be dealt with in Chapter 3.

The Lourdes Formation is a mixed carbonate-siliciclastic succession, and carbonate sediment accumulation was not in physical isolation from siliciclastic input and distribution largely controlled by the rate of sea-level rise. Abundance of chemically mature siliciclastic sediments in the lower Lourdes Formation, compared to the underlying Goose Tickle strata and higher in the Lourdes platform (Figs. 2-13, 2-15) indicate either (1) a sedimentary source related to erosion of Grenville crystalline basement or Lower Paleozoic sandstones, or (2) weathering of Goose Tickle Group and/or Humber Arm strata and concentration of quartzose sediments during the 6-8 my time period represented by the Taconic Unconformity. The first possibility seems unlikely given the position of the platform within the foreland basin (Cooper et al. 2001). Instead, tens to several hundred metres of rock-surface reduction of Humber Arm and Goose Tickle Group strata could have occurred in the time interval represented by the Taconic Unconformity assuming very conservative rates of sandstone weathering (Turkington and Paradise 2005). As suggested by the shift in REE profiles (Fig. 2-15), the availability of strongly weathered sediment decreased upsection with platform development, suggesting that continued influx of siliciclastics included less chemically mature sediment derived from ongoing erosion, probably of Goose Tickle and Humber Arm strata. This recycling likely explains the inconclusive trace-element provenance dataset (Fig. 2-14A).

At times of slow sea-level rise and stillstand (Highstand Systems Tract, HST) during platform growth, fluvial sources reworked by longshore transport provided sand to inner ramp regions whereas finer sediment, carried in suspension, was transported to more distal reaches of the ramp (Fig. 2-16). During periods of rapid rise in relative sea level (Transgressive Systems Tract, TST), large portions of the siliciclastic source area would have been submerged and sand and shale trapped in shoreline areas, leaving starved or “winnowed” clean carbonates forming grainstone sheets or bars across much of the ramp (Fig. 2-16). Similar models have been proposed for Ordovician mixed successions in the U.S. (Holland 1993; McLaughlin and Brett 2004; McLaughlin et al. 2004), for a storm-dominated Upper Jurassic ramp in Spain (Bádenas and Aurell 2001), and for a Cretaceous carbonate ramp in the Sinai region (Bachmann and Kuss 1998).

A seaward environmental gradient from shoreward carbonates to mid-ramp shale as defined for the Lourdes ramp (Fig. 2-16) predicts that the slowest rates of deposition will reside in Facies C5 and M1. This is where carbonate and shale lithologies overlap, and where there is an inhibiting effect of terrigenous deposition on carbonate production (Walker et al. 1983).

Within the framework of regional onlap (Fig. 2-2; Cooper et al. 2001), demise of the Lourdes platform marked by increased abundance of siliciclastics at the Lourdes-Winterhouse formation boundary is unexpected unless renewed tectonism increased siliciclastic input. At approximately this same time in the mid-Mohawkian within epicontinental platforms in the eastern United States, a major pulse of siliciclastic sediment related to the northern phase of the Taconic orogeny influenced the north-central portion of eastern Laurentia (Holland and Patzkowsky 1996).

Upper Ordovician platform successions, eastern North America

The Lourdes carbonate ramp is equivalent to Upper Ordovician epicontinental foreland platforms along eastern Laurentia represented by Black River and Trenton platform successions of eastern Ontario and southern Quebec (e.g., Lavoie 1995; Lavoie and Asselin 1998; Prave et al. 2000; Salad Hersi and Dix 1999; Stait 1988), central and eastern New York (Cameron and Mangion 1977), and sequences M1 to M3 of Holland and Patzkowsky (1996), or supersequence 2 of Pope and Read (1998), of the central Appalachians.

In contrast to the interpreted narrow platform width for the Lourdes Formation, the above successions formed extensive platforms allowing establishment of oceanographically restricted litho- and biofacies within the platform interior regions. There are similar interpreted ramp morphologies (e.g., High Bridge Group; Read 1980) and general facies distribution as found in the Lourdes Formation. Pervasive bioturbation and wavy-bedded nodular limestone are reported from these successions, and widespread skeletal and peloidal carbonates, as well as carbonate buildups, are common throughout the region (Holland and Patzkowsky 1996; Ludvigson et al. 2004). Notably different from the Lourdes Formation are the presence of major oolite bodies, presence of diverse green and red algae, and in the Nashville Dome region, the development of a wide, low-energy, flat-topped carbonate shelf (Holland and Patzkowsky 1996; 1997). This may be explained by the much greater width of the foreland platforms allowing for more diverse oceanographic (salinity, temperature, energy) characteristics.

Significance to Late Ordovician biodiversity

A large-scale shift in carbonate depositional style and platform development

occurred in the western Newfoundland region from Cambrian through Ordovician time (Fig. 2-1B). This succession represents not only the influence of basin origin and tectonics, but probably also changes in the marine biosphere for the Cambrian to Lower Ordovician (James et al. 1989), and likely climatic factors influencing the transition from Middle to Upper Ordovician successions.

A secular change in biota appears to have been captured within the Lourdes interval. Bioherms (Facies C7) are among the earliest known reefs to show true dominance of a constructor guild (Batten Hender and Dix 2006). The Black Duck Member also contains the highest biodiversity of the Long Point Group: nektonic taxa (orthocone cephalopods), mobile benthic organisms (trilobites, gastropods), microbiota, sessile filter-feeders (corals, brachiopods, bryozoans, sponges, etc.), evidence of very active infauna, and common endolithic borings (compare Table 2-1 with Table 2-3). As the Long Point Group is part of a grand basin-fill succession otherwise dominated by siliciclastics, it remains to be determined if the short-lived mixed siliciclastic-carbonate depositional system of the Lourdes Formation established significant environmental pressures to cause changes in paleoecological structure of reef-forming biota; or, did the unit's seemingly fortuitous appearance simply capture a global temporal event?

CONCLUSIONS

The Lourdes Formation represents a storm-influenced, mixed siliciclastic-carbonate ramp succession that formed on the Laurentian margin during the early to middle Caradocian, within a foredeep basin developed during Taconic orogenesis. The ramp formed adjacent to a sedimentary source that initially supplied significant volumes of quartzofeldspathic siliciclastic sediment of mature continental block provenance.

Facies types represent a range of environments and water depths from inner ramp tidal flats to shaley mid-ramp deposits, with distribution related to energy, water depth, and supply of siliciclastic sediment likely related to rate of relative sea-level rise. Highstand systems tract deposits contain large amounts of sand and siliciclastic mud admixed and interbedded with carbonate, whereas transgressive systems tract deposits are relatively free of siliciclastics, and are characterized by thick sheets or shoals of skeletal grainstone and lower accumulation rates. The demise of the carbonate ramp was likely caused by increased influx of sand and mud linked to tectonism along the basin margin, as indicated by influx of increased amounts of ophiolitic detritus, as well as changes in paleoceanographic conditions including cooler water temperatures. The Lourdes ramp is equivalent to foreland carbonate ramps in eastern North America. Although ramp morphologies appear to be similar, some prominent differences in facies types may reflect the greater aerial extent of these latter ramp systems creating more variable platform-interior environmental settings.

CHAPTER 3:
CYCLES AND BOUNDARIES: TOWARDS A SEQUENCE STRATIGRAPHIC
FRAMEWORK FOR THE LOURDES FORMATION

INTRODUCTION

The previous chapter provided details of the stratigraphy, facies, and development of the Lourdes platform. Here, additional information and data are presented that will assist in future development of a sequence stratigraphic framework for the Long Point Group.

As established in Chapter 2, the Lourdes Formation is particularly important to our understanding of Late Ordovician Taconic basin evolution following the emplacement of allochthons. Outcrop sections along Long Point (Fig. 2-1) define development and demise of a short-lived (maximum 5-7 my) carbonate platform that lies on the opposite side of the foreland basin (Chapter 2) from the grand epicontinental platforms of eastern Laurentia (e.g., Holland and Patzkowsky 1998; Pope and Read 1997a). The Lourdes Formation offers a unique opportunity to explore the influence and timing of sea level change related to ongoing local and regional tectonism (Stockmal et al. 1995) and eustasy on patterns of platform development relative to patterns defined within epicontinental platform successions across the foredeep in eastern Laurentia.

METHODS

Field methods are outlined in Chapter 2. Selected samples of lime mud and calcite cement were used for stable isotope analysis (G.G. Hatch Isotope Laboratories, University of Ottawa). 0.4 mg powdered samples were reacted with 0.1 mL of H_3PO_4 at 25°C for 24 hours, and then extracted by continuous flow. Measurement was performed on a Thermo Finnigan Delta XP and Gas Bench II. Analytical precision (2σ) is +/- 0.1 permil.

FACIES MODEL

The Lourdes Formation is interpreted to represent the proximal portion (inner ramp and mid-ramp zones) of a high-energy, storm-influenced carbonate ramp. Facies of the Lourdes (Fig. 2-16; Tables 2-1, 2-2) include a range of environments and corresponding water depths, from carbonate tidal flats, across shallow, high-energy grainstone shoals, to mid-ramp shales with thin storm beds composed of fossiliferous limestone (Chapter 2). The proposed facies model for the Lourdes Formation (Fig. 2-16) shows the interpreted distribution of facies during two different time intervals; 1) during periods of rapid rise in relative sea level (TST), and 2) during periods of slow rise in relative sea level and/or sea-level stillstand (HST). In the first interpretation, the ramp was effectively starved of siliciclastic input, due to retreat of the shoreline and resulting flooding of nearshore siliciclastic source areas. As a result, dominant lithologies during transgression are relatively clean carbonates, including thick skeletal grainstone beds, and oncolitic and hardground facies which suggest slow rates of sedimentation. In contrast, during periods of slow sea-level rise, siliciclastic sediment was supplied to the ramp via fluvial sources, and probably redistributed along the coast by longshore currents. Siliciclastic sand and mud were common during these time intervals, and bioturbation was pervasive.

DATA

Boundaries/Significant Paleosurfaces

In sedimentary successions, recognition of boundary types is essential to the development of a sequence stratigraphic framework. Boundaries form as a result of erosion or non-deposition, or from the abrupt vertical superposition of different facies.

General categories of boundaries described below include ambiguous, erosional, and depositional types (Fig. 3-1). Due to lack of condensed intervals and the rarity of subaerial exposure surfaces in carbonate ramp systems, sharp offsets of facies are often the best indicators of bounding surfaces (Emery and Myers 1996; McLaughlin et al. 2004).

Fault/Ambiguous Boundaries (F/A)

The base of the Long Point Group marks an important transition from the older, highly deformed, underlying Humber Arm allochthon, to the relatively undeformed, overlying Lourdes Formation. The boundary is poorly exposed at Tea Cove (Locations 1,2, Fig. 2-1), where the basal sandstone of Unit SP1 overlies highly sheared, soft, green argillite.

The base of the Lourdes Formation was considered to be an unconformity by earlier studies (Rodgers 1965; Stait and Barnes 1991), but unfortunately the significance of this boundary in terms of platform development is obscured by recent re-interpretation of the contact as a regional, north-west dipping thrust fault (Stockmal and Waldron 1993). If the surface is indeed a fault, then the stratigraphic significance of the surface is impossible to interpret. Such a basal fault would mark the plane over which significant (30-40 km) eastward transport of the Lourdes Formation during or after the Silurian took place (Waldron and Stockmal 1991). This fault could theoretically have occurred at any stratigraphic level, not necessarily at the base of the succession, and therefore may not represent the true base of the Lourdes Formation. Subsurface data further underscore the possible insignificance of the surface identified as the base in outcrop exposures; Burden and Williams (1995) report a significantly thicker Lourdes Formation in the subsurface to

Fig. 3-1: Composite measured section through the Lourdes Formation with sequence environmental interpretation and inferred sea-level change. Siliciclastic abundance is estimated based on field observations. Boundary types: F/A = Fault/ambiguous, SU = Subaerial unconformity, FS = Flooding surface, T-H = Transgressive to highstand transition.

Fig. 3-1 (continued).

the southwest, with additional units underlying the stratigraphy described in the current outcrop study.

Subaerial Unconformities (SU)

There are two prominent paleokarst unconformities within the Lourdes Formation, occurring at the top of the Shore Point and Black Duck members. In addition, some less significant, smaller-scale, probable paleokarst surfaces cap peritidal cycles in the Shore Point Member.

The top of the Black Duck Member (Figs. 3-2, 3-3) is the best exposed example, and is traceable across the study area. On a regional scale, it appears to be a relatively planar surface. Minor (ca. 1 m) paleotopographic relief was observed at some localities in the form of low-angle truncation of beds (Fig. 3-2), but there is no measurable difference in thickness of Unit BD3 among sections. Differences in thickness and distribution of siliciclastic beds of Unit BP1 directly above the surface may indicate more subtle topographic variations that are not easily observable in outcrops.

At the outcrop scale, there is some evidence of rare, m-scale solution pans, with flat bottoms and edges forming steep to overhanging surfaces of ca. 10 cm in height, similar to “kamenitza” features described by Desrochers and James (1988), although due to modern, and possibly syndepositional surface erosion, these features are only partially preserved, so the shape is inferred based on presence of a portion of the rounded, steep to overhanging wall (Fig. 3-3A). These pans likely developed on horizontal to slightly inclined, bare to lightly vegetated surfaces where meteoric water pooled and dissolved the underlying limestone (c.f. Desrochers and James 1988; Knight et al. 1991). Large *Labyrinthites chidlensis* colonies at this surface display flat, eroded tops, yet they

Fig. 3-2: Outcrop photographs of the sequence boundary capping the Black Duck Member.

A) Flattened top of a coral bioherm which has been truncated by interpreted subaerial erosion. Overlying beds of Facies S3 drape the resulting paleotopography. B) Differential erosion along the paleokarst surface (arrows). Note the wedge shape of the thick bed of Facies C6 (dotted outline) which directly underlies the sequence boundary. Irregular, unstratified mass to the left is a coral bioherm. Hammer for scale (circled). C) Basal beds of Unit BP1 onlap the irregular sequence boundary surface (dotted). Medium bed at top of Unit BD3 (arrow) is the same bed shown in B. Hammer for scale (circled).

Fig. 3-3: A-B: Detailed field photographs of interpreted paleokarst surface capping the Black Duck Member. A) Exposed edge of a m-scale solution pan, with its base approximately 10 cm below the portion of the karst surface to the upper right. The pan is partially filled by a thin bed of burrowed, calcareous sandstone (middle of photo), which contains larger bioclastic debris, including abraded and bored coral fragments (arrow). Large burrows in the limestone bed are preferentially dissolved providing additional relief at a smaller scale. Scale card is in cm. B) Portion of flat, smooth paleokarst surface, which truncates fossil corals (arrows). Small scale relief is due to preferential dissolution of burrows in the limestone bed.

Fig. 3-3 (continued): C-E: Detailed field photographs of interpreted paleokarst surface capping the Black Duck Member. C) Top surface of Unit BD3 contains large dissolution-enhanced burrows, filled by calcareous sandstone of overlying unit BP1. Red staining in burrows marks the location of a mm-thick crust of framboidal pyrite which lines burrows and coats the paleokarst surface. D, E) Cross-sectional view of small-scale paleokarst depressions (arrows), also lined by thin coatings of pyrite. Other minor, relatively flat sulphide-impregnated surfaces occur directly above.

