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STRATIGRAPHIC REVISION OF THE UPPER CHAZYAN TO TRENTONIAN SUCCESSION, AND SEDIMENTOLOGIC AND DIAGENETIC ASPECTS OF THE BLACKRIVERAN STRATA, OTTAWA EMBAYMENT, EASTERN ONTARIO, CANADA

BY

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A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfilment of
requirements for the degree of Doctor of Philosophy,
Department of Earth Sciences
Carleton University
Ottawa, Ontario
December 19, 1997

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Abstract

The purpose of this study is to unravel stratigraphic and sedimentologic attributes of the Middle-Upper Ordovician strata in the Ottawa Embayment. The embayment is an extension of the St. Lawrence Platform, part of a foreland basin. The stratigraphic interval investigated displays transition from siliciclastic (Rockcliffe Formation), through transitional (Hog's Back Formation), and carbonate-dominated (Ottawa Group) deposition. Major contributions of the study include: recognition of the Hog's Back Formation; stratigraphy and applicable lithostratigraphic nomenclature for the Ottawa Group; and, details of the sedimentology and diagenesis of the Blackriveran strata.

The Hog's Back Formation consists of shale, with subordinate mudstone and sandstone interbeds, overlain by calcareous dolostone with minor packstone and grainstone interbeds. It defines a siliciclastic - carbonate transition within the platform. Conodonts and other fossils indicate a Chazyan age for the formation.

The main carbonate platform phase developed during the Blackriveran and Trentonian stages (Ottawa Group). Stratigraphic correlations within Blackriveran strata between upstate New York and Ottawa Embayment suggest that Pamelia, Lowville and Chaumont are applicable lithostratigraphic terms. Lithofacies of the Blackriveran strata accumulated in peritidal (Pamelia & Lowville) and subtidal (Chaumont) environments. Diagenetic alteration of these strata developed in marine, vadose, meteoric and burial environments. Three dolomite generations are recognized; Dolomite I, which consists of fine euhedral to subhedral crystals, is predominant. Oxygen and carbon isotopes, as well as petrographic and field relationships, suggest a supratidal to shallow intertidal origin. The remaining two dolomite generations (II & III) are of burial origin.

Unlike the Blackriveran strata, upper (Trentonian) formations of the Ottawa Group are better correlated with coeval strata in south-central Ontario. Thus, the terms Bobcaygeon, Hull (re-established), Verulam and Lindsay, in ascending order, are applicable. Stratigraphic analysis illustrates that most of the Hull and Verulam strata are laterally equivalent.

Metre- to tens of metres-scale vertical stacking patterns in the Chazyan-Blackriveran-Trentonian strata identify several orders of relative sea-level changes superimposed on an overall deepening-upward succession. Three successions of contrasting depositional patterns

are recognized: shallowing-upward peritidal units (Hog's Back, Pamelia, & Lowville fms); shallowing-upward subtidal units (Chaumont & Bobcaygeon fms); and a deepening-upward subtidal succession (Hull, Verulam and Lindsay formations). These gross and higher order patterns reflect interplay of tectonic and higher-frequency allostratigraphic controls.

Acknowledgements

Field work for this research was supported by a research grant from the Natural Sciences and Engineering Council to G.R. Dix. Most laboratory work was done at Carleton University. Stable isotope, and trace and major element analyses were done at the Ottawa-Carleton Geoscience facility, Department of Geology, Ottawa University. Personal financial support was provided by Carleton University Scholarship.

I thank George Dix for his careful supervision of the thesis, including visits to the field, critical reading of the manuscript, critical constructive discussion, and providing lots of feedback. I extend my thanks to Dr. A.D. McCracken of the Geological Survey of Canada (GSC) for processing and identifying conodont fauna from samples collected from several key stratigraphic intervals. My thanks also go to the late Dr. T. Bolton, of the GSC, for identification of an orthocone specimen, as well as Dr. A. Desrochers of the University of Ottawa for an informal review of the original manuscript of Chapter 2. I also thank Dr. J. Blenkinsop for assisting me to understand previous geophysical work. Most of the studied sections are from quarries, and thier owners are greatly thanked for letting me map their quarries.

I am grateful to my field assistants W. Walsh, P. Brennan, and A. Hilowle for their help. Mr. A. Hussein is also thanked for helping me learn Surfer software for preparation of isopach maps.

I finally thank and appreciated the support given by my wife, Ward A. Jama. She has been a constant source of inspiration.

Statement of original contribution

During the course of my research, several publications have been published including parts of data reported in this thesis. Publications of which I am first author include abstracts in meetings (Salad Hersi and Dix 1994; 1997b; c), a non-peered review short paper published in the Proceedings of the 7th International Symposium on the Ordovician System (Salad Hersi and Dix 1995); and, a manuscript (Salad Hersi and Dix 1997a) in the Canadian Journal of Earth Sciences. The latter manuscript is presented as Chapter 2 of this thesis. The role of the second author in all these publications was as editor and scientific advisor. In addition, selected portions of my research have been reported in two recently published guidebooks (Dix et al. 1997a; b) for which I am second author. My role in preparation of the guidebooks was to contribute necessary data and review a preliminary version of the manuscripts.

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CHAPTER ONE

INTRODUCTION

General statement

The study area essentially encompasses the Ottawa Embayment in Eastern Ontario with one locality in the Hull (Quebec) city area (Fig. 1.1). The region is underlain by a Cambrian to Ordovician sedimentary succession. These lower Paleozoic rocks have been studied since work of Logan (1863), yet confusion concerning a suitable stratigraphic division and nomenclature for Middle Ordovician through Upper Ordovician strata, including Chazyan, Blackriveran, and Trentonian strata (Barnes 1964; Steele-Petrovich 1984), still remains. Previous work dealing with this stratigraphic interval can be separated according to whether it has used (1) terminology that was originally based on macrofaunal biostratigraphic zonation, first established by Raymond (1914) and Wilson (1946) or (2) terminology based on lithostratigraphic correlation with formation names imported from south-central Ontario because of an apparent general stratigraphic similarity, as first expressed by Liberty (1967a) and followed by Williams and Rae (1983), Williams and Telford (1986), Williams (1991), and Johnson et al. (1992). The intention of the workers who adopted the second approach was to eliminate the use of the faunal-based zonation as this contradicts the North American Stratigraphic Code (Committee on Stratigraphic Nomenclature 1933; North American Commission on Stratigraphic Nomenclature 1983).

The problem in defining a stratigraphic division leads to obvious difficulties in extracting well defined regional paleogeographic and paleoenvironmental frameworks. Williams' (1991) recent work, for example, was only of a very broad nature. Secondly, his