Fig. 3-3 (continued): F-G: Detailed field photographs of interpreted paleokarst surface capping the Black Duck Member. F) Burrows associated with the paleokarst surface, showing thick linings of framboidal pyrite and interior fill of greenish, argillaceous, sandy limestone. Boxed area contains mm-scale surface pits. G) Bioclastic and siliciclastic debris overlying the paleokarst surface. Some *Labyrinthites chidlensis* corals show high degrees of abrasion and rounding from rolling on the seafloor (R), which others remained *in situ* and were planed off by the unconformity (P). A blanket of bioclastic, calcareous sandstone of Unit BP1 overlies the coarse fossil lag.

Fig. 3-3 (continued): H) Hardground surface at top of Lourdes Formation. The surface appears black due to impregnation by finely crystalline pyrite and is overlain by laminated calcareous siltstone of the basal Winterhouse Formation.

commonly extend up to several centimeters above the paleokarst surface forming small-scale topographic plateaus; the dense coral skeletons were more resistant to dissolution than the surrounding bioclastic, bioturbated, more porous limestone.

Locally, especially on fine-grained, well lithified limestone substrates, the paleokarst surface is flat, smooth, and featureless (Fig. 3-3B). More commonly, the surface is dotted with cm- to dm-scale, sinuous to irregular solution karren (Fig. 3-3C), mimicking and exaggerating burrow morphologies. Burrow fill in Unit BD3 is typically sandy, and therefore more porous than wackestone and packstone of the surrounding sediment, favoring local dissolution. In rare cases, isolated cm-scale solution pits occur as isolated solution depressions, unrelated to burrows (Figs. 3-3D,E). The smallest-scale features are shallow, mm-scale micropits which are scattered across otherwise smooth areas (Fig. 3-3F). Small-scale karren are commonly lined by crusts of framboidal pyrite which probably formed post-depositionally, in a shallow-burial diagenetic environment.

The lack of significant surface karren across much of the surface may be due to a lack of slope; karst formation may have taken place on a relatively flat surface, possibly covered by sediment or a proto-soil (c.f. Desrochers and James 1988; Knight et al. 1991). Together with a complete lack of large-scale karst features (e.g., sinkholes, large grikes) the scarcity of karren over much of the surface may indicate a less humid and/or temperate climate.

Transgressive to Highstand Transitions (T-H)

The facies model developed for the Lourdes Formation (Chapter 2) detailed two different conditions for the Lourdes ramp: transgressive conditions, wherein relative sea level rose rapidly, and grainy, clean carbonate facies were dominant across the ramp, and

highstand conditions, during which time sea level rise was slow or at a standstill, siliciclastic sediments were distributed across the ramp, and sedimentation rates were higher. Most of the surfaces that mark a vertical transition between these two groups of facies (the transition from transgression to highstand) in the Lourdes Formation are sharp and easily discernable in outcrop. A typical transition consists of light grey, winnowed grainstone abruptly overlain by shale or argillaceous, green to grey, bioturbated sandstone. The surfaces generally lack any sign of erosion; however, hardground or firmground surfaces may be indicated in some cases, the former by endolithic borings and pyrite encrustation, or the latter by the colonization of the surface by large numbers of benthonic organisms (brachiopods, pelmatozoan holdfasts, bryozoans). Contrast in energy regime across such a boundary is striking. The underlying grainstone is typically medium or coarse grained, cross-stratified, and contains little or no clay, whereas the overlying shale is typically composed of laminated clay and silt.

Flooding Surfaces

Flooding surfaces are evident immediately above or coincident with surfaces of subaerial exposure, as is common in shallow marine settings (Sarg 1988). In the case of the Lourdes Formation, this is best exemplified by the sediments near the base of the Black Duck Member (Fig. 3-3G). Calcareous sandstones and shales containing marine fauna onlap the eroded surface and fill depressions in the paleokarst. No significant erosion/ravinement appears to coincide with flooding events in the Lourdes Formation, however some transgressive intervals likely re-worked lowstand lag debris to some extent.

Flooding surfaces also mark vertical transitions that do not contain evidence of

subaerial exposure. A flooding surface is identified based on sharp facies boundaries that juxtapose more distal, typically transgressive facies lying immediately above shallower, more proximal facies with higher siliciclastic content, characteristic of highstand conditions.

Hardgrounds

Hardground surfaces are common in the Lourdes Formation, particularly in the argillaceous sediments toward the top of the formation. A typical hardground is black on the surface, reflecting a high proportion of fine framboidal pyrite which fills pore space and replaces bioclasts, decreasing in concentration downward into the bed (Fig. 3-3H).

Many hardgrounds contain *Trypanites* borings. These are small, cylindrical cavities, rarely larger than 5 mm in diameter. Internal surfaces of borings are also rimmed by pyrite, as described above, indicating that boring post-dates lithification and erosion of intraclasts, but probably precedes pyritization.

Hardground surfaces are commonly overlain by local accumulations of intraclasts. The intraclasts usually consist of the same lithology as the underlying hardground-capped bed, and possess identical *Trypanites* borings and blackened, pyritic rims (Fig 2-10).

The top of the Lourdes Formation is a hardground surface, located near the northeastern tip of Long Point Peninsula (Fig. 3-3H). This surface displays a typical pyrite rim, and is sharply overlain by calcareous siltstone of the basal Winterhouse Formation. In this particular case, the hardground may represent a marine flooding surface, as it transitions into the siliciclastic-dominated Winterhouse Formation and represents the demise of the carbonate factory on the ramp. Whether this is attributable to a rise in relative sea level or an increase in the influx of siliciclastic detritus is equivocal.

Most other hardground surfaces within the Lourdes Formation are localized and occur with high frequency. They represent conditions of slow sedimentation, and are especially common in the deeper-water lithofacies, associated with periods of transgression. However, the individual surfaces are not laterally continuous or correlatable, and therefore are not likely significant to sequence stratigraphy.

Isotope Study of Paleokarst

Patches of sandstone fill associated with the paleokarst surface near the top of the Black Duck Member were sampled at varying depths below the subaerial unconformity. Stable isotope data for the calcite cement in these sandstones is presented in Fig. 3-4. Most of the values from below the paleokarst surface fall within the predicted $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ range for Caradocian sea water compositions (Shields et al. 2003), and therefore, the visually-identified trends illustrated may not be significant. However, some commentary is presented assuming that the trends in $\delta^{18}\text{O}$ values may reflect sedimentary control. In Sections 9, 12, and 15, $\delta^{18}\text{O}$ values decrease with depth, but without a significant accompanying trend in $\delta^{13}\text{C}$. This change can be explained by either an increase in salinity and/or decrease in temperature during successive upsection cementation, yet without significant input of isotopically light bicarbonate matter derived from organic oxidation (Tucker and Wright 1990).

The simplest series of events that could explain this relationship across an unconformity includes: 1) subaerial exposure leading to cementation of the host limestone and formation of paleokarst, 2) sand infill from terrestrial-derived siliciclastics, 3) progressive carbonate cementation of sand in cavities from the bottom up, precipitated from brackish to increasingly more saline pore water. The proposed increase in salinity

Fig. 3-4: Variation in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in calcite cement with depth, slightly above and immediately below the paleokarst surface that caps the Black Duck Member. Samples are intergranular cement from arenite that fills paleokarst cavities and burrows below the unconformity. Shaded areas indicate estimated $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values for Caradocian sea water according to Shields et al. (2003).

upsection would document progressive cementation during resumption of sea-level rise, arriving at fully marine conditions at the base of the Beach Point Member.

Section 11 shows the opposite trend of increasing $\delta^{18}\text{O}$ with depth, but this may be attributable to a single anomalous sample from 1 m below the paleokarst surface. This particular sample, being the deepest sample point, may not have undergone the same brackish-to-marine diagenetic transition as shallower samples. It is also possible that the sample may have been contaminated by the inclusion of fossils bearing a marine isotope signature within the sampled sand fill. Although every effort was taken to exclude skeletal material from the powdered sandstone samples, small fossil fragments may have been missed. More detailed work using micro-drilling of thin sectioned samples might eliminate some of this uncertainty and also allow better understanding of the complicated diagenetic history associated with this paleokarst surface.

Distribution of Lithofacies

Because onshore exposure of the Lourdes Formation is almost completely limited to a single cross-section parallel to strike, it is not possible to assess the stratal geometry of depositional sequences when traced into more proximal or more distal environments, nor to properly evaluate stacking patterns of parasequences, as might be possible in a study with more extensive regional outcrop or well control. However, the spectrum of facies does share a similar vertical succession at different localities, and general vertical trends are evident.

The Lourdes Formation has been divided into fourteen lithofacies, which are described and interpreted in Tables 2-1 and 2-2. The general facies trends for each member of the Lourdes Formation are outlined below.

Shore Point Member

The 16 m-thick Shore Point Member is distinct from the two overlying members, containing several facies that are unique to the member. The two basal units are poorly exposed, and were examined in trenches dug through overburden at localities 1 and 2 (Fig. 2-1). The lateral continuity of these units is therefore difficult to determine with any degree of certainty. Unit SP1 is composed of Facies S4; this is the only occurrence of this facies in the Lourdes Formation. It does not contain any features diagnostic of marine deposition, suggesting the possibility of terrestrial or marginal marine origin. The overlying Facies S5 beds contain minor lime mud matrix and small burrows, and may therefore indicate the earliest marine incursion.

Rhythmic packages. The upper half of the Shore Point Member (Units SP3 and SP4) contains facies with a distinct peritidal character (Facies C1, S1, S2). Cycles are typically 40-100 cm thick, and consist of calcareous sandstone (S1) at the base and micritic, commonly sandy mudstone to packstone (C1) in the top. Some cycles contain discrete sandstone and limestone beds as couplets, while other cycles are single, muddying-upward beds, locally churned and mixed by bioturbation, probably representing less restricted (subtidal) conditions (Fig. 3-5A). In some cases the sandstone portion is absent and the cycle consists solely of a sandy limestone bed, typically graded, with grading defined by concentration of sand toward the base of the bed. Most cycles are capped by desiccation cracks, reflecting shallowing to sea level and resultant subaerial exposure, although some beds are truncated erosionally at the top. Small tidal channels filled with Facies S2 sandstone erosionally cross-cut tabular beds. The environment is therefore interpreted as a sandy carbonate tidal flat.

Fig. 3-5: Two types of m-scale shallowing-upward cycle. A) Idealized peritidal cycle of the Shore Point Member, consisting of basal cross-bedded or structureless calcareous arenite, overlain by sandy, bioturbated lime mudstone with desiccation cracks or paleokarst features. B) m-scale grainstone cycle of the Beach Point Member, consisting of basal calcareous shale overlain by bioturbated to nodular packstone/rudstone, cross-bedded or hummocky cross-stratified grainstone, and a cap of *in situ* brecciated grainstone. Facies are indicated on the left.

Black Duck Member

The Black Duck Member consists of approximately 30 m of shale, limestone, and minor sandstone.

Unit BD1 consists of argillaceous, nodular to thin-bedded packstone and rudstone, intercalated with dark grey to green silty shale (M1, S6, C6) and rare thin to medium beds of sandstone (S5). The relative proportions of shale and limestone vary both vertically and laterally, possibly representing local point sources of shale input, or facies changes along strike.

Unit BD2 consists of medium to very coarse grained grainstone dominated by pelmatozoan fragments (C2a). Erosional scours, small channels, and planar and trough cross-beds indicate high-energy conditions. One notable bed within the unit is interpreted as a biostrome (Batten Hender and Dix 2006). This <55 cm bed is fairly laterally continuous between Localities 1 to 5 (Fig. 2-1), and is composed of coral, bryozoan, brachiopod, and molluscan fossils. Siliciclastic sand and mud are notably rare to absent in this unit; clean carbonate lithologies are otherwise rare in the Lourdes Formation. This predominantly grainstone unit is interpreted to represent open marine, moderate- to high-energy shoals or tempestites below or near normal wave base (Aigner 1985; Ausich 1997).

Unit BD3 consists mainly of thin to medium bedded, variably sandy wackestone to packstone, which is bioturbated to nodular, with rare, thin interbeds of silty shale (Facies C6). It is most notable for the presence of coral bioherms (Facies C7), composed predominantly of *Labyrinthites chidlensis*, which occur in the uppermost 16 m of the unit (James and Cuffey 1989; Chapter 4). The base of the unit is gradational, and is defined at the first thin, nodular bed above the encrinite beds. The top is a paleokarst surface (see

below).

Beach Point Member

The Beach Point Member marks a return to subtidal sedimentation following exposure and interpreted karstification. It contains a higher proportion of siliciclastic mud than the lower members, and is approximately 30 m thick.

The base of Unit BP1 is defined by sandstone (Facies S3, S5) that drapes and onlaps karst paleotopography and locally contains sandstone cobble intraclasts, highly abraded coral and stromatoporoid fragments, abundant brachiopods, and other assorted shallow marine fossils (Fig. 3-3; 3-6). The remainder of the unit is composed of interbedded silty shale and thin-bedded, nodular wackestone and packstone (Facies S6, M1, C3, and C5). Sporadic thin beds of fine peloidal-skeletal grainstone (Facies C4) have sharp to erosive bases and highly irregular, burrowed tops suggesting periodic storm deposition. The top of the unit is transitional and difficult to pinpoint. Stait and Barnes' (1991) rather arbitrary definition of this boundary, at the first thick (40 cm) biocalcarenite bed, provides inconsistent results when applied to different sections along the coast.

Unit BP2 consists of thin- to thick-bedded oncolite-intraclast grainstone (Facies C3), thin-bedded, bioturbated to nodular wackestone to packstone (C6), and silty shale beds (S6). Pyrite-coated, bored intraclasts and hardgrounds (C5) occur at multiple stratigraphic horizons, and likely formed due to the pyritization of buried hardgrounds and intraclasts below the sediment-water interface, indicating slow rates of deposition.

The uppermost 5 m of the Lourdes Formation constitutes Unit BP3. This interval is particularly argillaceous and nodular, marking a transition into the predominantly siliciclastic Winterhouse Formation. Like Unit BP2, it contains abundant hardgrounds

Fig. 3-6: Annotated mosaic of field photographs from Locality 7 (Fig. 2-1). The interpreted paleokarst unconformity at the top of the Black Duck Member is overlain by an argillaceous to calcareous sandstone bed (lowstand deposit reworked during sea-level rise), and calcareous shales passing upward abruptly into bioturbated limestone of Unit BP2.

and intraclasts with pyrite coatings (Facies C5) indicating slow rates of deposition, and dominant facies are C6, M1, S5, and S6.

Rhythmic packages. Unit BP2 contains m-scale shallowing upward cycles. A typical cycle consists of a basal thin bed of calcareous, commonly fossiliferous shale (Facies S6), sometimes overlain by a highly bioturbated packstone or grainstone (C6), progressing gradually upward to a medium to thick bed of oncoid-intraclast grainstone (C3; Fig. 3-5B). The grainstone facies is interpreted as a high-energy, shallow subtidal to emergent deposit. In some cases, the upper portion of the grainstone bed is brecciated (Facies C3b), with partially rotated blocks indicating early lithification prior to fragmentation, and pink staining due to thin ferruginous coatings of grains. These features may represent the effects of subaerial diagenesis (Flügel 2004).