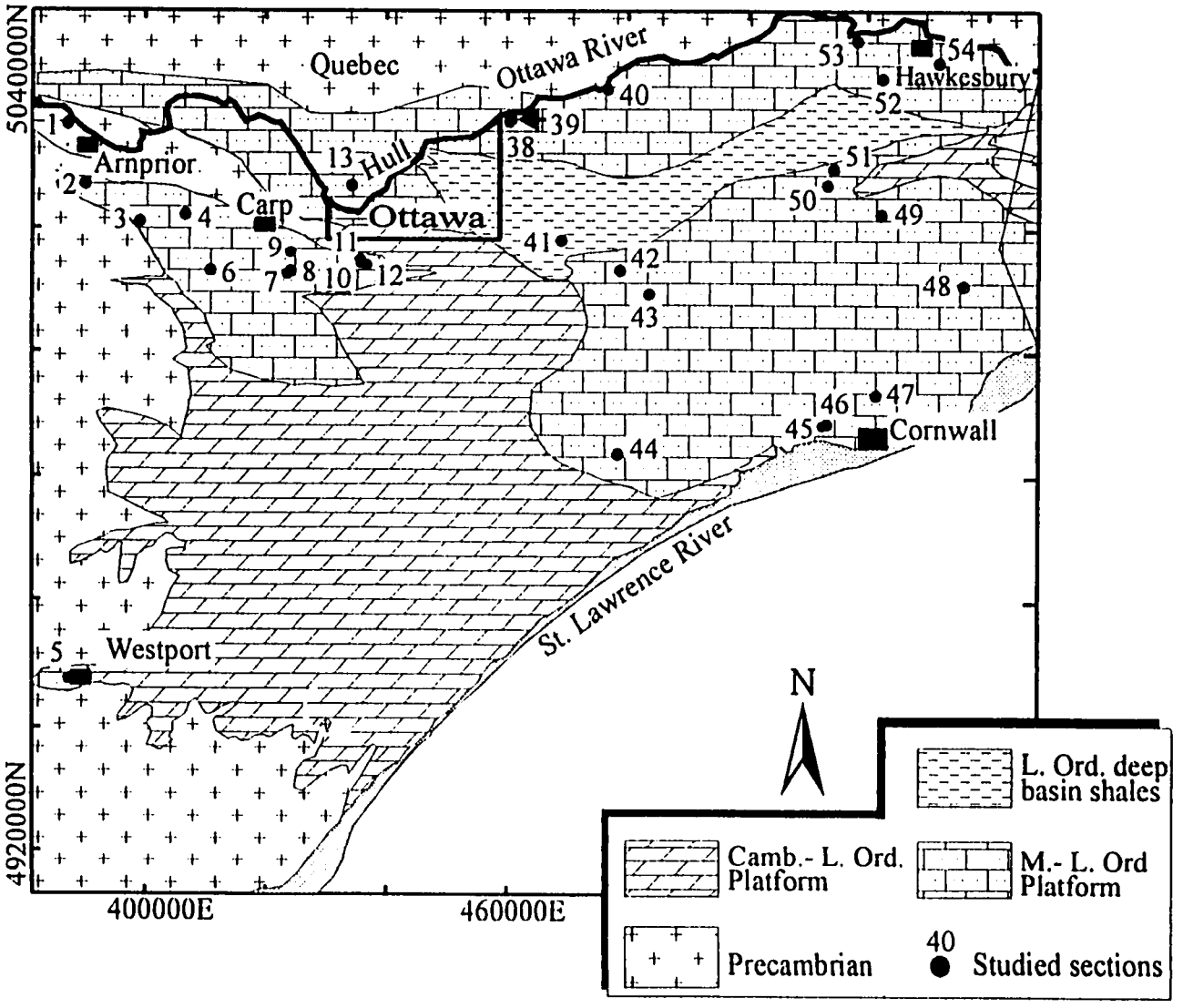


Fig. 1.1 General geologic map of the Ottawa Embayment with locations mentioned in the text. Localities 14 to 37 occur in and around the City of Ottawa (area in the box) and are shown in Fig. 1.6.

work appears to have ignored striking similarities in lithology between rock units in the Ottawa Embayment and upstate New York, as previously noted by Raymond (1914), Wilson (1932), and Young (1943a; b). Thus, lithostratigraphic terminology from New York State (Cushing 1908, Cushing et al. 1910) has precedence over terminology from southwest and central Ontario proposed in the 1950s and 1960s (Liberty 1955; 1967b; 1969). Whether terminology from upstate New York or south-central Ontario should be used for eastern Ontario will depend on similarity of geological history in basin development and fill. Detailed study of the Middle to Upper Ordovician stratigraphic succession in the eastern Ontario region, and comparison with the stratigraphy of the adjacent regions, will shed light on the relationship among tectonic, sedimentologic as well as eustatic signatures of adjacent basins. Such relationships will express the degree of commonality in geological history of continental-scale tectonic development to high frequency changes in sea level that affected sedimentation patterns and stratigraphy of each basin. Consequently, a study of this type will better define the appropriate nomenclature applicable for the Middle to Upper Ordovician rock succession in the Ottawa Embayment through correlation, or lack of, with equivalent stratigraphic successions of adjacent sedimentary basins.

Purpose of the study

Aspects of this study are summarized as follows: (1) to provide a general lithostratigraphic study of the Middle to Upper Ordovician succession in the Ottawa Embayment in order to rectify previous confusion in the stratigraphy of the region; (2) to study the Chazyan - Blackriveran boundary; and (3) to make lithostratigraphic correlations

between the Blackriveran and Trentonian succession of the Ottawa Embayment and its equivalent strata in the adjacent basins of southeastern Ontario and upstate New York. From this, a nomenclature applicable for the Middle to Upper Ordovician succession in the Ottawa Embayment is proposed. This study also concentrated on the diagenetic evolution of the Blackriveran succession in the Ottawa Embayment. Finally, stratigraphic and sedimentologic attributes of the studied rock succession allow a better understanding of relative sea-level changes.

Geological setting

Sanford (1993a) divided the St. Lawrence Platform into western, central and eastern divisions (Fig. 1.2). The Ottawa Embayment is a westward-elongating tectonic sub-province of the Central St. Lawrence Platform (Fig. 1.2). The evolution of the St. Lawrence Platform is linked to Paleozoic plate-tectonic events that occurred between late Precambrian to late Paleozoic time. These events began with extensional tectonics allowing the formation of the Iapetus Ocean in the Late Proterozoic. The opening of the Iapetus Ocean continued through Cambrian to Early Ordovician. Tectonic convergence occurred by late Early and Middle Ordovician time (Taconian orogeny) and eventually caused the closure of the Iapetus Ocean (Fig. 1.3).

The Ottawa Embayment is considered a westward extension of the Central St. Lawrence Platform which developed from an aborted tectonic depression (aulacogen) called "the Quebec Re-entrant". The latter began to develop in the early phase of the continental separation (Doolan et al. 1982). Enough data supporting early rifting of northeastern

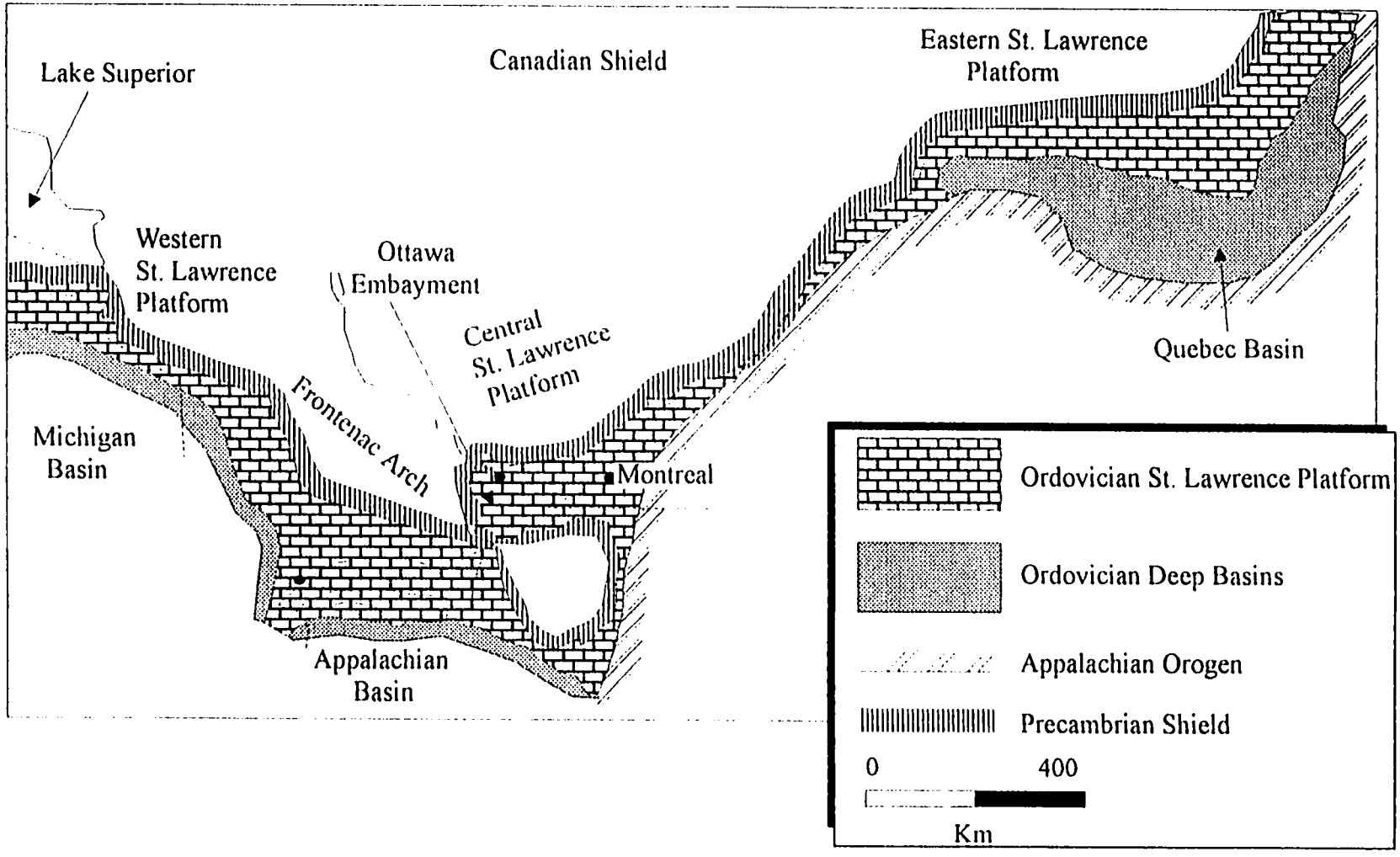


Fig. 1.2 Geographic position of the St. Lawrence Platform and its subdivision into western, central and eastern sub-platforms. (Modified after Sanford 1993a)

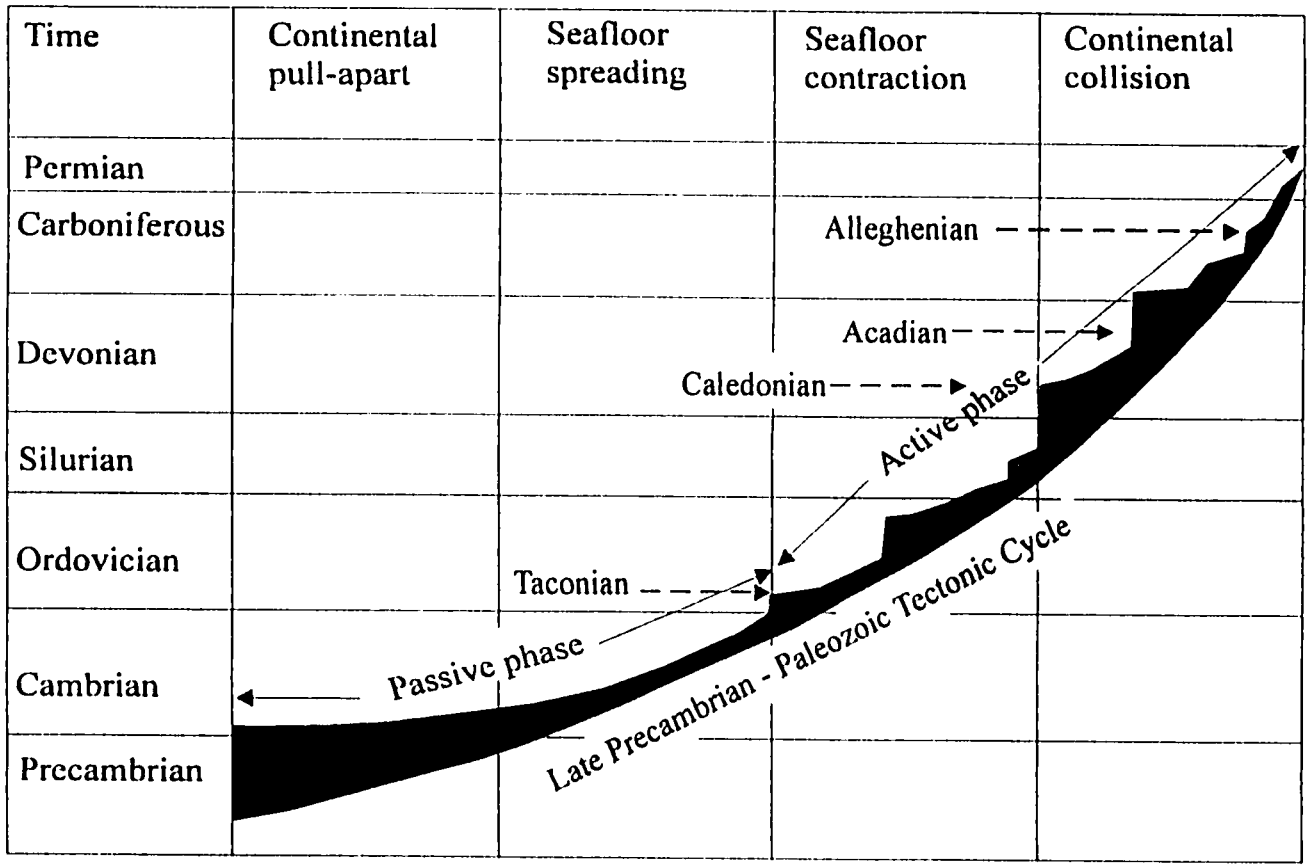


Fig. 1.3 Late Proterozoic - Paleozoic tectonic cycle in eastern North America. The passive phase of the cycle implies opening of the Iapetus Ocean from Late Proterozoic to Early Ordovician time. During early Mid. Ordovician, the extensional tectonic style reversed to a convergent style which subsequently caused the Taconian, Caledonian, Acadian, and Alleghenian orogenies. Their early stages are shown here by dashed lines. (Modified from Sanford 1993b).

America and existence of the "Ottawa Aulacogen" have been provided by previous work (e.g., Kumarapeli and Saull 1966; Wilson 1966; Doig 1970; Kumarapeli 1976; 1978; Rankin 1976; Doolan et al.; 1982; Sanford 1993a; b). It has been suggested that the two successfully developed arms of the rift-system were NW trending axis of the New England salient, and a northeastward direction more or less parallel with the St. Lawrence River (Kumarapeli 1976; 1978; Doolan et al. 1982). Minor extensional tectonics is assumed to have occurred in the Mesozoic era as suggested by (1) rejuvenated Taconian faults that cut the Ordovician strata in the Ottawa Embayment; and, (2) generation of the Ottawa-Bonnechere Graben (Kay, 1942). Further uplifting of some positive morphological features, such as the Frontenac Arch and Beauharnois Anticline, were probably formed in post-Taconian time (Sanford 1993b; Sawford 1972).

The oldest rocks in the Embayment are Precambrian in age and belong to the Grenville Province. The Embayment is bordered to the north by Laurentian highlands of the Canadian Shield whereas the Frontenac Arch occurs to the west. The Frontenac Arch is a NW-SE oriented corridor that joins the Canadian Shield with Precambrian rocks of the Adirondack mountains. The latter border the Embayment to the south. Allochthonous rocks related to the Appalachian orogeny define the eastern side of the platform and adjoined basins (Fig. 1.4).

The Paleozoic sedimentary cover in the Ottawa Embayment can be divided into two Sloss' sequences (Sloss 1963): Sauk and Tippecanoe sequences. The former is Cambrian to Early Ordovician in age, whereas the latter is Middle to Late Ordovician in age (Fig. 1.5, Johnson et al. 1992).

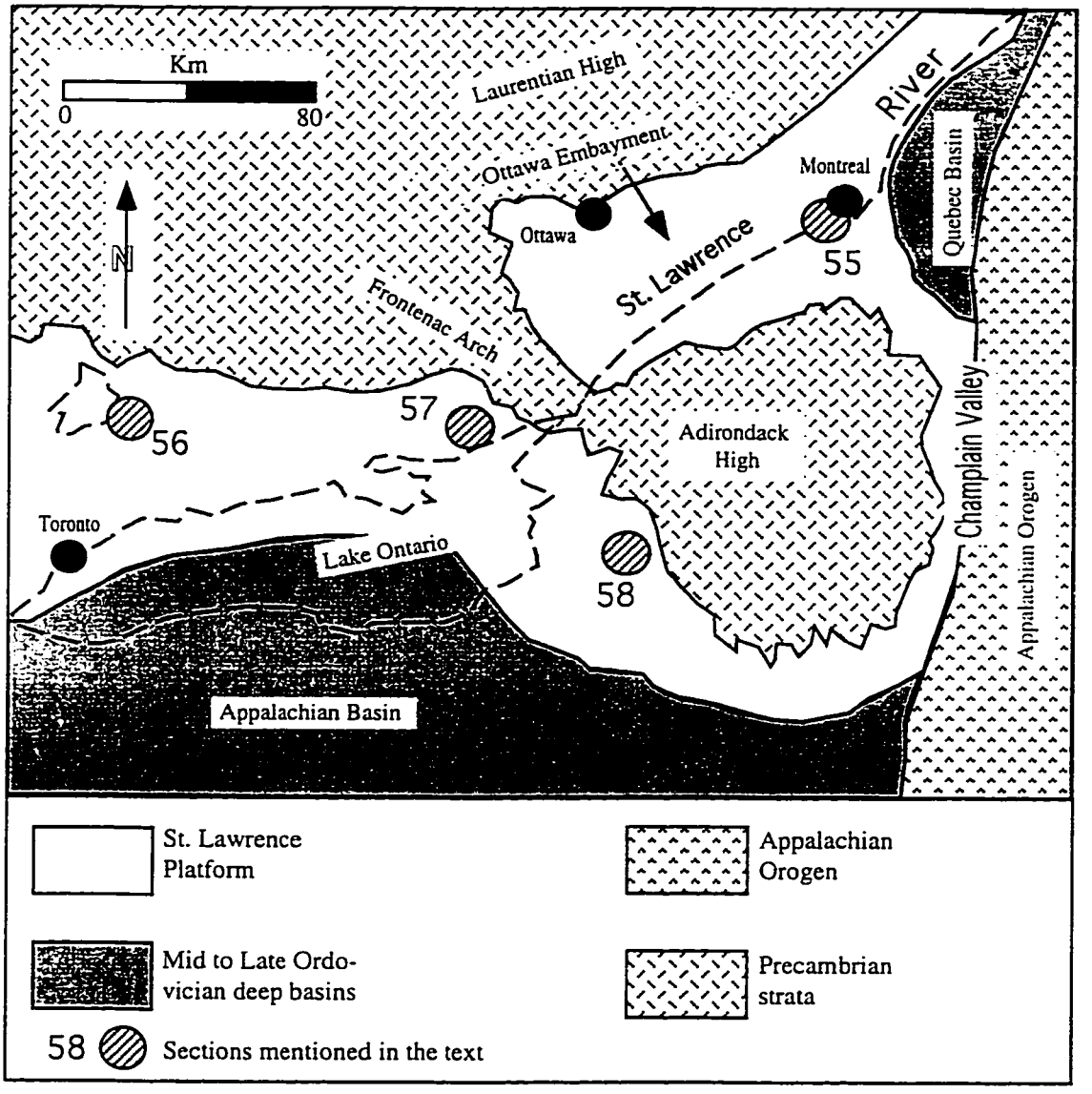


Fig. 1.4 General geology and location of the St. Lawrence Platform and adjacent geologic areas during the Ordovician period. Cross-hatched circles indicate key localities outside of the Ottawa Embayment and used for correlation. Sections for these localities are taken from previous work and discussed further. Loc. 55 = Pointe Claire quarry (Hofmann 1963); Loc. Lake Simcoe section (Liberty 1969); Loc. 57 = Kingston section (section 4 of Peterson 1969); Loc. 58 = Roaring Brook (New York) section of Textoris (1968). Modified from Johnson et al. (1992).