DISCUSSION

Towards a Sequence Stratigraphic Framework

Significant surfaces are difficult to distinguish in outcrops of the Lourdes Formation, due to the overall shallow-marine origin of the succession. Typical indications of maximum flooding in basinal settings, such as condensed intervals of pelagic fauna, or crusts of authigenic minerals (e.g., glauconite, phosphorite) for example (Handford and Loucks 1993), are not present. As a result, maximum flooding surfaces, or more accurately, maximum flooding intervals, must be interpreted from facies transitions in the shallow-marine deposits that are exposed (Schlager 2005). Maximum flooding intervals in onshore exposures of the Lourdes Formation are therefore placed at the boundary where transgressive facies, typically winnowed, high-energy carbonate grainstone, transition into siliciclastic-rich facies indicative of highstand conditions.

There is little independent physical evidence in the surfaces themselves to indicate significant deepening or condensation.

The identification of bounding surfaces, when combined with facies analysis (Chapter 2) and detailed stratigraphic sections, leads to the recognition of three different scales of cyclicity within the Lourdes Formation. These are described below, in order of increasing cycle thickness.

Meter-Scale Cycles

Peritidal Cycles

The smallest scale of cyclicity is observed in the form of m-scale peritidal shallowing-upward cycles in the Shore Point Member (Fig. 3-5A). These cycles are typical of Ordovician tidal flat deposits (Pratt et al. 1992). Siliciclastic sand is likely derived from fluvial input, possibly re-distributed along the coast by longshore currents. The fossil content of the limestone reflects a mix of restricted fauna (e.g., gastropods, ostracodes) and open-marine organisms (e.g., pelmatozoans) which were probably transported into the tidal flat environment periodically by storm waves.

These sandstone to lime mudstone m-scale cycles represent repeated shallowing to sea-level, suggesting autocyclic tidal flat progradation during sea level highstand (Pratt et al. 1992; Shinn 1986). There is no evident trend in cycle thickness to allow analysis of stacking patterns.

Meter-Scale Grainstone Cycles

Meter-scale cyclicity is also evident in the Beach Point Member. The upward transition from shale to high-energy grainstone, to possibly a poorly developed paleosol

horizon constitutes a second type of shallow-marine, m-scale, shallowing-upward cycle, indicating very different hydrodynamic conditions than the muddy peritidal cycles described above.

Depositional sequences

A sequence is defined as a conformable succession of genetically related strata, bounded at the top and bottom by unconformities or their correlative conformities (Van Wagoner et al. 1988; 1990). Sequences may be interpreted at several different scales in the Lourdes Formation, but the most obvious at the outcrop scale are relatively symmetrical sequences, on the order of 10-20 m, consisting of transgressive and highstand deposits, and in a single case, associated lowstand lag debris.

Systems tracts, which compose sequences, are sets of contemporaneous deposits from linked depositional systems (Sarg 1988). They are defined on the basis of bounding surfaces, as described above, position within the sequence, and relative water depth as interpreted from facies analysis (Chapter 2). Due to the limits of essentially two-dimensional outcrop exposure in the study area, it is not possible to consider large-scale three-dimensional stratal geometry in the interpretation of systems tracts in the current study.

Lowstand Systems Tracts (LST). Lowstand deposits are rare in the Lourdes Formation because of the proximal setting of the exposed sections. In ramp settings, LSTs tend to be thin, and the majority of the sediment is typically deposited in the deeper part of the basin. Stream incision and sediment bypass are usually the most common LST signatures in proximal ramp settings (Sarg 1988; Van Wagoner et al. 1988). Accordingly, the only example of LST deposits occurs in association with the prominent

paleokarst surface (sequence boundary) at the top of the Black Duck Member. There, cobble-sized intraclasts of well-lithified sandstone and pebbles composed of reworked hydrothermal saddle dolomite indicate a terrestrial origin. During subaerial exposure and karst formation, fluvial sources transported terrestrially derived detritus across the exposed portion of the ramp. Most of this material would have bypassed the shallow inner ramp and therefore a related onlapping lowstand wedge is predicted to occur in a deeper-water portion of the ramp. The minor amount of detritus that is preserved directly above the paleokarst surface is a lag deposit that was trapped in surface depressions; most galleries and cavities in the upper portion of the Black Duck Member are filled with sand from the same lowstand source. Some of the material deposited during lowstand was reworked and incorporated into lag deposits associated with the overlying transgressive surface (Fig. 3-6).

Transgressive Systems Tracts (TST). On siliciclastic shelves, rapid rise in relative sea level can force the locus of sedimentation to retreat with the shoreline, leading to minimal terrigenous clastic sediment deposition in distal environments (Van Wagoner et al. 1988). In contrast, carbonate systems typically react to transgression by rapid deposition of carbonate sediment, once an initial lag time has allowed sufficient water depth for full functioning of the “carbonate factory” (Handford and Loucks 1993). On carbonate ramps with a significant siliciclastic input, such as the Lourdes ramp, it is common for transgressive deposits to include clean carbonate grainstone, resulting from the cut-off of siliciclastic sediment supply related to transgression of shorelines (Bádenas and Aurell 2001; Holland 1993; McLaughlin et al. 2004). As opposed to thin grainstone beds produced by storm winnowing during sea level highstand, the whole systems appears winnowed due to siliciclastic sediment starvation (McLaughlin et al. 2004). In

the Lourdes Formation, thick deposits of Facies C2, C4, and C6 constitute the majority of TST deposits (Fig. 3-1). For example, the relatively clean carbonate grainstone of Unit BD2 is interpreted as a TST deposit.

Highstand Systems Tracts (HST). HST deposits form during times of slow sea-level rise and stillstand. Highstand deposits in the Lourdes Formation contain high amounts of siliciclastic sand and clay, supplied from fluvial sources. Sand was likely reworked by longshore transport prior to deposition in inner ramp regions whereas finer sediment, carried in suspension, was transported to more distal reaches of the ramp (Fig. 2-16). Bioturbation is pervasive in highstand sediments, destroying most primary sedimentary structures and imparting a nodular fabric to limestone; only rare high-energy bedforms are preserved indicating episodic storm activity. Small coral bioherms (Facies C7) also formed during the highstand of Unit BD3, within the high-energy inner ramp region. Common HST facies of the Lourdes include C6, M1, and S6, punctuated by storm beds of C4.

Possible higher-order cycles (Subsurface data)

Drilling records from Hunt – PanCanadian Port au Port #1 well indicate that the dominantly limestone portion of the Lourdes Formation exposed on Long Point Peninsula is underlain by two slightly older units: a lower limestone unit, and an upper graptolitic shale (Burden and Williams 1995). In addition, the Lourdes Formation is overlain by the siliciclastic Winterhouse Formation, which has been interpreted by past authors to represent deepening (Stait and Barnes 1991). The resulting pattern of alternating limestone and deep-water shale suggests a higher order of cyclicity, on the order of 100 m, resulting from higher amplitude fluctuations in relative sea level, above that which is

recorded in outcrop exposures. Stockmal and Waldron (1993) suggested that the interpreted deepening event that accompanied Winterhouse deposition may have resulted from very early initiation of the platform and basement-involved overthrusting of the Acadian orogeny.

Scale of Cyclicity in the Lourdes Formation

Traditionally, sequence stratigraphic analysis involves the packaging of sedimentary successions into “orders” of cyclicity, ranked by the duration of the cycle and depositional architecture, and driven by hierarchical fluctuations in relative sea level (Goldhammer et al. 1990; Vail et al. 1977). Often, the most prominent features in outcrops of carbonate platforms are related to higher-frequency (third- to fifth-order) cycles, since longer-duration first- and second-order cycles are longer than the lifespan of most carbonate platforms (Kendall and Schlager 1981). However, it is often very difficult to determine the duration or potential global extent of lower orders (e.g., 3rd order) of sea-level change because of the temporal resolution and spatial limits of biostratigraphy (Barnes et al. 1995).

Given the inherent uncertainty in the interpretation of duration and significance of the various orders of relative sea-level fluctuation, a new conceptual model was proposed by Schlager (2005), based on the fractal nature of sequences. This model recognizes two types of sequences: 1) standard sequences, similar to previous models, containing a lower sequence boundary caused by relative lowering of sea level (forced regression), and 2) parasequences, with a lower sequence boundary defined by a flooding surface that overlies marine deposits without demonstrable evidence of terrestrial exposure or forced regression. Given that the formation of observable evidence for exposure on a surface

(e.g., karstification, pedogenesis) takes significant time to develop and favourable conditions for preservation, it is reasonable to assume that not all sequence boundaries will exhibit visible or even geochemical evidence for exposure. Unlike earlier models wherein parasequences were considered smaller-scale cycles that constituted larger cycles, application of Schlager (2005) model appears to allow the two types of sequences to occupy the same scale of relative sea-level change; it is simply the presence or absence of a well-defined subaerial exposure surface related to forced regression which dictates the type of sequence. Within this model, the Lourdes Formation can be interpreted to contain at least four complete depositional sequences, of which two are standard sequences with true sequence boundaries, and two are parasequences.

Using the sequence stratigraphic hierarchy established by Vail et al. (1977), James et al. (1989) summarized the early Paleozoic sequence stratigraphic history of western Newfoundland in terms of a second order sequence (the Sauk Sequence) comprising the whole platform succession, and reflecting prolonged eustatic sea-level rise that gradually inundated the North American continent; third-order cycles on the order of hundreds of metres thick, represented by “Grand Cycles”, generally attributed to eustasy in the Cambrian of western Newfoundland (Chow and James 1987); and superimposed fourth-order cycles and smaller metre-scale cycles, the driving mechanism for which is poorly understood (James et al. 1989).

Using this pre-existing scheme, it is possible to estimate that the larger-scale cyclicity reported from subsurface data of the Lourdes Formation, (Units A and B, Fig. 2-2) may represent third-order sequences, with the portion of the Lourdes Formation exposed on Long Point Peninsula forming an entire (or nearly whole) third-order cycle. Smaller-scale depositional sequences interpreted from outcrop would then be classified as

fourth-order sequences, including both standard sequence and parasequences types, following the nomenclature of Schlager (2005). Finally, m-scale cycles, including peritidal cycles in the Shore Point Member, and m-scale grainstone shallowing-up cycles in the Beach Point Member would therefore be classified as fifth-order sequences. This last category consists of very asymmetric cycles, repeatedly showing only flooding at a basal surface, and subsequent upward shallowing. The duration of m-scale shallowing-upward peritidal cycles has been estimated to represent 10-100 k.y. intervals (Algeo and Wilkinson 1988).

Sequence Stratigraphic Development of the Lourdes Platform

Distribution of facies in the Lourdes Formation and their arrangement from peritidal to mid-ramp settings suggest that the formation represents a relatively high-energy carbonate ramp (Fig. 2-6; Burchette and Wright 1992). The presence of coarse-grained, cross-bedded sandstones in the subtidal portion of peritidal cycles indicates relatively high-energy, shoreline-proximal environmental conditions.

The Shore Point Member differs strongly from the other two members, in that it is predominantly peritidal in origin. m-scale peritidal cycles (Fig. 3-5A) provide the only obvious cyclicity, the hallmark of tidal flat carbonate sediments (Pratt et al. 1992). Sandstones of the lower part of the Shore Point Member (Unit SP1 and SP2) do not give any true indication of sea level history, but may represent terrestrial to marginal marine deposition. An upward progression through Units SP3 and SP4, from dominantly muddy sandstone beds to a higher proportion of lime mudstone with fenestrae and desiccation cracks, suggests overall shallowing of the peritidal system. This suggests that the early history of the Lourdes platform involved slow rates of sea-level rise, with initial peritidal

carbonate sedimentation in subtidal to intertidal zones, gradually filling available accommodation and shallowing to sea level, keeping pace with sea-level rise. The peritidal portion of this partial depositional cycle may therefore represent highstand deposition.

Depositional sequences of the Black Duck and Beach Point members show a better-defined progression of facies. This repeated overall pattern suggests that similar processes were repeated with the start of each sequence; once transgression occurred, the carbonate ramp re-established itself following a lag time, progressed to siliciclastic-starved carbonate growth, and then the re-introduction of siliciclastic sediment as sea-level rise slowed. An overall shift occurs in highstand deposits of the Beach Point Member relative to the subtidal, nodular, highly bioturbated Facies C6 and coral bioherms (C7) that make up HST deposits in the Black Duck Member. HST deposits of the Beach Point Member tend to contain m-scale shale-to-carbonate cycles that appear to represent shallowing to sea level and a higher energy environment, are free of bioherms, and are almost entirely devoid of colonial corals. This difference in HST facies suggests that relative sea level remained slightly higher during deposition of the Black Duck Member, and sedimentation did not keep pace with rising sea level. Perhaps local subsidence accompanied deposition of the Black Duck Member, precluding rapid shallowing to sea-level. The narrow, aggrading growth form of many of the coral bioherms of the Black Duck Member suggest a keep-up growth strategy (James and Bourque 1992), which could occur in a slowly subsiding basin.

The complete absence of muddy peritidal sediments in the Black Duck and Beach Point Members is notable. Indeed, the carbonate mud content in inner-ramp limestone appears to decrease upward with each member (C1 in the Shore Point; C6 in the Black

Duck, C3 in the Beach Point). The Beach Point Member contains m-scale shallowing upward cycles which may have shallowed to sea level. Why then is there a pronounced difference in facies? The switch to grainstone-dominated facies in nearshore environments probably reflects a change through time from muddy tidal flats to nearshore grainstone shoals. This may reflect a changing energy regime, possibly related to changing paleogeography of the basin, or it may indicate that the skeletal shoals identified in the Beach Point Member formed slightly basinward of tidal flats if such flats existed. Alternatively, this shift in inner ramp facies composition may support previous suggestions that the region may have undergone climate cooling throughout Long Point Group deposition (Chapter 2). Micritic mudstones are most common on tropical carbonate platforms, whereas skeletal grainstones are a more common building block of temperate carbonate platforms (Read 1998).

Controls on Cyclicality

The Lourdes Formation, as a mixed siliciclastic-carbonate succession deposited within a tectonically active foredeep remnant basin, has a complex sequence stratigraphic history involving the interplay between eustasy, tectonics, and supply of siliciclastic material.

The largest global transgression of the entire Phanerozoic occurred in the Caradoc, submerging large tracts the North American continent, and forming broad, epeiric seas (Hallam 1992); the transgression may have been related to a mantle superplume event (Barnes 2004b). Interpreted sea-level curves for both North America and Baltoscandia (Fig. 3-7) show an overall rise in sea level during the time of Lourdes Formation deposition. A smaller perturbation in the North American curve indicates a

Fig. 3-7: Biostratigraphic summary, Lourdes and Winterhouse formations. Darker shaded area indicates most likely age range for the Lourdes Formation. Absolute dates on column are based on Webby et al. (2004) North American stages. Alternate stage names (denoted “Holland”) are based on usage by Holland and Patzkowsky (1996), and are correlated to biostratigraphic zones, but not to absolute age. Time slices are based on subdivisions by (Webby et al., 2004), and sea-level curves are after Ross and Ross (1992; North American curve) and Neilsen (2004; Baltoscandian curve).

smaller, short-lived drop in sea level during Lourdes deposition; it is possible, although though difficult to confirm given the low biostratigraphic resolution, that this could correlate to the prominent sequence boundary capping the Black Duck Member.

Given the presence of two different types of depositional sequences of similar thickness in the Lourdes Formation (parasequences which were terminated by a deepening event, and standard sequences which were terminated by forced regression), it is possible that the effects of eustasy and tectonics were expressed by different stratigraphic responses on the Lourdes ramp. Perhaps the non-paleokarst sequence boundaries were caused by sudden increases in subsidence rate related to tectonic deepening of the basin, whereas the paleokarst sequence boundaries relate to eustatic lowering of sea-level which caused the inner ramp zone to be exposed and eroded for extended time intervals.

Siliciclastic sediment supply to the ramp could also have played a significant role in determining the rate at which accommodation was filled. As described above, siliciclastic input is interpreted to have been highest during times of sea-level lowstand and highstand, and lowest during transgression. Sediment supply may also have been controlled by tectonic movements within the basin. For example, uplift of a source area would be expected to increase the rate of siliciclastic input. The significant increase in siliciclastic sediment that coincided with platform drowning at the Lourdes-Winterhouse transition occurred at approximately the same time as a major pulse of siliciclastic sediment related to the northern phase of the Taconic orogeny in the north-central portion of Laurentia (Holland and Patzkowsky 1996).

Absence of Bentonite in the Long Point Group

Bentonite (diagenetically altered volcanic ash) deposits are a common feature of Black River and Trenton-age strata throughout much of the eastern United States, and into Ontario and southern Quebec (Brun and Chagnon 1979; Kolata et al. 1996). Representing explosive volcanic eruptions and simultaneous deposition over wide areas, these clay beds are particularly useful for correlating over long distances (Huff 1983) and for precise radiometric dating of portions of the sedimentary succession and calibration of biostratigraphic zones (Goldman et al. 1994; Mitchell et al. 1994). Despite their presence in coeval strata elsewhere in the Appalachians and Baltoscandia (Huff et al. 1996; Kolata et al. 1996) and in older strata (Table Head and Cow Head groups) in western Newfoundland (James and Stevens 1982; Maletz et al. 2006), no bentonite beds are known from the Long Point Group.

Isopach maps by Huff et al. (1996) illustrate the distribution of the two thickest bentonite beds in North America, the Upper Ordovician Millbrig and Deike K-bentonites, ca. 454 Ma (Huff et al. 1992). These wide-ranging and confidently correlated beds thin away from an interpreted point-source in regular contour intervals: the interpreted point source location was likely an island arc or microplate offshore to the southeast of the present-day Carolina coast. Very regular thickness trends of the bentonite beds are corroborated by similar trends in decreasing grain size of the ash debris away from the centre of the eruption. Bed thickness and grain size both decrease inland and northward toward the Great Lakes region; however the contour pattern indicates that these significant ash deposits do not extend to Atlantic Canada.

Since collisional events of the Taconic orogeny in Newfoundland preceded orogenesis in the central and southern Appalachians, perhaps the older bentonites

observed in western Newfoundland (e.g., the Table Head Group) are related to earlier tectonism, and by the time of Lourdes deposition, the locus of explosive volcanism had shifted farther to the south, excluding the Newfoundland portion of the Humber Zone from the large fall-out radius of ash deposits. During the Caradocian, the dominant ocean current along the east coast of Laurentia flowed to the southwest (Wilde 1991), so it is unlikely that ash would have been transported to western Newfoundland, which was located northeast of the interpreted source of volcanism (Jurdy et al. 1995). Alternatively, ash may have been deposited in the region in a very thin layer that was poorly preserved, or reworked in the high-energy shallow marine environments that are characteristic of the Lourdes Formation. Deeper-water equivalent strata in the subsurface might offer better preservational conditions; data from future drilling in the Anticosti Basin may shed some light on this, and provide better constraints on the distribution and correlation of bentonite units in the region.

Comparison/Correlation to other Areas

Direct correlation to strata outside of western Newfoundland is uncertain, largely due to the poorly constrained age of the Lourdes Formation, and the restricted outcrop exposure, which limits interpretation of facies in deeper and shallower ramp environments. Given that time-equivalent units in eastern Canada and the northeastern United States had yet to undergo the Taconic orogenic event at the time of deposition, it is likely that they would record a more reliable record of eustatic sea-level history in contrast with the highly tectonically-influenced Lourdes platform.

CONCLUSIONS

Using the facies model established in Chapter 2, it is possible to identify subaerial unconformities (sequence boundaries), transgressive-to-highstand transition surfaces, flooding surfaces, hardgrounds, and ambiguous/faulted surfaces within the stratigraphic succession of the Lourdes Formation. An isotopic evaluation of sand-filled cavities below the most prominent paleokarst surface suggests a complicated diagenetic history, involving subaerial exposure and cementation, deposition of sand fill, and progressive cementation of sand during subsequent transgression.

Cyclicity is evident on at least three different scales in the Lourdes Formation, ranging from m-scale shallowing upward cycles (Shore Point and Beach Point members), depositional sequences (4th order?), and larger-scale (3rd order?) cycles comprising the entire exposed portion of the Lourdes Formation, together with slightly older units identified from subsurface drilling. Although only two traditional sequence boundaries, with clear evidence of subaerial erosion, are present in the Lourdes Formation, facies changes suggest that, in fact, 4 to 6 depositional sequences maybe present.

Overall, the portion of the Lourdes Formation exposed in outcrop appears to deepen upward, culminating with deep-water deposition of the overlying Winterhouse Formation. Controls on cyclic sedimentation during Lourdes deposition include allocyclic shallowing (peritidal cycles), eustatic sea-level changes, tectonic influence on subsidence, and the rate of influx of siliciclastic sediment. Better biostratigraphic control on the timing of Lourdes Formation deposition may allow future correlation of sequence stratigraphic events with equivalent successions elsewhere in eastern Laurentia, but at present, confident correlation is not possible. Paleogeography appears to explain the absence of bentonite deposition on the Lourdes platform, as the region was likely outside

the range of ash fall deposits during Caradocian explosive volcanism in the southeastern United States.

CHAPTER 4:
FACIES, GEOMETRY, AND GEOLOGICAL SIGNIFICANCE OF CORAL
BIOHERMS

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ABSTRACT

Late Ordovician (Caradocian) coral bioherms in the Lourdes Formation of western Newfoundland exhibit a complex mixing of architectural elements, including framework, boundstone, and suspension deposits. The bioherms occur within a narrow (16 metres) stratigraphic interval, and a prominent unconformity truncates the interval of bioherm growth and tops of many of the bioherms. The buildups developed along a carbonate ramp. They occur isolated and in groups, individuals in groups are aligned in parallel orientation. The sizes of the bioherms range from small (50 - 100 cm) coral piles to columnar and dome-shaped masses (1 - 15 m); however, topographic relief was never more than ~1 m. Bioherm construction reflects: 1) stacking of the tabulate coral *Labyrinthites chidlensis*, and less common stromatoporoids; 2) accumulation of microbial-stromatoporoid boundstone and suspension deposits within shelter cavities between corals; and 3) detrital bioherm-flank skeletal grainstone beds. *Trypanites* borings are common in the tops of coral heads. The bioherms exhibit three growth-development stages: (1) seafloor stabilization, wherein rare, abraded coral colonies lie scattered within pelmatozoan/skeletal grainstone lenses; (2) colonization, wherein corals (*Labyrinthites chidlensis*), rare stromatoporoids (*Labechia* sp.), and other biota (bryozoans) produced a bioherm overlying the basal sediment base; and (3) diversification, which is marked by a more diverse range of fauna and flora as well as occurrence of shelter-cavity deposits. The diversification stage usually makes up more than 70% of a bioherm structure, and, in some defines multiple periods of start-up and shut-down of bioherm growth. The latter is defined by bored omission surfaces and/or deposition of inter-bioherm sediment. The Lourdes bioherms have a similar ecological structure, biotic diversity, and depositional

environment to patch reefs in the equivalent Carters Limestone in Tennessee. The mixture of coral stacking and boundstone as architectural elements identify an Early Paleozoic transition of reef-design development along shallow-water platforms that began to displace the muddy (boundstone, bafflestone) carbonate buildups more typical of the Early and Middle Ordovician time.

INTRODUCTION

The Ordovician was a pivotal period of reef evolution (Webby, 2002). Although many basic structural attributes of modern reefs had been established in the Neoproterozoic (Turner et al. 2000b) and Early Cambrian (James and Kobluk 1978), metazoans and flora (algae) emerged as important reef builders by the Middle Ordovician (Webby 2002). Many of these early Paleozoic buildups were skeletal mounds (James and Bourque 1992) containing one or two biotic groups (corals, stromatoporoids, bryozoans, or sponges) and significant amounts of mud and/or microbial boundstone. By the Late Ordovician (early Caradocian), reefs began to develop a framework-like structure, displacing boundstone and bafflestone fabrics that otherwise dominated Early and Middle Ordovician reef facies (Fagerstrom 1987).

This chapter describes the facies architecture of Late Ordovician (early Caradocian) coral bioherms that occur within the Lourdes Formation, which outcrops along 18 km of coastline on Long Point Peninsula, western Newfoundland (Fig. 4-1). The bioherms were first reported by Schuchert and Dunbar (1934), then described by James and Cuffey (1989) and Stait and Barnes (1991). However, details of biohermal architecture, spatial biotic diversity, and associated facies have not been previously presented. The Lourdes bioherms formed during the period of peak diversification in

Fig. 4-1: A, B) Location of the study area on Long Point Peninsula, Port au Port Peninsula, western Newfoundland. C) Location of stratigraphic sections (white circles) and distribution of bioherms (shaded areas). Boxed numbers (9 to 12) indicate location of bioherms pictured in Figs.4-9 to 4-12. Strike and dip indicated are a regional average. Paleocurrent data (inset) are for bi-directional cross-beds and ripples within inter-bioherm grainstone and packstone beds at Locality 8.

Ordovician metazoan reef-building organisms (Webby 2002). They display overt coral-head stacking, with associated stromatoporoids, bryozoans, sponges, microbial boundstone, and intra-bioherm detrital sediment. Similar facies are associated with the equivalent Carters Limestone, Tennessee (Alberstadt et al. 1974). Together, these bioherms identify an evolutionary change in Ordovician reef structure, the first indication of a shift from bryozoan-microbial mud mounds found elsewhere along eastern Laurentia (Alberstadt et al. 1974; Read 1982; Walker and Ferrigno 1973) to very different Silurian-Devonian reef framework facies (Copper 2001)

GEOLOGICAL SETTING

Ordovician stratigraphy of western Newfoundland defines three successive periods and styles of carbonate continental shelf development along the ancient northeastern margin of North America (James et al., 1989): (1) passive-margin deposition from the Neoproterozoic through to Middle Ordovician; (2) Taconic foreland basin deposition from the Middle to early Late Ordovician; and, (3) early Late Ordovician platform development represented by the Lourdes Formation, the basal formation of the Long Point Group (Fig. 4-2). Until recently, the Long Point Group was considered to be *neoaautochthonous* (Schillereff and Williams 1979); that is, deposition occurred disconformably on the once transported Taconic allochthon (James et al. 1989; Knight et al. 1991; Rodgers 1965). However, from offshore seismic reflection data and re-examination of onshore geology, the base of the Long Point Group has been re-interpreted to lie above an east-vergent regional thrust fault marking the roof of a Late Devonian structural triangle zone (Stockmal and Waldron 1990; Waldron and Stockmal 1991). According to these authors, the Long Point Group was deposited above the

Fig. 4-2: General lower Paleozoic succession for western Newfoundland, and a composite stratigraphic column for the Long Point Group. Locations of biostrome and coral bioherms are noted.

Mainland Formation (Goose Tickle Group), then displaced north-westward to its current position after deposition of the Silurian Clam Bank Formation (Fig. 4-2).

LOURDES FORMATION

Stratigraphy, Sedimentology, and Age

The following summary provides a geological context for our interpretation of carbonate buildups in this formation, and is based partly on recent re-examination of the formation's geology (Batten Hender, unpublished data; Batten and Dix 2004; Batten and Dix 2005).

The Lourdes Formation is approximately 75 metres thick, and is exposed along the south-eastern coastline of Long Point Peninsula (Fig. 4-1). It consists of fossiliferous marine limestones and calcareous sandstones. There are three unconformity-bounded members; in ascending order, the Shore Point Member, the Black Duck Member, and the Beach Point Member (Fig. 4-2; Stait and Barnes 1991). The Shore Point Member consists of peritidal carbonate and siliciclastic sediments. The top of the Shore Point Member is a disconformity that represents subaerial exposure and minor karst development. The overall depositional environment of the Shore Point Member can be characterized as a sandy carbonate tidal flat, locally dissected by tidal channels.

The overlying Black Duck Member defines renewed transgression and mostly subtidal deposition. There are three units (Fig. 4-2): in ascending order, (1) BD1, an argillaceous, highly bioturbated to nodular limestone; (2) BD2, a composite unit consisting of grainstone with bedforms indicative of high-energy, wave-dominated conditions, and a coral biostrome (Fig. 4-2); and (3) BD3, highly bioturbated to nodular, very fossiliferous limestone (packstone, grainstone) that hosts coral bioherms (Fig. 4-2). Unit BD1 represents a fully subtidal, low-energy environment with a high input of

siliciclastic sediments, while Unit BD2 is interpreted as a grainstone shoal deposited in a shallow subtidal, high-energy, wave-swept, inner- to mid- ramp setting. The biostrome within Unit BD2 appears to represent a period of relative quiescence marking a hiatus in the migration of grainstone shoals. Unit BD3 hosts the coral bioherms, and it reflects fully subtidal, lower-energy, open-marine conditions on a periodically storm-influenced carbonate ramp (see below). Paleocurrent data from bi-directional cross-beds and ripples from inter-bioherm strata in Unit BD3 indicate a dominant NNE-SSW transport direction. The Black Duck Member is capped by a prominent unconformity that erosionally truncates the tops of many of the bioherms. Although horizontal in some areas, the surface also exhibits scalloped and pitted features, and is overlain by a discontinuous bed of feldspathic arenite containing well rounded cobbles of well lithified sandstone. These attributes identify lowering of base level, exposure and karstification of the platform, and seaward transport of siliciclastic detritus.

The upper Beach Point Member marks a renewal of subtidal carbonate sedimentation, but there is a greater abundance (increasing upsection) of silt and clay than in the underlying Black Duck Member. Siliciclastics represent ~50-60% of strata in the uppermost 5 m of the formation. Laterally discontinuous hardground surfaces marked by *Trypanites* borings, and locally encrusted by framboidal pyrite occur throughout the Beach Point Member, and become common upsection. The Beach Point Member is characterized by shallowing-upward cycles, and marks an increase in supply of siliciclastics to the basin which partially inhibited carbonate accumulation. The contact with the overlying Winterhouse Formation is an erosional contact.

Available biostratigraphy indicates that the Long Point Group likely represents an extended time interval, with deposition occurring during the Whiterockian, Mohawkian,

and possibly Cincinnati stages (Fig. 4-3). The Shore Point Member contains few fossils, none of which are biostratigraphically diagnostic (Stait and Barnes 1991), and is likely older than the earliest microfossil assemblage collected from the Black Duck Member (Bergstrom et al., 1974). Unit BD3 of the Black Duck Member, host to the bioherms, contains early Caradocian conodonts (*gerdae* biozone; Bergström et al. 1974; Fåhræus 1973) and graptolites (*multidens* biozone – equivalent to North American *bicornis* and *americanus* biozones; Bergström et al. 1974). Nautiloids support a latest Whiterockian age (Stait 1988). Finally, a possible Cincinnati age for the lower Winterhouse Formation (Bergstrom et al., 1974) may indicate that the uppermost Lourdes is of similar age.