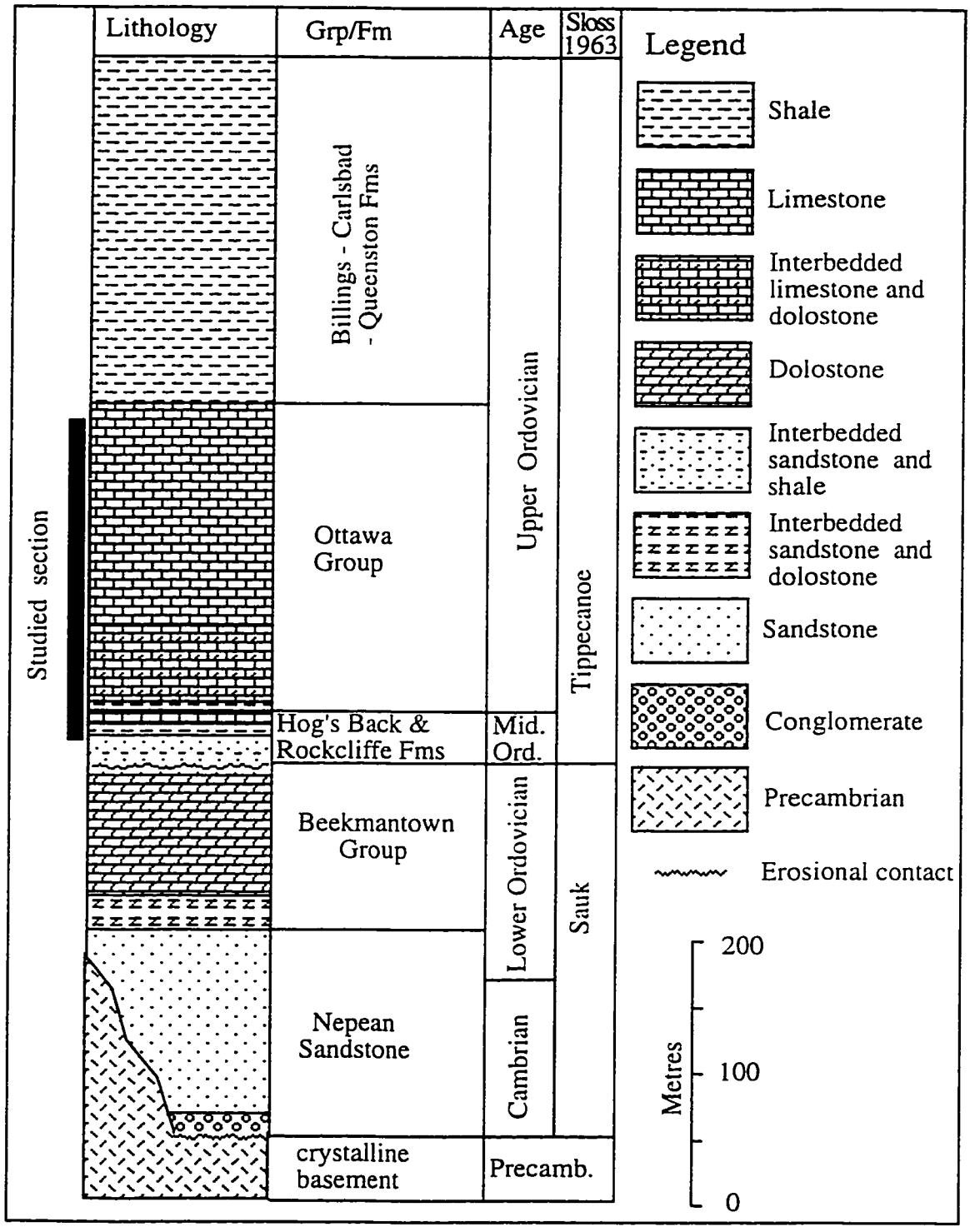


Fig. 1.5 Stratigraphic column of Lower Paleozoic strata in the Ottawa Embayment showing the stratigraphic range (black vertical line to the left of column) discussed in this study. Modified from Williams and Telford (1982).

Cambrian to Early Ordovician (Sauk) sequence

In the Ottawa Embayment, rocks of this sequence are about 300 metres thick and include the Potsdam and Beekmantown groups. The Potsdam Group is represented by a prominent, thick sandstone (Nepean Formation, up to 310 m thick, Williams 1991) which disconformably onlaps a rugged Precambrian surface (over 100 m in relief) in the Ottawa Embayment (Wilson 1946; Dix et al. 1997a). The Nepean Formation consists of cross-bedded, coarse to medium grained, cream-coloured, quartz arenite with subordinate conglomerate. Both lithologies weather to grey. The upper boundary of the Nepean Formation is marked by the base of the first dolomitic bed of the Beekmantown Group. Raymond (1912) recognized lithologic similarities within the Beekmantown Group of eastern Ontario, southwest Quebec and up state New York. Raymond (1912) adopted the term Therèse and Beauharnois as formation names to form the Beekmantown Group. Wilson (1946) proposed the terms March and Oxford to replace these, respectively, due to assumed age differences with and inaccessibility of Raymond's original sections. This practice was followed by later workers (e.g., Williams and Rae 1983; Williams and Telford 1986; Williams 1991; Johnson et al. 1992). Bernstein (1992) re-examined the Beekmantown Group of the region and proposed the abandonment of Wilson's terms. Bernstein (1992) adopted the earlier terms of Therèse and Beauharnois formations and included a third formation (Carillon Fm) to form the highest formation of the group (for further details see Bernstein 1992).

The Nepean Formation mainly accumulated in a high energy, shallow marine environment (Wilson 194 6; Williams 1991). However, aeolian and fluvial-channel deposits occur in the lower part of the formation (Wolf and Dalrymple 1985). The rocks of the

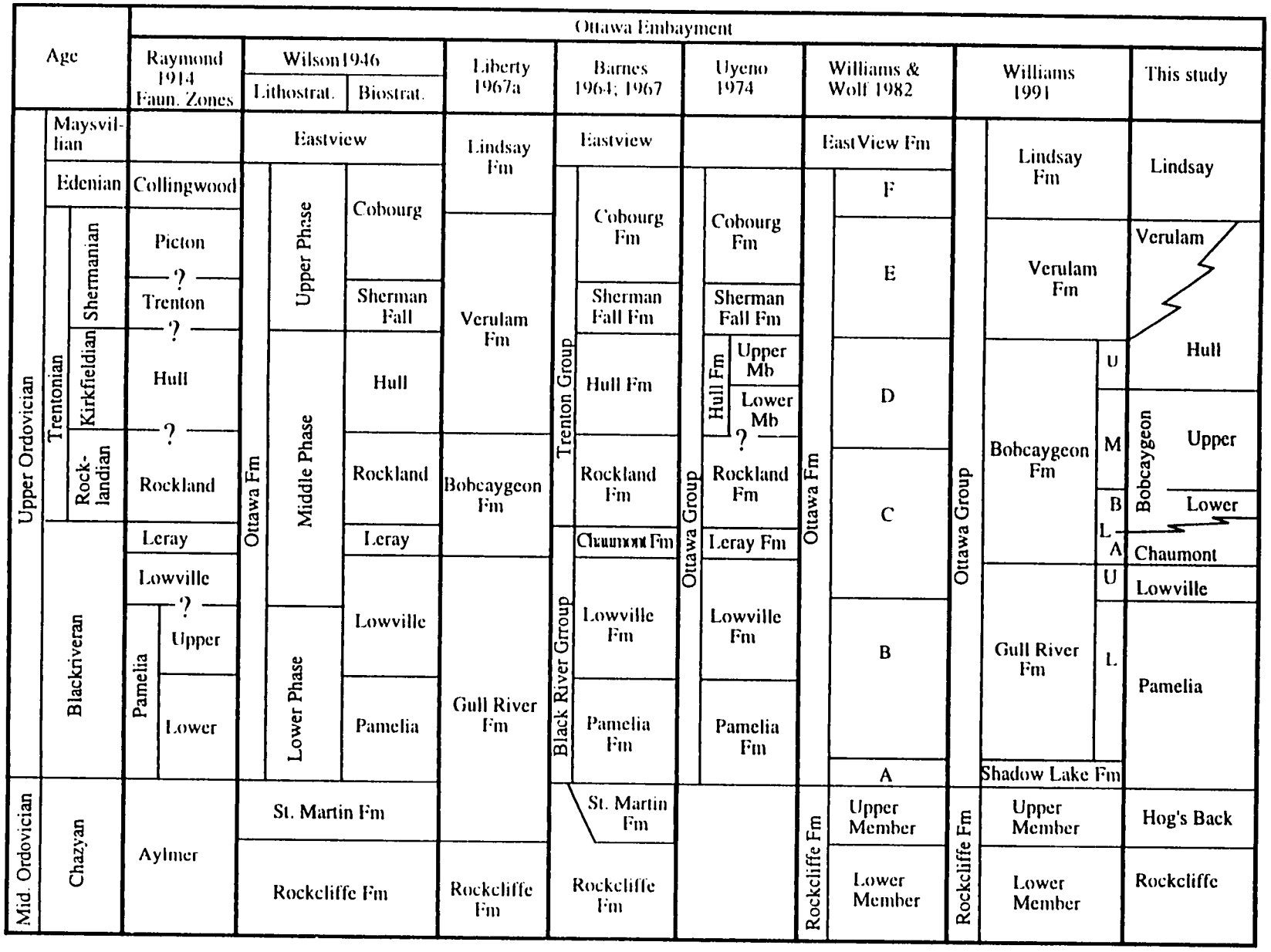
Beekmantown Group accumulated in a hypersaline to normal marine depositional environments (Bernstein 1992; Dix et al. 1997a).