CARBONATE BUILDUPS

Location, Distribution, and Orientation

Buildups within the Black Duck Member outcrop along the east side of Long Point Peninsula, from the village of Black Duck Brook in the south to just beyond Beach Point in the north (Fig. 4-1). There are two styles of coral buildups (Fig. 4-2); biostrome (James 1983), and laterally restricted buildups, or bioherms (James and Bourque 1992).

The biostrome forms a relatively thin (< 55 cm) unit within Unit BD2. It outcrops discontinuously (in places it is below the waterline) from Locality 1 in the south to Locality 5 in the north. It is stratigraphically restricted to ~ 5-10 metres below the lowest bioherm.

The overlying coral bioherms also occur within a relatively restricted interval, within the uppermost 16 m of Unit BD3 (Fig. 4-2). Between Locality 3 and Locality 6, the bioherms are still present but are inaccessible due to steep cliffs. In general, the

Fig. 4-3: Biostratigraphy of the Long Point Group. Thick vertical lines show distribution based on previous authors; solid portions represent intervals with diagnostic fossils, and dashed portions represent estimated ranges. L=Lourdes Formation; WH=Winterhouse Formation. Previous work: 1 = (Fåhræus, 1973), 2 = (Bergström et al., 1974), 3 = (Stait and Barnes, 1991), 4 = (Quinn et al., 1999). Chrono- and biostratigraphic base charts are based on Webby et al. (2004).

buildups range from small (< 1 m) abraded coral piles to bioherms ranging from 1-15 m in thickness. Some bioherms are isolated (Figs. 4-4A,B), but typically they form small (3-5) and large (9-12) groups. Within a given group, the bioherms lie in close proximity (e.g., 3-15 m apart), and are commonly aligned parallel to each other. In large groups (e.g., Locality 7), the horizontal component of bioherm growth identifies a common ~ NNW-SSE orientation (Fig. 4-5). This attitude appears to represent progradational growth towards the northwest.

Coral Biostrome Facies

The biostrome biofacies was not studied in the same detail as the younger bioherms. However, there appears to be a similar biotic assemblage in both (see Table 4-1). The biostrome is medium-bedded and forms a sheet-like deposit that is underlain and overlain by medium to thick beds of cross-bedded, coarse bioclast-oncoid grainstone. The matrix of the biostrome contains laterally equivalent coarse bioclast-oncoid grainstone in which biostromal constituents show signs of significant abrasion and reworking, as well as more muddy carbonate textures that also contain upright delicate fossil remains (e.g., the coral *Aulopora* sp.), and local recessively-weathering calcareous siltstone and shale. Rare patches of micritic boundstone (see below) occur between framework elements. The siliciclastics also form local interbeds. Quartz sand grains occur throughout much of the Lourdes Formation, but the biostrome is locally particularly rich (< 20 %) in this sediment type.

Bioherm and Associated Facies

A given bioherm contains four lithofacies, each differing in its volume and spatial

Fig. 4-4: A) A bioherm near Locality 2 showing uneven distribution of grainstone facies. Debris is localized in wedges (outlined) on the right (north) side of the bioherm, while on the left, nodular inter-bioherm sediments continue uninterrupted to onlap the framework of the bioherm core. Hammer for scale (circled). B) Small “reef pile” at Locality 6. Buildup is composed of a few *L. chidlensis* colonies and lenses of bioclastic grainstone. C) An elongate bioherm at Locality 6, viewed looking north (stratigraphic top is to the left). This bioherm shows a distinctive narrowing in the middle, giving an overall hourglass shape.

Fig. 4-5: Orientation of bioherms in Unit BD3 for each of the local study areas (shaded). Direction indicated is horizontal component of growth direction of bioherms, and indicates a NNW progradation, and overall parallel alignment of bioherms.

Table 4-1: Biota within coral bioherms, according to paleoecological guild.

Ecological Stage	Builders	Sediment binders/buffers	Bioherm dwellers/debris contributors
<i>Stabilization/ Pioneer</i>	n/a	pelmatozoans, bryozoans	pelmatozoans, bryozoans, brachiopods, trilobites, gastropods (including <i>Maclurites</i> sp.), cephalopods, pelecypods
<i>Colonization</i>	<i>Labyrinthites chidlensis</i> , rare stromatoporoids	bryozoans (ramose and encrusting), rare stromatoporoids	as above, along with coral fragments
<i>Diversification</i>	Corals: <i>L. chidlensis</i> <i>Lyopora</i> sp. <i>Aulopora</i> sp. <i>Eofletcheria</i> sp. Stromatoporoids: <i>Labechia</i> sp. Sponges: <i>Epiplastospongia coactilis</i> lithistids <i>Solenopora</i> sp. (chaetetid)	stromatoporoids, bryozoans (ramose and encrusting), <i>Girvanella</i> sp.	pelmatzoans (including cystoids and holdfasts), bryozoans, brachiopods (including <i>Rostricellula</i> sp.), cephalopods, pelecypods, coral fragments, ostracodes, sponges (spicules)

distribution among individual bioherms (Table 4-2). A fifth, inter-bioherm, lithofacies comprises the surrounding level-bottom deposits.

Bioherm Facies

Bioherm Framework. The bioherm framework is dominated (60-95 %) by *in situ* heads of the tabulate coral *Labyrinthites chidlensis*. Other contributors include lithistid sponges, rare occurrences of the corals *Lyopora* sp., *Eofletcheria* sp. (P. Copper, pers. comm. 2004) and *Aulopora* sp., *Solenopora* sp. (a chaetetid sponge; Riding 2004), the stromatoporoid *Labechia* sp. (Stait and Barnes 1991) and rare calcareous sponges identified by Rigby (1977) as *Epiplastospongia coactilis* (Table 4-1).

The coral colonies are on average 30 cm high and 50 cm wide, but are up to 1 m in width. Growth forms of *L. chidlensis* include hemispherical, high-peaked domical, plate-like, and irregular growth forms, often differing according to bioherm development (see also Cuffey (1980)). In stacking of colonies, smaller plate-like corals commonly rest on top of larger dome or bell-shaped colonies. Domical and hemispherical are the most abundant growth forms. Where they have not grown directly on top of other corals, most colonies sit directly on local lenses of coarse skeletal debris. However, corals rarely occur within the inter-bioherm facies suggesting that *L. chidlensis* colonies preferred more stable substrates, either hard or possibly more consolidated skeletal deposits.

Most *L. chidlensis* heads within the bioherm framework are upright to slightly inclined, and are interpreted to be in growth position. At the bases of bioherms and toward the outer flanks of the bioherms, there is a tendency for some coral heads (< 50%) to be overturned. *Trypanites* borings are common in the tops of *L. chidlensis* colonies and on the upward-facing sides of overturned colonies. There is no evidence of marine

Table 4-2: Characteristics of lithofacies within and enclosing Lourdes Formation bioherms.

	Position/ Dimensions	Components	Physical/ biogenic structures	Interpretation
Bioherm framework	Stacked in-situ fossils; 1-15 m high, < 50 cm by 50 cm to 5 m by 15 m in cross-section	<i>Labyrinthites chidlensis</i> ; other colonial corals; sponges; stromatoporoids	<i>Trypanites</i> borings in corals	Bioherm framework, dominated by in-situ stacking of sessile benthic organisms
Boundstone	Shelter voids between framework components, and periphery of bioherm; up to 60 cm high by 40 cm wide	Laminar to encrusting stromatoporoids, sponges, encrusting bryozoans; structureless to spongiostromate lime mud; local skeletal wackestone-packstone	Burrow mottling, stromatactoid cavities resulting in "polymud" fabric	Skeletal-microbial boundstone formed <i>in situ</i>
Laminated internal sediment	Shelter voids between framework components; 5-25 cm diameter	Mudstone to packstone; wackestone most abundant lithology; disseminated silt to fine sand	Thin to thick laminae, commonly graded	Mixture of bioherm biota and fine detrital sediment swept in during storms
Grainstone	Beds and lenses near bioherm base, wedges and lenses onlapping framework; beds extend laterally ~ 4 m from edge of core	Coarse grainstone to rudstone containing skeletal fragments, intraclasts, and oncoids coated by micrite or <i>Girvanella</i>	Horizontal and draping beds $\leq$ 50 cm; amalgamated beds $\leq$ 1 m	Fragmented skeletal material derived from bioherm biota and/or level-bottom community; intraclasts and oncoids transported or formed by <i>in situ</i> reworking
Inter-bioherm sediments	Fine- to coarse-grained, skeletal packstone, grainstone, and rudstone	Fine- to coarse-grained, thinly bedded skeletal packstone, grainstone, and rudstone	Thinly bedded; highly bioturbated to nodular; most physical sedimentary structures destroyed	Level-bottom sedimentation; relatively low energy; open marine circulation

cementation between stacked corals. Instead, the spaces between framework elements are filled by the remaining three bioherm facies; boundstone, laminated internal sediment, and grainstone.

Boundstone. Boundstone commonly occurs within shelter porosity created between framework components, but is also found on the periphery of the bioherms where it likely also contributed to bioherm construction (Fig. 4-6). The boundstone contains two structural components. A skeletal component includes laminar and encrusting stromatoporoids, typically with anastomosing growth habit and interlaminated with micritic sediment (Fig. 4-7A). Encrusting bryozoans present in this facies are volumetrically less significant. The second component of the facies is micrite that is interbedded or interlaminated with the stromatoporoids and bryozoans. Locally, there is coarser (skeletal wackestone and packstone) micrite-bearing sediment as well. In these sediments, bioclastic components include sponge spicules, whole ostracodes, pelmatozoan plates, whole cystoids, and fragments of brachiopods, trilobites, molluscs, bryozoans, and corals. Microborings are common, especially associated with brachiopod, mollusc, and pelmatozoan fragments (Fig. 4-7F).

Ramose bryozoans spatially associated with the boundstone facies may have contributed to baffling of fine-grained sediment. However, thin sections show that at least some micrite was likely associated with microbial activity. In addition to structureless micrite, a portion of the micrite within the boundstone facies occurs as diffuse masses of peloidal to clotted micrite enclosing small, irregularly shaped, cement-filled inter-particle voids (Figs. 4-7C, E). The peloids are typically silt-sized, with diffuse margins, and commonly occur in association with patches of *Girvanella* filaments. This clotted

Fig. 4-6: Photo enlargement of a bioherm depicted in Fig. 11 showing a patch of micritic boundstone facies (b) and bedded grainstone/packstone of the inter-bioherm facies (g). The sharp onlapping and inter-fingering nature of the contact suggests that the two were deposited during alternate time intervals.

Fig. 4-7: Boundstone facies. A) Intricately intergrown relationship of micrite (m) and stromatoporoid (s) in outcrop. From Horizon 4 of Fig. 12. B) Micritic wackestone containing elongate sponge spicules, which have been replaced by calcite. C) Peloidal/spongiostromate mud, probably originating from microbial processes, surrounded by blocky calcite cement and bounded above and below by bryozoans. A thin, dark crust of *Girvanella* is indicated by the arrow. D) Microbial crust within a cavity. Patches of *Wetheredella* sp. (w) occur throughout, and rare strands of *Sphaerocodium* sp. are indicated by arrows. E) Peloidal/spongiostromate microfabric from bioherm boundstone facies. Peloids are micritic, and surrounded by calcite spar. F) A pelmatozoan ossicle within the boundstone facies, containing mud-filled microborings. All photomicrographs are vertically oriented and PPL.

texture, variously termed “spongiostromate”, “spongiform”, “grumuleuse” or “grumous”, is commonly attributed to microbial activity (e.g., Chafetz 1986; Devuyst and Lees 2001; Monty 1995; Riding 2000). Similar fabrics have been described from reefs and mud mounds throughout the geological record, forming stromatolites, thrombolites, micritic crusts, and massive boundstones (e.g., Riding 2000; Riding and Tomás 2006; Sun and Wright 1989; Webb 1987). In particular, this texture has been interpreted as resulting from the *in situ* calcification of partially decomposed cyanobacteria (Pratt 1982; Turner et al. 2000a). Other microfossils within the boundstone facies include mats of *Girvanella* and thin crusts of *Wetheredella* sp., together with scattered strands of *Sphaerocodium* sp. (Fig. 4-7D), all three of which are frequently interpreted as calcified cyanobacteria (Riding 1975; Wray 1977).

Detailed examination of the mud portion of the boundstone facies reveals multiple generations of microcrystalline carbonate, forming fabrics typical of multi-component mudstones, termed “polymuds” by Lees and Miller (1985; 1995; Fig. 4-8). This fabric consists of a carbonate mud matrix punctuated by small rounded to irregular voids filled by a combination of geopetal sediment, encrustations, and/or calcite cement. Multiple generations of cavity formation and fill result in a highly complex history of diagenesis and internal sediment deposition. The small stromatactoid cavities are typically 1-3 mm in diameter, and contain detrital lime mud, silt, and fine bioclastic debris, geopetal microspar, possibly originating from recrystallization of lime mud, and blocky calcite spar. Some cavities have darkened micritic rims (Fig. 4-8A), and concentrations of framboidal pyrite also line some cavities. Darkened micritic rims always appear to precede any geopetal fill, whereas pyrite distribution indicates multiple episodes of formation, both preceding and post-dating geopetal fill (Fig. 4-8B). In rare cases, dark,

Fig. 4-8: Polymud fabric within boundstone facies. A) Successive generations of lime mud: precursor mud matrix (M1) containing cavities filled by mudstone to skeletal wackestone (M2). Younger stromatactoid cavities are filled by successive generations of geopetal micrite (M3 and M4) and pore-occluding blocky calcite spar (S). White arrows indicate darkened micritic rim of latest-stage cavities. Note varying dip angles of sediment floors. B) Stromatactoid cavity containing geopetal peloidal micrite (P), overlain by a geopetal layer of microspar (M), and subsequently filled by blocky calcite spar (S). Pyrite framboids (arrow) form a sparse rim that post-dates deposition of geopetal sediment. C) Dissolution cavities associated with a lithistid sponge. One cavity on the periphery of the skeleton (arrow) contains geopetal fill identical to that found in isolated stromatactoid cavities, supporting interpretation of polymud fabric as the result of soft-tissue diagenesis of sponges. All photomicrographs are vertically oriented and PPL.

pendant micrite suggests deposition via microbial encrustation of the cavity interiors. The sediment fill contains irregular sediment floors that dip shallowly in different directions among adjacent voids.

Laminated Internal Sediment. Thinly to thickly laminated internal sediment fills smaller (5 to 25 cm diameter) shelter voids between bioherm framework components. The sediment size ranges widely, from coarse skeletal grains to micrite; however, wackestone is the most abundant lithology. Individual laminae are commonly graded. Skeletal grains include sponge spicules, whole ostracodes and brachiopods, pelmatozoan plates, and fragments of brachiopods, trilobites, and molluscs. Quartzose silt to fine sand is finely disseminated throughout and the sediments are locally bioturbated. Some laminae contain bedding-parallel, elongate, irregular fenestrae, with geopetal sediment fill. Some of this sediment fill is composed of silt-sized calcite crystals suggesting a detrital fill. The facies is volumetrically less significant than the boundstone facies; only a few occurrences were noted in the studied bioherms.

Grainstone. Some grainstone beds are laterally continuous through the bioherm core, especially near bases of bioherms; however, this facies is visually dominant on the present-day north sides of many bioherm exposures, and, in some bioherms, occurs only on the north flank. The sediment consists of coarse grainstone to rudstone forming beds typically ~ 20 cm thick, but up to 50 cm locally. Beds also onlap bioherm framework components, and thin away from the core, extending up to ~4 m away from the interior margin of the bioherm flank. In places, amalgamated bioherm-flank bedding forms thickness of > 1 m.

Skeletal components making up grainstone facies sediment include abundant pelmatozoan ossicles and stem fragments, bryozoans, abraded brachiopod valves, broken nodules of *Solenopora*, trilobite fragments, molluscan debris, small lithistid sponges, and fragments of *L. chidlensis*. Intraclasts are very common. Many grains are coated by isopachous to irregular rims of dense, laminated and un-laminated micrite and, less commonly, *Girvanella* encrustations, forming oncoids.

Inter-Bioherm Sediments

Inter-bioherm sediments are mostly light to medium grey, fine- to coarse-grained, thinly bedded skeletal packstone, grainstone, and rudstone. The most common bioclasts are pelmatozoan ossicles, brachiopods, trilobite fragments, ostracode fragments, and bryozoans. Where present, the matrix is composed of micrite or microspar. However, thin grey-green shale laminae and interbeds, locally bioturbated, are common. Overall the facies is highly bioturbated, resulting in irregular bed surfaces, obliteration of original sedimentary structures, and production of local nodular bedding. Quartz sand occurs as burrow fill, thin discontinuous laminae, or as disseminated grains. There are also isolated lenses and scour-channel-fills (5-25 cm thick, <10 m wide) of coarse grainstone to rudstone similar in composition to the grainstone facies. They locally exhibit faint bi-directional cross-bedding (Fig. 4-1).

Bioherm Architecture

Five bioherms were studied in detail. Orientation of framework elements and distribution of facies were traced over photomosaics of outcrops (Figs. 4-9 to 4-12). The bioherms range from < 50 cm by 50 cm to 5 metres by 15 metres in cross-section, and up to 15 metres in true thickness. The smallest coral accumulations were referred to as “reef

Fig. 4-9: Coral bioherm at Locality 2. A) Photomosaic. B) Diagram showing distribution of facies and framework elements.

A **B**

Fig. 4-10: Coral bioherm at Locality 2. A) Photomosaic. B) Diagram showing distribution of facies and framework elements. For legend, see Fig. 4-9.

Fig. 4-11: Coral bioherm at Locality 3. A) Field photograph. B) Diagram showing distribution of facies and framework elements. Horizons 1 to 4 are indicated on the right. For legend, see Fig. 4-9.

Fig. 4-12: Coral bioherm at Locality 3. A) Field photograph. B) Diagram showing distribution of facies and framework elements. Horizons 1 to 4 are indicated on the right. For legend, see Fig. 4-9.

piles” by James and Cuffey (1989; Fig. 4-4B), and are never greater than one metre in height. They occur interspersed between the larger coral buildups. Most coral colonies in these piles are overturned or show signs of abrasion. The abrasion and present orientation of these coral colonies reflects a significant component of erosion.

The overall shape of the bioherms is quite variable. Although three-dimensional exposures are few, there appears to be a continuum from small bioherms that are rounded in plan view, to more elongate shapes which would have created small horizontal ridges on the seafloor. Some are columnar to domical in cross-section (e.g., Fig. 4-12), whereas, more commonly, there is a narrowing of the bioherm midway from the base, giving an hour-glass profile in cross-section (Fig. 4-11, Horizon 3). In some cases, this narrowing is associated with a higher proportion of micritic boundstone compared with framework components. It is within this interval that domical coral colonies are most predominant (Fig. 4-10). Other bioherms show multiple “start-up” growth stages, each following a period of bioherm cessation as indicated by deposition of intra-bioherm facies. In some cases, “shut-down” or termination of one growth phase coincides with a surface of erosion and abundant *Trypanites* borings, indicating an omission surface (Fig. 4-13). The bioherm depicted in Fig. 4-9 shows such a pattern, with three discrete growth stages separated by intervals of intra-bioherm sediments. Bedding planes traceable through the bioherm cores indicate that none of the bioherms likely attained more than 1 m of topographic relief on the seafloor. Differential post-burial compaction has led to structural drape of some limestone beds adjacent to bioherms, as well as the downward warping of the strata directly below many of the bioherms.

Overall, most bioherms show a vertical zonation in stages of growth. Typically, the bioherm base is defined along the base of a bed or lens of grainstone or rudstone, with

Fig. 4-13: Abraded coral heads at the base of bioherm shown in Fig. 12 (horizon 1). Arrow indicates an eroded surface that has been encrusted by a stromatoporoid.

local, often overturned domical heads of *L. chidlensis* and abraded bioclastic debris. The second stage is identified by the presence of abundant *in situ* colonies of *L. chidlensis* and rare encrusting bryozoans and stromatoporoids, exhibiting stacked, upward growth. About 50 cm to 1 m above a bioherm's base there appears a much more diverse assemblage of metazoans, including corals (Table 4-1). This stage also contains boundstone and laminated internal sediment within what was once more abundant shelter porosity. In some bioherms, the boundstone increases in abundance upsection (Figs. 4-10, 11, 12).

DISCUSSION

Environmental conditions for bioherm growth

The Lourdes Formation represents a carbonate ramp; there is no evidence of a reef rim in its transition with the overlying Winterhouse Group. It had been suggested previously that the platform developed along a shallow submarine ridge separated from the North American craton (James and Cuffey 1989). Concentration of grainstone wedges on the north side of the Lourdes bioherms suggest a preferential location of this facies relative to an energy or circulation gradient. But whether the grainstones reflect a habitat facing a SSE-directed energy or circulation gradient, or they represent accumulation leeward of bioherm ridges forming obstacles to NNW-directed currents remains unclear at present.

Sedimentology and biofacies illustrate that the Lourdes bioherms grew in a subtidal, open-marine setting that was subjected to at least intermittent periods of high-energy. There are no fossils that specifically identify a photic-zone environment, e.g., fossils previously used to identify a photic zone environment (e.g., *Solenopora*) are now

classified in a different phylum (Riding 2004) and cryptic habits of microfossils interpreted as calcified cyanobacteria (e.g., *Girvanella*) precludes the need for photosynthesis (Riding 1975). Nonetheless, lithofacies around the bioherms identify a well bioturbated setting, suggesting a stable subtidal environment. The presence of stenohaline taxa (e.g., pelmatozoans), together with pervasive bioturbation, indicate a fully open marine setting, with good circulation. The growth of *Girvanella* oncoids has been linked to environments with slow rate of sedimentation (Bowman 1983; Peryt 1981), and irregular to incomplete coatings of dense micrite or *Girvanella* around bioclasts in the grainstone facies adjacent to the bioherms, suggest lower energy conditions that precluded frequent rolling of grains to produce sub-spherical oncoids (Wright 1983). However, the bioherms inhabited an environment influenced by sufficient turbulence, at least intermittently, to overturn massive coral colonies (e.g., Fig. 4-11, Horizon 2). The accompanying presence of intraclasts and highly abraded fragments suggests that much of the skeletal material was either transported from a nearby source or subjected to *in situ* reworking by waves. Taken together, this evidence points to a setting on an open ramp, below normal wave base, but periodically influenced by storms.

With bioherm framework development, an increasing amount of protected localities became available for cavity dwellers. The skeletal debris within the shelter porosity boundstone and laminated internal sediment may represent a mixture of biota once colonizing the tops of the bioherms, cavity biota, and inter-bioherm level-bottom community debris swept into the bioherm interior during storms. Graded bedding suggests that the fine sediment fraction could have been pumped into the cavities by wave and/or current action, settling out after storms.

Polymud fabric is a common component in mud mounds; e.g., the Waulsortian

mounds (Devuyst and Lees 2001; Lees 1964). Although the irregular shape of these paleovoids suggests that they are not burrows or borings, their origin remains uncertain. One suggested mechanism for their formation is shrinkage resulting from soft-tissue diagenesis, especially related to decomposition of sponges (Devuyst and Lees 2001; Neuweiler et al. 2001; Neuweiler et al. 1999; Reitner et al. 1995). In some cases, degradation of lithistid sponges can be directly linked to formation of stromatactoid cavities (see Fig. 4-8C), and the abundance of sponge spicules in the boundstone facies (Fig. 4-7B) further attests to the importance of sponge growth in the Lourdes Formation bioherms. Sponge decay is, therefore, a plausible explanation for development of polymud fabric within this facies.

There is no clear evidence for marine cementation strengthening the stacking arrangement of coral colonies, nor associated with the grainstone facies. However, the presence of uncompacted fenestrae and irregular voids within peloidal/spongiostromate microfabric of the boundstone facies, may indicate that some cementation was associated with microbial processes and very early burial (Riding and Tomás 2006). Microbial binding may also have increased the mechanical coherence of the bioherm muds (Lees and Miller 1995).

Bioherm Development

The reasons for initiation and distribution of bioherms only within a narrow stratigraphic interval of the Lourdes Formation, and, specifically, only in the upper part of Unit BD3, remains uncertain. There is little indication that environmental conditions changed significantly during accumulation of Unit BD3, especially at the stratigraphic horizon where bioherms first appear. Highly destructive bioturbation has effectively

obscured original depositional sedimentary structures within the inter-bioherm sediments, precluding fully understanding what subtle environmental change, if any, might have occurred. Nevertheless, a gradual change in environmental conditions, such as decreasing turbidity, water depth, or rate of subsidence may have created conditions suitable for bioherm growth. There is no evidence for local structural controls influencing location of individual bioherms.

The biostrome bed within Unit BD2 may offer evidence that some threshold in a shallowing water depth was important. The biostrome lacks an ecological stratigraphy; intervals of abraded, reworked biostromal elements within the grainstone deposits, occur only where shale and muddy biostromal facies with upright biota are absent. This suggests that the grainstone facies does not represent a fair-weather facies, but likely reflects reworking by storm-related currents that created a local sheet of bioclastic rubble. The biostrome, therefore, may have developed below normal storm wave base, and subsequent shallowing to normal storm wave base triggered bioherm development.

The documented vertical zonation of bioherm growth matches three of the four classic stages of reef ecological succession (Alberstadt et al. 1974; Lowenstam 1950); notably, stabilization, colonization, and diversification. Despite the regional unconformity that truncates many of the bioherms, there is no evidence of a final domination stage being present even within those whose tops lie below the stratigraphic boundary. It is possible that a climax community never existed because bioherm development was terminated by a relatively rapid extrinsic control. Certainly the several “start-up” phases of bioherms during the diversification stage (e.g., Fig. 4-9) suggest that a delicate balance existed between bioherm growth and its temporary rapid demise.

The *stabilization* (or *pioneer*) phase of reef growth is commonly represented by a

series of shoals or other accumulations of skeletal lime sand (James 1983). In the Lourdes Formation, piling up of bioclastic debris including overturned coral heads and abundant pelmatozoan and bryozoan fragments provided nucleation sites for the growth of *L. chidlensis*. The common occurrence of overturned coral heads at the bases of bioherms suggests preferential initiation of bioherm growth on top of pre-existing skeletal debris (e.g., Fig. 4-10). Growth of coral colonies was favoured on these lenses of debris due to either more stable substrates or, perhaps, slightly elevated surfaces. Absence of an obvious bioclastic base may be due to outcrop exposure, the true base of the bioherm core not being exposed.

The *colonization* phase of bioherm growth comprises the lowermost 50 cm to 1 m of each bioherm wherein there are large, highly domical specimens of *L. chidlensis* with only rare examples of encrusting bryozoans and stromatoporoids. Intra-bioherm sediment between coral heads contains a slightly higher proportion of coarse grainstone and rudstone relative to the bioturbated inter-bioherm packstone.

The *diversification* stage makes up the bulk of most bioherms, and is marked by an increase in diversity of visually prominent metazoans (stromatoporoids, large bryozoans, sponges, etc.), and production of *in situ* micritic boundstone. *L. chidlensis* remains the most common species. Stromatoporoids and a wide variety of bryozoans, sponges, and other corals contributed to the bioherm framework during this growth phase (Table 4-1), while increased nestling space created habitats for brachiopods, such as *Rosticellula* sp., which is almost exclusively found within bioherms in the Black Duck Member, as well as other sediment-producing organisms (e.g., pelmatozoans, *Aulopora* sp., etc.). Presence of cystoids and unidentified pelmatozoan holdfasts indicate colonization of the hard substrates provided by the bioherm framework.

Thin section evidence from the boundstone facies suggests that, as found in many Paleozoic reefs (Pratt 2001), production and accumulation of bioherm micrite is at least partially attributable to microbial activity, possibly related to growth and partial decomposition of marine cyanobacteria. This facies appears abruptly at the same stratigraphic position as *Wetheredella* and *Sphaerocodium*, and contains *Girvanella*, suggesting an environmental change that encouraged both cyanobacterial growth and accumulation of lime mud. Perhaps initiation, colonization and especially diversification of bioherm biota resulted from both shallowing and upward growth of the bioherms into a shallower, better illuminated, or more agitated environment.

The abundance of microbial boundstone and highly domical coral colonies within the laterally restricted middle parts of many of the bioherms (Fig. 4-11) may represent a measure of biological competition for space. Previously, Cuffey (1980) suggested that it might reflect rapid upward growth of corals as a response to periodic influxes of mud. However, thin section evidence indicates that the micrite pods are of *in situ* microbial origin, suggesting that biological competition for substrate space may offer another explanation for rapid coral growth.

Significance to Ordovician Reef Diversification

The Late Ordovician (early Caradocian) witnessed the continued diversification of reef patterns that began ~ 4 to 7 million years earlier in the late Darriwilian (Webby 2002; Fig. 4-3). At this time, there occurred the most dramatic change in Ordovician reef evolution, the emergence of metazoans and flora (algae) as significant contributors to reef-building (Webby 2002). The late Darriwilian Chazy Group reefs, for example, are dominated by only one or two reef-building groups (bryozoans, corals, sponges, and very

rarely, stromatoporoids) although there are some more complex paleoecologies (Webby 2002). Many of these reefs are actually more properly described as “organic mounds” (Kapp 1975) or skeletal mounds (James and Bourque 1992). In contrast, early Caradocian shelf and ramp settings contain a wide range of buildup types and environments. Peritidal buildups were dominated by tube worms, stromatolites or *Tetradium* coral; a variety of subtidal buildups include coral-and/or stromatoporoid- and bryozoan-dominated reefs, as well as smaller sponge and algal buildups (Webby 2002). Deeper shelf-edge and downslope buildups appeared for the first time in the early Caradocian, dominated by bryozoans but with significant contributions from pelmatozoans and lime mud such that they have been compared with Carboniferous Waulsortian mounds (Read 1982; Webby 2002).

The Ordovician reefs that most closely resemble those of the Lourdes Formation occur in the time-equivalent Carters Limestone of the Central Basin of Tennessee (Alberstadt et al. 1974). These patch reefs are typically larger in size (up to 18 m thick), and have a similar general biotic composition and ecological community succession. They are interpreted to have formed in a shallow subtidal environment. The Carters Limestone reefs also developed from a base of pelmatozoan grainstone stabilized by upright pelmatozoans, bryozoans, and receptaculitids. The reef core contains corals and stromatoporoids, several genera of algae, and a small assemblage of bryozoans, along with other reef-dwelling organisms. The last stage of reef growth contains abundant stromatoporoids as the dominating (climax) community (Alberstadt and Walker 1976; Alberstadt et al. 1974).