Middle to Upper Ordovician (Tippecanoe) sequence

In the Ottawa Embayment, the Tippecanoe Sequence is represented by a Middle to Upper Ordovician succession from sandstone, through limestone with minor interbeds of dolostone and thick shale, and capped by sandy shale. The lowest unit of the succession is predominantly sandstone (Rockcliffe Formation) and is overlain by shale, dolostone and limestone originally assigned to the St. Martin formation (Wilson 1936; 1946, Fig. 1.5). These two formations form Middle Ordovician (Chazyan) strata in the Ottawa Embayment. They are overlain by a thick (210 - 230 m), shallow marine, carbonate-dominated succession of Blackriveran to Trentonian in age (Wilson 1946; Bolton and Liberty 1972; Williams 1991). Wilson (1946) named this succession the Ottawa Formation. Uyeno (1974) raised the latter to group status (Ottawa Group) which consisted of seven formations similar to seven faunal zones previously assigned to Wilson's (1946) Ottawa Formation (Table 1.1).

Thick, black shale-dominated rocks of the Billings Formation lie above the Ottawa Group (Fig. 1.5). The former is deposited in an open marine environment. It is followed by shallow marine to deltaic, dark to greenish grey calcareous shale and siltstone (Carlsbad and Queenston Fms; Williams and Telford 1986; Williams 1991). The fine-grained siliciclastic beds which dominate the three formations above the Ottawa Group represent westward prograding, orogen-derived terrigenous materials that caused shut-down of carbonate production and the foundering of St. Lawrence Platform during Late Ordovician time.

Table 1.1 Chart comparing stratigraphic nomenclature applied to the Chazyan to Maysvillian strata in the Ottawa Embayment.


Age
Ottawa Embayment
Raymond 1914 Faun. Zones
Wilson 1946
Lithostrat.
Biostrat.
Liberty 1967a
Barnes 1964; 1967
Uyeno 1974
Williams & Wolf 1982
Williams 1991
This study
Upper Ordovician
Mid. Ordovician
Maysvil-lian
Edenian
Trentonian
Shermanian
Kirkfieldian
Rock-landian
Blackriveran
Chazyan
Collingwood
Picton
Trenton
Hull
Rockland
Leray
Lowville
Pamelia
Upper
Lower
Aylmer
Ottawa Fm
Upper Phase
Middle Phase
Lower Phase
Eastview
Cobourg
Sherman Fall
Hull
Rockland
Leray
Lowville
Pamelia
St. Martin Fm
Rockcliffe Fm
Lindsay Fm
Verulam Fm
Bobcaygeon Fm
Gull River Fm
Rockcliffe Fm
Trenton Group
Black River Group
Cobourg Fm
Sherman Fall Fm
Hull Fm
Rockland Fm
Chaumont Fm
Lowville Fm
Pamelia Fm
St. Martin Fm
Rockcliffe Fm
Ottawa Group
Hull Fm
Upper Mb
Lower Mb
Rockland Fm
Leray Fm
Lowville Fm
Pamelia Fm
Ottawa Fm
Rockcliffe Fm
EastView Fm
F
E
D
C
B
A
Upper Member
Lower Member
Ottawa Group
Rockcliffe Fm
Lindsay Fm
Verulam Fm
Bobcaygeon Fm
Gull River Fm
Shadow Lake Fm
Upper Member
Lower Member
U
M
B
L
A
U
L
Lindsay
Verulam
Hull
Bobcaygeon
Upper
Lower
Chaumont
Lowville
Pamelia
Hog's Back
Rockcliffe

Previous work and terminologies

The early Paleozoic geology of the Ottawa Embayment was originally mapped under the sponsorship of the Geological Survey of Canada (GSC) by Logan (1863) and Ells (1894; 1898; 1902; 1904). They recognized the existence of lower, middle and upper divisions of the Ordovician succession in the Ottawa Valley based on correlation with strata in southern Quebec and New York state. Later workers (e.g., Raymond 1905; 1911; 1912; 1913; 1914; Wilson 1932; 1946; Twenhofel et al. 1954; Liberty 1967a; Williams and Telford 1986; Williams 1991; and many others) studying the Middle to Upper Ordovician strata in the Ottawa Embayment refined these divisions yet introduced a confusion of terms based on (1) faunal zonations; (2) mixture of lithostratigraphic, chronostratigraphic, biostratigraphic terms; and, (3) lithostratigraphic terms established for equivalent strata in south-central Ontario (Liberty 1969). Details of the work of previous researchers and development of stratigraphic terms as applied to the Chazyan, Blackriveran and Trentonian strata in the Ottawa Embayment will be provided in their respective chapters.

The stratigraphic approach used by previous workers (Table 1.1) can be sorted into two groups. (1) Application of a mixed lithostratigraphic, chronostratigraphic and biostratigraphic nomenclature. Raymond (1905; 1911; 1912; 1913; 1914) was the first to introduce a combination of newly proposed nomenclature that incorporated lithostratigraphic terms originally established for equivalent Ordovician rocks in upstate New York (Table 1.1). However, most of his new subdivisions were based on biostratigraphic criteria. Wilson (1932; 1946) modified Raymond's subdivisions, yet her classification scheme remained biostratigraphic in content. Further modifications (e.g., Barnes 1964; 1967; 1968; Kay 1942;

1968a; Sinclair 1968; Uyeno 1974, among others), in the hope of reconciling the confusion of terminologies, still retained some of the gross biostratigraphic divisions introduced by Raymond and Wilson. Until the 1980's, use of Wilson's (1946) nomenclature as modified later (e.g., Barnes 1964; 1967; 1968) was in common use.

(2) Application of lithostratigraphic nomenclature imported from south-central Ontario (Liberty 1967a; 1969). The initial proposal for this nomenclature (Liberty 1967a) was contained in an abstract for a Geological Association of Canada - Mineralogical Association of Canada meeting in Ottawa (1967). Importantly, the stratigraphic nomenclature was independent of earlier lithostratigraphic terms originally introduced from upstate New York. Later workers (e.g., Williams and Telford 1986; Williams 1991; Johnson et al. 1992; Rowell 1995) who adopted Liberty's (1967a) nomenclature added further refinement to positions of stratigraphic boundaries.

There is a considerable volume of work related to study of the Ordovician rocks in the Ottawa Embayment that remained unpublished. For example, there are two PhD dissertations (Sawford 1972; and Steele-Petrovich 1984). The work of Sawford (1972) was never published. Steele-Petrovich (1986; 1989; 1990) published short papers in the form of GSC Current Research reports, and addressed stratigraphic problems of the embayment in general, as well as stratigraphy of northwest of Ottawa in particular. She presented new informal subdivision for these strata. Several MSc and BSc theses (e.g., Volrath 1962; Maloney 1969; Rosenstein 1973; Simpson 1978; Smith 1978; Troyer 1979; Bilodeau 1983; Mainville 1983; Sami 1987; Boggs 1989; Wilson 1990) have addressed various stratigraphic aspects of Middle - Upper Ordovician strata in the Ottawa Embayment. However, most deal with local distribution or sedimentology of strata only, and lack a regional perspective. These

studies did not address the overwhelming nomenclature problem, instead adopted one of the existing stratigraphic terminologies for eastern Ontario.