Other early Caradocian buildups along the eastern Laurentia margin are dominated by bryozoans, algae, sponges, or microbial mudstone, often with associated

pelmatozoans and *Solenopora*. In these buildups, the primary reef-building processes were baffling and binding via encrustation (Breland and Walker 1980; Crow 1985; Crow et al. 2001; Gault and McKinney 1980); continuance of a reef development pattern inherited from the Tremadocian (Fagerstrom 1987; Webby 2002). By Caradocian time, bryozoans were important sediment binders and debris producers at different water depths (Ross 1981), with pelmatozoan-bryozoan dominated bioherms appearing along deep shelf margins and downslope environments (Read 1982; Walker and Ferrigno 1973); e.g., Bromide Formation, Oklahoma (Longman 1982), and Rockdell Formation, southwest Virginia (Read 1982). This environmental shift may have resulted from ecologic pressure and displacement in shallow-water settings by colonial rugose and tabulate corals, stromatoporoids, and algae (Webby 2002).

The Lourdes Formation bioherms and Carters Limestone reefs are the earliest carbonate buildups to show true dominance of a *constructor guild* over a *binder and baffler* guild; and they are the only early Caradocian bioherms to display an *in situ* stacking and intergrowth of calcified metazoans. This intrareefal architecture defines the principal framework bioherm structure accompanied by subordinate accumulation of mud and encrustation by other organisms (Fagerstrom 1987; Hubbard et al. 2001). The Lourdes Formation bioherms and the Carters Limestone reefs mark an important transition in global reef paleoecology, and provides an early indication of the character of Silurian-Devonian reefs that emerged following a brief decline in reef-building during the latest Ordovician extinction event (Copper 2001).

Despite the stated ecological contrast between early Caradocian buildups, most contain a micrite facies as part of the core, surrounded or intercalated with grainier sediments (Alberstadt et al. 1974; Read 1982; Ruppel and Walker 1982; Stock and

Benson 1982; Walker and Ferrigno 1973). Several authors have noted that this mud is either an *in situ* deposit, originating from microbial processes, or a diagenetic (mechanical, biological) product of degradation of skeletal material within reefs (Alberstadt et al. 1974; Read 1982). The ubiquity of a micrite or mud facies associated with reef cores, and an association with microbial activity, marks an ecological holdover from the bryozoan- and microbe-dominated mud-mound composition typical of the Tremadocian (Fagerstrom 1987; Webby 2002).

CONCLUSIONS

Coral bioherms of the Lourdes Formation grew in an open-marine, shallow-ramp environment. They occur within a relatively narrow (16 m) stratigraphic interval, and may have been initiated by shallowing of water depth and/or an association with decreasing turbidity. The bioherms contain a framework built primarily by the coral *Labyrinthites chidlensis*, with lesser contributions from stromatoporoids, sponges, and other corals. Stromatoporoids, bryozoans, and cyanobacteria aided in binding of fine-grained sediment, but this role was less important than in most of the older Ordovician reefs. The bioherms show a distinct ecological succession, from stabilization of the substrate in the form of pelmatozoan sheets or lenses, to colonization by *L. chidlensis*, to diversification that includes a wide range of metazoans and algae. The coral bioherms bear many similarities to reefs of the Carters Limestone in Tennessee, and together these two localities mark the beginning of an important transition from Early and Middle Ordovician muddier carbonate buildups, dominated by binding and baffling strategies, towards the rigid framework reefs of the Silurian and Devonian eras.

CHAPTER 5:
CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

CONCLUSIONS

Despite its relatively thin stratigraphic thickness, the Lourdes Formation records a complex history of changing facies, sediment supply, relative sea-level change, and basin hydrodynamics.

The Lourdes Formation represents a short-lived, early Caradocian, storm-influenced, mixed siliciclastic-carbonate ramp succession that formed on the margin of the continent of Laurentia. The ramp developed within a foredeep basin during the late stages of Taconic orogenesis in western Newfoundland, adjacent to a siliciclastic source of quartzofeldspathic sand.

Facies of the Lourdes Formation record a range of water depths, from tidal flats to shaley mid-ramp deposits, with distribution controlled by the interplay of energy level, allocyclic processes, water depth, and supply of siliciclastic sediment related to rate of relative sea-level rise. Highstand systems tract deposits contain large amounts of sand and siliciclastic mud admixed and interbedded with carbonate sediment, whereas transgressive systems tract deposits are relatively free of siliciclastic input, and are characterized by extensive sheets of clean (“starved”) grainstone and lower accumulation rates. Periods of sea-level lowstand are marked by prominent paleokarst surfaces, and terrestrial-derived lag sediments. Cyclicity is evident on at least three different scales, including m-scale shallowing-upward cycles, depositional (4th order?) sequences, and possibly a single larger-scale (4th order?) sequence. The demise of the carbonate ramp was likely due to increased influx of siliciclastic sediment linked to tectonism along the basin margin, culminating with the deeper-water, overlying Winterhouse Formation.

Lack of precision in biostratigraphic age assignment renders correlation with similar-aged deposits elsewhere in eastern North America difficult. Nevertheless, it

appears that coral bioherms within the Black Duck Member of the Lourdes Formation, together with reefs of the Carters Limestone in Tennessee, constitute some of the oldest known reefs with a rigidly constructed coral framework. These two occurrences represent the beginning of an important transition from skeletal-mud mounds, dominated by binding and baffling processes, toward the rigid reef frameworks that became the dominant reef model throughout the Silurian and Devonian.

RECOMMENDATIONS FOR FUTURE WORK

Past work on the Lourdes Formation has been fairly limited, focusing on basic stratigraphy and sedimentology or biostratigraphic study of particular fossils groups. While the current project has achieved a more detailed and comprehensive record of the sedimentology and stratigraphy, provided the first in-depth study of the coral bioherms, and contributed to our understanding of tectonics and relative sea level in Humber Zone, opportunities for future work in the Lourdes Formation abound.

In terms of better understanding the diagenetic history especially related to subaerial exposure surfaces and possible paleo-protosoil horizons in the Beach Point member, a detailed study of stable isotopes throughout the Lourdes Formation would be very valuable. Subtle exposure surfaces can often be recognized geochemically where they are not easily visible in the field, especially in relatively condensed and sediment-starved conditions that recur frequently in the uppermost Lourdes Formation (Ludvigson et al. 2004). This could greatly increase the resolution of the sequence stratigraphic record for this interval.

Analysis of P_2O_5 in limestones of the region (Lower and Middle Ordovician, Lourdes and Winterhouse formations) would also be useful to compare with carbonates

of the same age in adjacent regions. Lavoie and Asselin (1998) have identified an upward increase in P_2O_5 in the Ordovician of Quebec, interpreted to record cooling and/or upwelling conditions. Cooling trends are also identified in the northeastern United States, and a similar trend may help to further explain the short-lived nature of carbonate sedimentation in the Long Point Group.

The trends in rare-earth element (REE) compositions identified in the current study are based on a limited number of widely spaced samples. Further work on REE compositions of siliciclastic deposits throughout the Long Point Group and extending into older strata would be helpful to better constrain the paleogeography of the region related to sources and transport of siliciclastic sediment. Also, detrital zircons are abundant in sandstones of the Lourdes Formation, and may be useful to tie in with geochronological provenance studies in the region (e.g., Cawood and Nemchin (2001)).

While several studies have attempted to date the Lourdes Formation using biostratigraphy, none has been successful in obtaining biostratigraphically diagnostic fossils from the Shore Point Member. Therefore, the maximum age of the formation remains uncertain. A detailed study of acritarchs, particularly from shale units of the Lourdes Formation may help to provide a maximum age for the Lourdes and further refine the age and paleogeography. Work by Gillespie (1998) on acritarchs of the overlying Winterhouse would provide a good basis for comparison.

The Lourdes contains an abundant, diverse, and well preserved brachiopod fauna in a variety of environments ranging from reefs and shallow shoreface to siliciclastic-dominated mid-ramp settings. This would be an ideal location for a detailed paleontological study of brachiopod populations and paleoecology, and possibly isotopic analysis of brachiopods. The diverse and abundant trace fossil assemblage throughout the

Long Point Group would also be an excellent candidate for an ichnological study. Ichnofacies interpretations would further refine lithofacies and paleoenvironmental interpretations.

As petroleum exploration continues in western Newfoundland, petrophysical data and lithological data in the form of well cuttings are becoming more readily available. Future work on subsurface data will be important in better defining the true base of the Lourdes Formation and its relationship to underlying units. Lateral correlation of stratigraphy into the subsurface will hopefully lead to a better understanding of sequence stratigraphy based on three-dimensional data, and will provide a better understanding of relationships of the Long Point Group to the realm of Ordovician sedimentary rocks in eastern North America.

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APPENDIX A: STRATIGRAPHIC SECTIONS

Bioclast types

- Calcareous red algae
- *Epiplastospongia* sp.
- *Eofletcheria* sp. (or *Billingsaria* sp.)
- Rugose coral
- *Labyrinthites*
(upright, overturned)
- Echinoderm debris
- Ramosse bryozoa
- Fenestrate bryozoa
- Brachiopods
- Pelecypods
- Gastropods
- Nautiloids
- Molluscan debris
- Graptolites
- Ostracods
- Trilobites
- Stromatoporoids
- Bioclastic lag

Ichnofossils

- Vertical burrows
- Horizontal burrows
- *Chondrites*
- Bioturbation
slight
- } moderate
- } } intense

Non-skeletal Grains

- Intraclasts
- Peloids
- Ooids
- *Girvanella* oncoids
- Accessory quartz sand
- Out-size clasts
(granule/pebble)

Physical Structures

- Parallel lamination
- Current ripples
- Oscillation ripples
- Combined flow ripples
- Planar tabular cross-beds
- Trough cross-beds
- Hummocky cross-stratification
- “Wispy” shale interlaminae
- Crinkly lamination
- Normal grading
- Reverse grading
- Desiccation cracks
- Fenestrae
- Scoured surface
- Karst surface
- Slump / soft sediment deformation
- Nodular bedding
- Paleocurrent
(single measurement)

Diagenetic Effects

- Chert nodules
- Pyrite
- Framboidal pyrite
- Probable hardground
- Saddle dolomite
- Shearing

Lithology

- Lime mudstone
- Wackestone
- Packstone
- Grainstone
- Rudstone
- Floatstone
- Framestone
- Argillaceous limestone
- Silty shale
- Siltstone
- Sandstone
- Calcareous sandstone
- Conglomerate
(framework supported)
- Breccia

Bedding:

- Thin bedding
- Medium Bedding
- Thick bedding
- Lenticular bed

(Section continues upward, but access is difficult. Same as TC1.)

← Start of cliff-forming sandstones.

Lithified, brown- to buff-weathering, calcareous sandstone. Thin to medium-bedded.

Single bed of well-cemented, brown sandstone.

Poorly sorted, rounded, slightly better consolidated, beige to brown (green tint on fresh surfaces).

Poorly sorted, well rounded, poorly consolidated, green to red. Pink feldspar grains, and fragments of argillite.

Soft, dark green to red clay/argillite. Bedding sub horizontal but sheared.

Section TC-2 (Tea Cove)
Location 2

Section TC3 (Tea Cove)
Location 3

Section TC6 (Tea Cove)
Location:

Section P-1 (Portage)
Location 4

Section P-2 (Portage)
Location 5

Section P-3 (Portage)
Location 6 (page 1 of 2)

Section BD1
(Black Duck Brook)

Lt. grey, rubbly weathering.

Some sst. beds pinch out (lenses)

Sst. w/ sharp bases & irregular, borrowed tops.

Section BD-2 (Black Duck Brook)
Location 7 (page 2 of 2)

Section S (Shed Section)
Location 9 (page 2 of 2)

Section BP (Bench Point)
Location 10

Section FI-3 (Fox Island)
Location 11

Section LP-1 (end of Long Point)
Location 18

Section LP-3 (end of Long Point)
Location 19

Section LP-4 (end of Long Point)
Location 20

Section TR (Three Rock Cove)
Location: 48°37.567'N 59°05.901'W

APPENDIX B: FAUNAL LIST

The following table lists fossils identified during the course of the current study. It is not intended as an exhaustive faunal list; additional references listed below provide more complete information on paleontology and paleoecology of the Long Point Group. Fossils marked by an asterisk are present in the coral bioherms of the Black Duck Member.

Stratigraphic position	Fossil type	Genus, species	Other
Winterhouse Fm.	Brachiopods Receptaculitids	<i>Leangella</i> sp.	
Beach Point Mbr.	Trilobites	<i>Isotelus</i> sp. <i>Calyptaulax</i> sp.	Assorted pelmatozoan ossicles, plates, columnal sections, and holdfasts
	Echinoderms		
	Brachiopods	<i>Strophomena</i> sp. <i>Sowerbyella</i> sp. <i>Megamyonia</i> sp. <i>Megamyonia</i> cf. <i>nitens</i> <i>Leangella</i> sp. <i>Rafinesquina</i> sp. <i>Hesperorthis</i> sp.	rugosans diverse forms: ramose, frondose, fenestrate, encrusting
	Corals Bryozoans	<i>Labyrinthites chidlensis</i>	
Black Duck Mbr.	Echinoderms		Cystoid calyxes, Class Diploporita Assorted pelmatozoan ossicles*, plates, columnal sections, and holdfasts*
	Corals	<i>Labyrinthites chidlensis</i> * <i>Lyopora</i> sp.* <i>Aulopora</i> sp.* <i>Lambeophyllum</i> sp. cf. <i>Streptelasma</i> sp.	
	Stromatoporoids	<i>Labechia</i> sp.*	
	Sponges	<i>Epiplastospongia</i> <i>coactilis</i> * <i>Solenopora</i> sp.*	
			Lithistids, spicules*

Shore Point Mbr.	Brachiopods	<i>Sowerbyella</i> sp. <i>Glyptorthis</i> sp. <i>Rafinesquina</i> sp. <i>Megamyonia</i> sp. <i>Rostricellula</i> sp.*	
	Bryozoans		Lingulids (fragmentary) diverse forms: ramose*, frondose, fenestrate, encrusting* orthocones
	Cephalopods		
	Gastropods	<i>Maclurites</i> sp. <i>Sublites</i> sp.	
	Trilobites		
	Microfossils	<i>Girvanella</i> sp.* <i>Wetheredella</i> sp.* <i>Sphaerocodium</i> sp.*	
	Gastropods		
	Ostracodes		
	Microfossils		calcareous red algae
	Sponges	<i>Girvanella</i> sp.	spicules
	Trilobites		fragments
	Brachiopods		fragments
	Bryozoans		fragments
	Echinoderms		assorted pelmatozoan ossicles and plates
	Molluscs		fragments

Previous work on Lourdes Formation paleontology:

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APPENDIX C: GEOCHEMICAL DATA

ICP-AES data (ppm)

	Sample	Lith.	Position	Al	Ba	Be	Ca	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na
1	4C-7	shale	Misty Pt. Fm.	78920	425	0.7	29544	18	246		41849	11083	16	29679	298	27013
2	4C-6	sst	Misty Pt. Fm.	50006	848	0.5	8293	6	300	6	12408	18655	13	8724	184	21846
3	4C-4	sst	Misty Pt. Fm.	63838	530	0.9	4495	18	250	5	31982	24217	32	24174	321	23711
4	4C-27	shale	Winterhouse Fm (uppermost)	77490	383	1.5	17291	26	146	8	54459	26749	59	38346	583	7038
5	4C-26	sst	Winterhouse Fm (upper)	58217	675	0.5	53960	14	213	6	22818	15611	25	12840	1175	24260
6	4LP3- 13c	sst	Beach Pt. Mbr.	66114	395	1.1	45680	13	142	5	33473	27098	79	29122	294	8798
7	TC2-1	sst	Shore Pt. Mbr.	12800	252	0.1	59022	2	11	33	5056	4876	13	5735	1019	4075
8	TC5-4	sst	Shore Pt. Mbr.	6954	109		>100000	2	22		3242	3843	3	5306	406	2138
9	4C-9A	sst	Mainland Fm.	49519	375	0.7	18471	18	326	19	35260	17777	42	26576	354	9383
10	4C-9	shale	Mainland Fm.	38116	320	0.5	38945	17	320	12	27400	12705	35	26970	559	8428
11	S4	sst	Mainland Fm.	8470	90	0.2	>100000	7	9	3	12484	5838	8	>60000	>2500	915
12	S5	shaly sst	Mainland Fm.	52408	315	0.7	51096	17	150	25	34776	18128	49	21376	863	9043
13	4C-11	shale	Mainland Fm.	66598	390	1.1	18292	23	177	24	45491	26327	74	33444	366	9429
14	TC-HA	sst	Humber Arm Sgrp.	53548	481	0.5	12592	9	45	14	23425	19327	27	5201	525	13976
15	04C-3	sst	Humber Arm Sgrp.	62228	389	1.0	43994	15	102	24	40761	22357	60	26519	451	6332

ICP-AES data, continued (ppm)

	Sample	Lith.	Position	Ni	P	S	Sc	Sr	Ti	V	W	Y	Zn
1	4C-7	shale	Misty Pt. Fm.	118	1176		16	526	3598	98	4	27	52
2	4C-6	sst	Misty Pt. Fm.	38	98	90	6	379	1013	40		8	18
3	4C-4	sst	Misty Pt. Fm.	127	215	59	14	292	1517	73	2	10	47
4	4C-27	shale	Winterhouse Fm (uppermost)	141	467	>400	15	72	3522	99	4	20	98
5	4C-26	sst	Winterhouse Fm (upper)	59	513	>400	12	280	2648	78	3	16	37
6	4LP3- 13C	sst	Beach Pt. Mbr.	55	293	>400	11	108	3593	78	5	16	60
7	TC2-1	sst	Shore Pt. Mbr.	6	122	61	2	49	396	9	2	11	8
8	TC5-4	sst	Shore Pt. Mbr.	6		>400	1	96	172	4	3	5	23
9	4C-9A	sst	Mainland Fm.	138	636	98	9	88	2782	92	6	16	96
10	4C-9	shale	Mainland Fm.	207	461	>400	8	113	1928	74		13	55
11	S4	sst	Mainland Fm.	16	84	>400	2	165	304	11		16	40
12	S5	shaly sst	Mainland Fm.	78	642	134	11	111	3017	93	6	20	104
13	4C-11	shale	Mainland Fm.	185	673	>400	12	77	3652	105	3	17	94
14	TC-HA	sst	Humber Arm Sgrp.	24	170	48	6	95	2790	44	10	12	47
15	04C-3	sst	Humber Arm Sgrp.	85	580	>400	11	115	3029	97	4	19	109

ICP-MS data (ppm)

Sample	Lith.	Position	Ce	Cs	Dy	Er	Eu	Gd	Hf	Ho	La	Lu	Nb	Nd	Pr	Rb
1 4C-7	shale	Misty Pt. Fm.	69.76	0.695	5.184	3.285	1.576	5.673	4	1.08	35.59	0.54	6.3	36.51	9.254	28.75
2 4C-6	sst	Misty Pt. Fm.	29.66	0.451	1.828	1.037	0.789	2.16	1.8	0.36	14.22	0.15	3.2	13.75	3.535	35.03
3 4C-4	sst	Misty Pt. Fm.	45.44	1.405	2.212	1.279	0.926	2.569	2.2	0.43	23.84	0.19	3.8	19.01	5.174	44.58
4 4C-27	shale	Winterhouse Fm (uppermost)	69.71	4.552	4.422	2.705	1.268	4.733	3.6	0.91	35.14	0.39	11.9	30.1	7.96	120.36
5 4C-26	sst	Winterhouse Fm (upper)	46.96	0.899	3.563	1.922	1.27	4.091	3.9	0.69	19.82	0.26	4.6	22.45	5.598	39.29
6 4LP3-13c	sst	Beach Pt. Mbr.	55.81	4.206	3.343	2.043	0.884	3.487	4.9	0.69	28.95	0.3	13.4	24.13	6.468	115.55
7 TC2-1	sst	Shore Pt. Mbr.	22.37	0.499	2.079	1.133	0.573	2.189	1.3	0.41	9.34	0.15	1.5	11.52	2.861	19.06
8 TC5-4	sst	Shore Pt. Mbr.	12.15	0.173	0.771	0.435	0.264	0.848	3	0.16	6.35	0.06	0.6	4.9	1.349	11.98
9 4C-9A	sst	Mainland Fm.	51.73	2.739	3.431	1.935	0.961	3.804	5	0.68	25.17	0.27	8.9	23	6.02	77.49
10 4C-9	shale	Mainland Fm.	37.72	1.447	2.65	1.47	0.743	2.889	2.9	0.51	18.58	0.2	5.7	17.03	4.495	49.34
11 S4	sst	Mainland Fm.	37.25	0.374	3.109	1.51	0.883	3.545	0.8	0.6	15.89	0.16	1.1	17.81	4.453	14.35
12 S5	shaly sst	Mainland Fm.	57.04	2.788	4.166	2.348	1.141	4.53	4.8	0.84	27.19	0.32	8.8	25.93	6.747	75.34
13 4C-11	shale	Mainland Fm.	62.79	4.651	3.758	2.139	1.097	4.208	4.5	0.73	31.69	0.3	12.5	27.45	7.351	117.78
14 TC-HA	sst	Humber Arm Sgrp.	52.17	1.523	2.5	1.43	0.794	2.82	7.2	0.49	24.4	0.22	9	20.74	5.681	78.41
15 04C-3	sst	Humber Arm Sgrp.	63.45	4.642	4.231	2.248	1.261	4.873	3.5	0.81	30.5	0.29	10.9	29.64	7.689	109.69

ICP-MS data, continued (ppm)

Sample	Lith.	Position	Sm	Sr	Ta	Tb	Th	Tm	U	Y	Yb	Zr
1 4C-7	shale	Misty Pt. Fm.	7	589	0.4	0.8	8	0.5	2.1	32	3.4	156
2 4C-6	sst	Misty Pt. Fm.	3	409	0.2	0.3	5	0.2	1.1	10	1.0	68
3 4C-4	sst	Misty Pt. Fm.	3	319	0.2	0.4	4	0.2	2.2	11	1.2	79
4 4C-27	shale	Winterhouse Fm (uppermost)	6	80	0.7	0.7	10	0.4	2.1	24	2.6	132
5 4C-26	sst	Winterhouse Fm (upper)	5	313	0.3	0.6	6	0.3	1.2	19	1.7	154
6 4LP3-13C	sst	Beach Pt. Mbr.	4	118	0.8	0.5	10	0.3	2.2	18	2.0	189
7 TC2-1	sst	Shore Pt. Mbr.	2	52		0.4	2	0.2	0.4	12	1.0	50
8 TC5-4	sst	Shore Pt. Mbr.	1	101		0.1	1	0.1	1.1	5	0.4	119
9 4C-9A	sst	Mainland Fm.	4	96	0.5	0.6	7	0.3	2.2	18	1.9	192
10 4C-9	shale	Mainland Fm.	3	123	0.3	0.4	5	0.2	1.7	14	1.3	113
11 S4	sst	Mainland Fm.	3	191		0.5	1	0.2	0.8	19	1.1	33
12 S5	shaly sst	Mainland Fm.	5	121	0.5	0.67	7	0.3	2.4	23	2.2	192
13 4C-11	shale	Mainland Fm.	5	84	0.7	0.6	9	0.3	2.6	19	2.0	173
14 TC-HA	sst	Humber Arm Sgrp.	4	103	0.5	0.4	8	0.2	1.4	14	1.5	278
15 04C-3	sst	Humber Arm Sgrp.	6	128	0.6	0.7	8	0.3	2.7	22	2.0	132

WRF data (wt%)

Sample	Lith.	Position	Al2O3	CaO	Fe2O3	K2O	LOI	MgO	MnO	Na2O	P2O5	SiO2	TiO2	LOI	TOTAL
1	4C-7	shale	Misty Pt. Fm.	16.21	4.27	6.07	1.44	5.53	5.07	0.05	3.79	0.29	55.76	0.69	99.2
2	4C-6	sst	Misty Pt. Fm.	9.98	1	1.59	2.34	1.83	1.41	0.03	3.1	0.03	78.23	0.18	99.7
3	4C-4	sst	Misty Pt. Fm.	13.31	0.6	4.32	3.16	3.72	4.13	0.05	3.31	0.05	67.81	0.29	100.8
4	4C-27	shale	Winterhouse Fm (uppermost)	15.86	2.41	7.89	3.62	9.07	6.66	0.1	1.02	0.12	52.28	0.68	99.7
5	4C-26	sst	Winterhouse Fm (upper)	11.98	7.6	3.38	2.1	7.83	2.33	0.19	3.24	0.13	60.51	0.54	99.8
6	4LP3- 13c	sst	Beach Pt. Mbr.	13.34	6.48	4.9	3.59	10.95	5.1	0.05	1.19	0.08	53.05	0.69	99.4
7	TC2-1	sst	Shore Pt. Mbr.	2.5	7.39	0.71	0.64	7.69	1.01	0.15	0.54	0.03	79.63	0.08	100.4
8	TC5-4	sst	Shore Pt. Mbr.	1.34	22.9	0.46	0.53	21.06	0.99	0.07	0.27		53.54	0.04	101.2
9	4C-9A	sst	Mainland Fm.	9.92	2.68	4.9	2.31	7.46	4.56	0.06	1.22	0.15	65.93	0.54	99.7
10	4C-9	shale	Mainland Fm.	7.72	5.49	3.92	1.71	8.23	4.61	0.09	1.14	0.12	66.37	0.39	99.8
11	S4	sst	Mainland Fm.	1.7	32	2	0.86	38.49	12.19	0.86	0.12	0.05	12.89	0.08	101.2
12	S5	shaly sst	Mainland Fm.	10.64	7.31	5.24	2.43	10.46	3.85	0.14	1.26	0.17	58.1	0.59	100.2
13	4C-11	shale	Mainland Fm.	13.97	2.54	6.67	3.59	9.49	5.98	0.06	1.24	0.16	54.42	0.7	98.8
14	TC-HA	sst	Humber Arm Sgrp.	10.85	1.72	3.18	2.6	3.73	0.93	0.08	1.93	0.04	73.56	0.51	99.2
15	04C-3	sst	Humber Arm Sgrp.	13	6.7	6.2	3.25	12.78	4.88	0.08	0.77	0.16	50.57	0.61	99.0

Stable Isotope Data

Lab ID	Sample ID	Sample #	Delta 13C (VPDB)	Delta 18O (VPDB)
Paleokarst Study (depth below paleokarst in cm)				
C-17955	1	M1 +16	-1.41	-5.88
C-17956	2	M1 -3	-0.66	-5.54
C-17957	3	M1 -9	-0.76	-5.64
C-17958	4	M1 -35	-0.68	-6.06
C-17959	5	M1 -40	-0.63	-6.28
C-17960	6	BB2 +1	-0.68	-5.73
C-17961	7	BB2 -.5	0.14	-5.97
C-17963	8	BB2 -16	-0.36	-5.73
C-17964	9	BB2 -33	0.59	-6.22
C-17965	10	BB2 -61	0.02	-6.57
C-17966	11	BB2 -72	0.6	-6.82
C-17967	12	BB2 -84	-0.08	-6.34
C-17968	13	FI1 +1	-0.7	-6.25
C-17969	14	FI1 -13	-0.36	-5.79
C-17970	15	FI1 -20	-0.47	-5.22
C-17971	16	FI1 -25	-0.52	-4.9
C-17972	17	FI1 -33	-0.5	-5.98
C-17974	18	FI1 -100	-0.02	-4.83
C-17975	19	S +1	-2.29	-4.92
C-17976	20	S -25	-0.35	-5.03
C-17977	21	S -45	-0.07	-6.59
C-17978	22	S -70	-0.46	-6.29
Selected micrite samples – reef fill				
C-17992	M	4S-R8	0.32	-4.49
C-17994	O	4S-R1	0.18	-4.28
C-20136	BD1-R9	BD1-R9	0.73	-4.39
C-20137	4S-R6	4S-R6	0.24	-4.45
C-20138	4S-R9	4S-R9	0	-4.3
C-20139	BP-4a	BP-4a	0.24	-4.66
Selected micrite samples – peritidal lime mud				
C-17993	N	4P1-1b	-0.38	-4.92
C-17996	P	TC5-2	-2.1	-4.55
C-20140	4P3-2a	4P3-2a	-1.71	-4.1
C-20141	TC5-2	TC5-2	-2.14	-4.5
C-20142	TC5-3	TC5-3	-0.65	-4.81
C-20143	TC1-11	TC1-11	-1.04	-4.76
Selected cement samples				
C-20144	TC1-11x	TC1-11x	-1.2	-9.65
C-20145	LP4-4a	LP4-4a	-0.15	-5.09
C-20146	LP2-11b	LP2-11b	0.05	-4.71
C-20147	LP3-5a	LP3-5a	-0.12	-4.63

APPENDIX D: LOCATION OF STUDY SITES

Locality	Section	Latitude	Longitude	NTS Map Sheet (1:50 000)
1	TC1	48°39.4' N	58°57.2' W	Stephenville 12/B10
2	TC2	48°39.5' N	58°57.15' W	Stephenville 12/B10
3	TC3	48°40.0' N	58°56.25' W	Stephenville 12/B10
4	P1	48°40.25' N	58°56.0' W	Stephenville 12/B10
5	P2	48°41.2' N	58°54.8' W	Stephenville 12/B10
6	P3	48°41.3' N	58°54.6' W	Stephenville 12/B10
7	BD2	48°41.65' N	58°54.05' W	Stephenville 12/B10
8	BD1	48°41.55' N	58°54.25' W	Stephenville 12/B10
9	S	48°42.5' N	58°52.8' W	Stephenville 12/B10
10	BP	48°43.0' N	58°52.0' W	Stephenville 12/B10
11	FI2	48°43.7' N	58°50.95' W	Stephenville 12/B10
11	FI3	48°43.7' N	58°50.95' W	Stephenville 12/B10
12	M1	48°44.9' N	58°49.2' W	Stephenville 12/B10
13	M2	48°45.0' N	58°49.1' W	Shag Island 12/B15
14	BB1	48°45.6' N	58°47.55' W	Shag Island 12/B15
15	BB2	48°45.95' N	58°47.05' W	Shag Island 12/B15
16	BB3	48°46.1' N	58°46.8' W	Shag Island 12/B15
17	BB4	48°46.3' N	58°46.75' W	Shag Island 12/B15
18	LP1	48°44.4' N	58°46.6' W	Shag Island 12/B15
	LP2	48°44.5' N	58°46.4' W	Shag Island 12/B15
19	LP3	48°44.75' N	58°46.1' W	Shag Island 12/B15
20	LP4	48°44.9' N	58°45.95' W	Shag Island 12/B15
Three Rock Cove	TR	48°37.7' N	59°05.6' W	Mainland 12/B11