Methodology

For the present study, sections were measured at outcrops, quarries, and in cores (see Figs. 1.1 and 1.6 for section locations), noting lithologic attributes and relative abundance of particles types. The stratigraphic sections, along with their respective thickness, field and laboratory data, were drawn by using Applecore® and then graphically enhanced with Canvas®. Many of these sections are similar to locations visited by Williams (1991), and some other previous workers. During field mapping, each section was divided into different lithofacies units according to changes in sedimentary (physical and biogenic) structures, colour, texture, grain size, and particle types and abundances. At least one sample was taken from each lithofacies. Additional samples were collected from specific stratigraphic intervals for geochemical analyses. Brief visits to key sections reported by Liberty (1969), Okulitch (1939a) and McFarlane (1992) were made in order to provide some regional stratigraphic comparison among Blackriveran to Trentonian successions in south-central Ontario, the Kingston area, and the Ottawa Embayment. In addition, previous observations from published and unpublished (mostly theses) work have been incorporated into my study. These works include those of Cushing et al. (1910); M.E. Wilson (1924); Okulitch (1936; 1939b); Young (1943a; b); A.E. Wilson (1946); Hofmann (1963; 1979); Barnes (1964; 1967; 1968); Liberty (1967a; 1969); Rollif (1967); Textoris (1968); Peterson (1969); Clark (1972a); Uyeno (1974); Cameron and Mangion (1977); Williams and Telford (1986); Sami

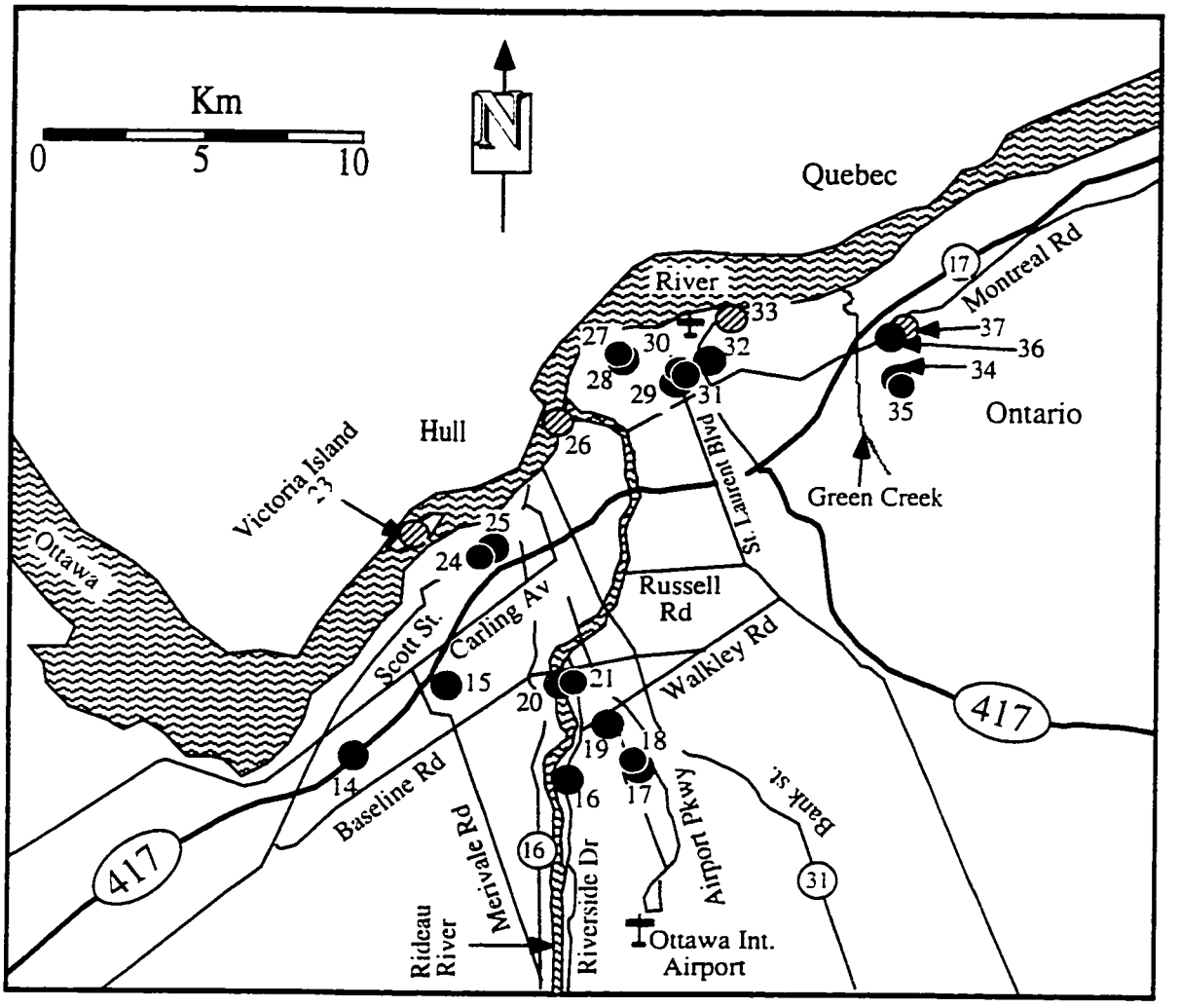


Fig. 1.6 Map of the Ottawa City area showing localities referred in the thesis. Note that localities 1 to 13 and 38 to 54 are shown in Figure 1.1, whereas localities 55 to 58 are shown in Figure 1.4. Cross-hatched circles indicate sections mapped by previous workers and mentioned in this thesis.

(1987); Copeland et al. (1989); Bolton et al. (1991); Williams (1991); Johnson et al. (1992); Sanford (1993a; b); and, McCracken (1995).

The time scale of the Ordovician System and its subdivisions are not yet established and the International Commission on Stratigraphy (ICS), Subcommission on Ordovician Stratigraphy (SOS) is still trying to delimit and subdivide the system (Webby 1995). I follow the tri-partite subdivision (Lower, Middle, and Upper) of the Ordovician System. The Lower comprises the Ibexian Series, the Middle comprises the Whiterockian Series (including, in ascending order, the Rangerian, Kanoshian, and Chazyan stages), and the Upper comprises Mohawkian (including, in ascending order, the Blackriveran, Rocklandian, Kirkfieldian, and Shermanian stages), Cincinnatian (including Edenian, Maysvillian, and Richmondian stages), and Gamachian series (Ross and Ross 1995). The Rocklandian, Kirkfieldian and Shermanian stages are also sometimes grouped under the Trentonian Stage (Harris et al. 1995).

About 750 samples were collected for petrographic and geochemical analyses. About 300 standard thin sections were prepared and stained with Alizarin Red-S and Potassium Ferrocyanade solution in order to distinguish calcite from dolomite and iron-rich from iron-poor phases. About 2 minutes were allowed for each thin section to react with the staining solution, and mineralogical identification of colour products was based on Dickson (1966) and Evamy (1969). Petrographic descriptions of most of the thin sections were based on visual estimates of percentages using the comparison charts (e.g., Baccelle and Bosellini 1965). Polished thin sections from 18 samples taken from diagenetically interesting beds of Pamelia and Lowville formations were prepared for microprobe analyses. Remaining samples lacking thin sections were slabbed, and their fresh and polished surfaces were

studied using reflected light. Dunham's (1962) classification of carbonate rocks as refined by Embry and Klovan (1971) is employed for field and petrographic lithologic descriptions.

Brief descriptions of analytical conditions and methods used for my work are as follows:

(1) In cathodoluminescence: a Nuclide Luminoscope® ELM model 2B, at 20 millitorr and 0.5 milliamps was used for the relative luminescence determination of the various carbonate cements;

(2) For X-ray diffractometry: a Philips Automated X-ray Diffractometer, with Cu kα radiation, was used for the determination of mineralogical constituents of selected samples. Powders were examined in the 25° to 55° 2θ range at a horizontal scale 1 cm : 1° 2θ.

(3) For microprobe analysis: a Cambridge Microscan 5 electron probe was used. The machine used Wavelength-Dispersive Spectrometry (WDS), at 15kv (accelerating potential) and 30 nanoamperes (beam current). A set of well characterized natural mineral standards were used for calibration purposes. Raw X-ray counts were reduced to elemental weight % by a modified version of EMPADR VII data reduction program of Rucklidge and Gasparinni (1969). The following standards were used for the trace and major elements: for Ca and Mg, Dolomite USNM; for Fe and Mn, Siderite USNM; for Sr, $SrSO_4$; and, for Na, Kakanui Hornblende USNM. For major elements, analyses are accurate to ± 1-2%. For minor or trace elements, relative error increases to ± 50% as the minimum detection limit is approached.

(4) Stable Isotope analyses: Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotope analysis was conducted at the Ottawa-Carleton Geoscience Centre Stable Isotope Facility, Department of Geology, Ottawa University. CO_2 was generated by reacting the sample with 100% phosphoric acid (McCrea 1950). The ^{18}O fractionation factors used for the carbonate-

H_3PO_4 reactions are: $\alpha = 1.01025$ for calcite at 25°C (Sharma and Clayton 1965; Friedman and O'Neil 1977), and $\alpha = 1.01065$ for dolomite at 50°C (Rosenbaun and Sheppard 1986). The CO_2 is analyzed on a triple collector VG SIRA 12 mass spectrometer. The routine precision (2σ) on a pure carbonate analysis is 0.10 ‰.

(5) Trace and major elements analysis: This type of analysis was done by using Inductively Coupled (argon) Plasma Atomic Emission (sequential) Spectrometry (ICP-AES) housed at the Department of Geology, University of Ottawa. 100 mg of powdered sample were weighed and placed in a 15-ml centrifuge tube (Falcon™). 10 ml of 8% hydrochloric acid (using 5 ml aliquots) were added into the tube, agitated, and left for 24 hours. The solution was allowed to settle, and, a 5-ml aliquot was removed for analysis. Repeats, internal standards and blanks were analyzed every ten samples as reference checks. Data reduction program, CALCITE-, was developed by John Loop for Thermo Jarrell Ash Atmoscan 25 ICP-AES using THERMOSPEC software5.0.

CHAPTER TWO

HOG'S BACK FORMATION: A NEW (MIDDLE ORDOVICIAN) STRATIGRAPHIC UNIT, OTTAWA EMBAYMENT, EASTERN ONTARIO, CANADA

Preface

This chapter deals with the upper part of the Chazyan Stage in the Ottawa Embayment. In this chapter, the Chazyan - Blackriveran contact is, for the first time, well described. The Chazyan strata are divided into two lithologic units of which the upper one is newly proposed formation and becomes the focus of the chapter. Description and proposal of the new formation is published in the Canadian Journal of Earth Sciences (Salad Hersi and Dix 1997a). The chapter is written in such a way as to stand independently from the rest of the thesis (except shared references). The original manuscript was written prior to the thesis was completed. As a result, there has been a change in the numbering of some localities. In order to make this change fit the rest of the thesis, I indicate below how the localities mentioned in this chapter correspond with the localities mentioned in the rest of the thesis.

Localities in this chapter		Corresponding localities in the rest of the thesis	
1 Prince of Wales Falls (Ottawa)	⇒	Locality	16
2 Rockcliffe Airforce Base (Ottawa)	⇒	"	33
3 East of Green's Creek (Eastern Ottawa)	⇒	"	37
4 Russell Well (Russell County, Ontario)	⇒	"	41
5 Eastern Hawkesbury	⇒	"	54
6 Pointe Claire (Quèbec)	⇒	"	55

Introduction

The lower part of Sloss's (1963) Tippecanoe Sequence is represented in the Ottawa Embayment (Fig. 2.1) by a Middle to Upper Ordovician succession of (1) basal siliciclastics (Rockcliffe Fm); (2) overlying shales followed by mixed siliciclastic - carbonate strata (St. Martin fm); and (3) thick, relatively pure carbonates (Ottawa Group) (Johnson et al. 1992). The first two units were considered Chazyan (Llandeilian) in age (Wilson 1946). Objecting to the use of an indicator fossil to define, in part, the position of the St. Martin formation (Wilson 1946), Williams (1991) subsequently revised the Rockcliffe Formation to include the lower, more shaly part of Wilson's St. Martin formation, whereas the upper carbonate-dominated section was placed in the overlying Blackriveran - Trentonian (Caradocian) Ottawa Group. Re-examination of this revision shows that lithologies placed in the Ottawa Group are correlative with the carbonate-rich facies of the underlying Laval Formation in Montreal, and field evidence demonstrates inconsistencies that exist between the correlation of upper member of Rockcliffe and St. Martin formational boundaries as described by Williams (1991). Wilson's (1946, p. 19-20) interpretation suggests that a distinct, regionally extensive lithostratigraphic unit occurs between the Rockcliffe Formation and Ottawa Group strata.

The purpose of this chapter is to identify the geological importance of this unit and propose new formal stratigraphic nomenclature. Stratigraphic relationships with Chazyan rocks in the eastern and southeastern regions of Montreal, and in the Champlain Valley of New York are discussed. I also briefly describe facies and depositional environments. My study is based on outcrops at Prince of Wales Falls, Rideau River, Ottawa (Loc. 1, Fig. 2.1;

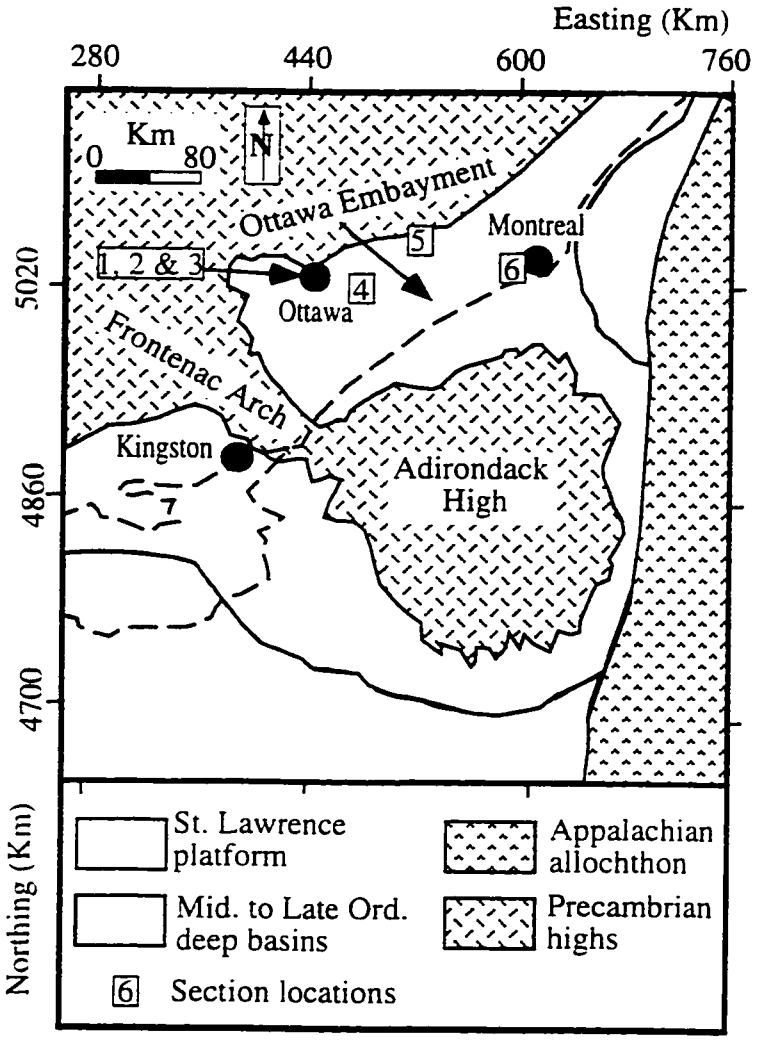


Fig. 2.1 Distribution of Middle to Late Ordovician platforms, and related deep basins, Precambrian highs and Appalachian allochthon. Localities referred in the text are also shown (1 to 6). See Table 2.1 for coordinates of these localities, see also the "Preface" at the beginning of Chapter 2 to identify corresponding locality numbers in other chapters of the thesis.

Table 2.1), and at Rockcliffe Park (Loc. 2); core (GSC, Russell Well, Ontario; Loc. 4); and previous work (Raymond 1911; 1912; Wilson 1946; Hofmann 1963; 1979; Clark 1972a; Copeland et al. 1989; Bolton et al. 1991).

No	Locality	Easting	Northing
1	Prince of Wales Falls (Ottawa)	444870	5024275
2	Rockcliffe Airforce Base (Ottawa)	450750	5033750
3	East of Green's Creek (Eastern Ottawa)	456750	5034000
4	Russell Well (Russell County, Ontario)	469400	5017600
5	Eastern Hawkesbury	533000	5047750
6	Pointe Claire (Quèbec)	590750	5034500

Table 2.1 UTM coordinates of section localities referred in the text.

Previous studies and terminology

Raymond (1905) introduced the term Aylmer formation for a 250-foot (~ 76 m) thick section lying between Beekmantown Group dolomite and Lowville limestone in the Ottawa Valley. He considered the succession to be of Chazyan (Llandeilian) age, but later (Raymond 1911; 1912) recognized the upper 115 - 125 feet (35 - 38 m) as Blackriveran (Caradocian). Thus, his revised Chazyan Aylmer formation contained a lower division of shale and sandstone overlain by an upper division of carbonate and interbedded shale. Wilson (1946)

raised these informal divisions to formation status: the sandstone and shale interbeds were placed in the Rockcliffe Formation, and the shale and carbonates where placed in the St. Martin formation (Table 2.2). Although Wilson (1946; pp. 19 - 20) describes a section east of Ottawa, the name St. Martin was chosen for apparent equivalent, well-developed limestones in the Cap St. Martin region of Montreal. Today, Wilson's (1946) mapped section (Loc. 3, Fig. 2.1, Table 2.1) in the Ottawa area is no longer exposed but from her description (Wilson 1946, p. 19-20), it consisted of interbedded, dark grey, green grey and brown shales succeeded by thickly bedded (30 - 75 cm) dolostone lithology. Like the upper boundary of Raymond's (1912) Aylmer formation, the upper boundary of the St. Martin formation is defined by the upper extent of the brachiopod *Camarotoechia plena* Hall (now called *Rostricelluia plena*).

However, Hofmann (1963) and Clark (1972a) showed that massive calcarenites that are dissimilar to carbonates of St. Martin formation are present in the Montreal region; these strata form the St. Martin facies or St. Martin Member of the Laval Formation (Hofmann 1963; Clark 1972a). These calcarenites are present at various intervals throughout the upper Laval Formation. Hofmann (1963) emphasized that lithologic attributes of Wilson's (1946) St. Martin formation are probably restricted to the region of Ottawa. Near Hawkesbury (Loc. 5; Fig. 2.1, Table 2.1), Bolton et al. (1991, p. 3) recommend that "where St. Martin facies of cross bedded calcarenite is recognizable ..., it is recommended that the term Laval Formation be adopted." In the Ottawa region, previous work (Poole et al. 1970; Williams and Telford 1986; Bolton et al. 1991; Williams 1991; Johnson et al. 1992) applied Rockcliffe Formation to all Chazyan rocks, and abandoned the term St. Martin formation. Recently, Williams (1991) suggested that the lower shaly part of Wilson's St. Martin formation be

Ottawa - St. Lawrence Lowland												
Ottawa Embayment											Montreal Area (Que.)	
Age		Wilson 1946 Faunal z.		Williams 1991			This Study				Clark 1972a; Hofmann 1963	
Mohawkian (Caradocian)	Blackriveran	Ottawa Fm	Pamelia	Ottawa Grp	Gull River Fm		Ottawa Grp	Pamelia Fm	Lower Mb		Pamelia Fm	
	?				Sh.L Fm							
Whiterockian (Llandeilian)	Chazyan	St. Martin fm		Rockcliffe Fm	Upper Mb		Hog's Back Fm		U			
									L			
		Rockcliffe Fm			Lower Mb		Rockcliffe Fm				Laval Fm	
											St. Therèse Mb	Beacons-field Mb
												St. Martin Calcarenites

Table 2.2 Chart showing different nomenclatures used for the Chazyan and lower Blackriveran formations in the regions of Ottawa and Montreal. Sh.L.Fm = Shadow Lake Formation

considered an upper member of the Rockcliffe Formation, whereas the overlying carbonate-rich section becomes part of the Ottawa Group succession. In contrast to previous workers, Williams (1991) also revises the Ottawa Group stratigraphy using nomenclature of the equivalent Simcoe Group in south-central Ontario (Liberty 1969).

In a preliminary report, Salad Hersi and Dix (1995) used Wilson's St. Martin formation in reference to a regionally extensive unit that is lithostratigraphically distinguishable from the prominent sandstone of the Rockcliffe Formation (*sensu* Wilson 1946) and overlying basal mixed siliciclastic-carbonate strata of the Ottawa Group. Because use of faunal zonation to define formation boundaries (Wilson 1946) is contrary to basic discrimination of a lithostratigraphic unit (Committee on Stratigraphic Nomenclature 1933, Article 5, Remarks b & c ; North American Commission on Stratigraphic Nomenclature 1983, Article 22, Remarks d & e), I propose new stratigraphic nomenclature to rectify past confusion in terminology and to re-define regional correlation. In doing so, I believe that this unit defines an important geologic stage of deposition in this Ordovician basin.

New stratigraphic nomenclature

Hog's Back Formation

The Hog's Back Formation is proposed for strata between Wilson's (1946) Rockcliffe Formation and interbedded thick layers of shale, sandstone, and thin limestone that comprise the basal unit of the Pamelia Formation (lowest formation of the Ottawa Group; Salad Hersi and Dix 1995, see also Chap. 3). The type locality of the formation is Prince of Wales Falls, Rideau River, Hog's Back Park, Ottawa (NTS 31G/05, Lat. 45° 22' N, Long. 75° 50' W, UTM

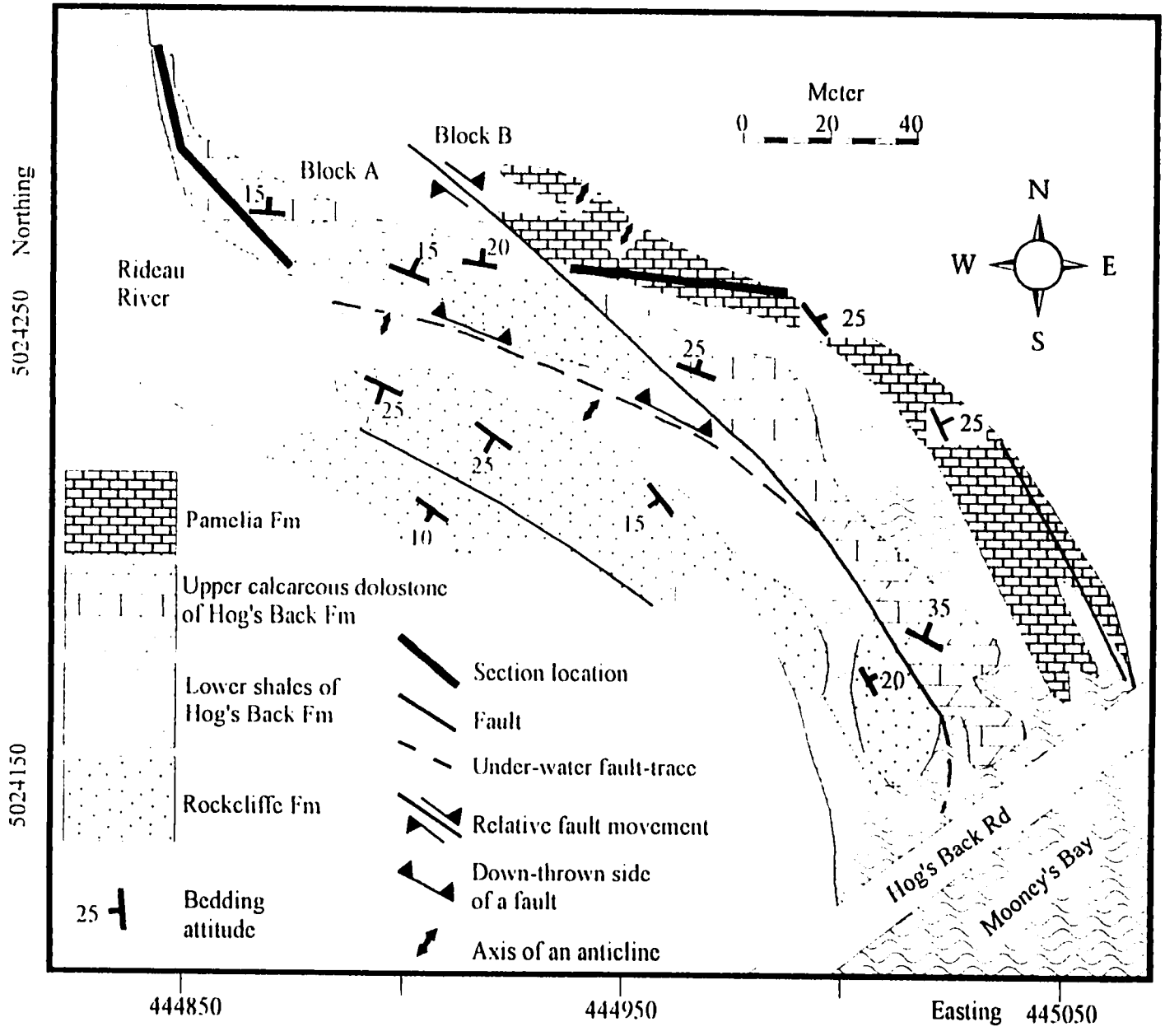
Zone 18, 444870 E- 5024275 N; Loc. 1, Figs. 2.1, 2.2, Table 2.1). Geological structure and stratigraphy of the outcrop region are shown in Fig. 2.2. The type section is composite, within two fault blocks (see thick lines, Fig. 2.2). Block A exposes most of the measured section, with the upper contact of the formation preserved in the adjacent block B; correlation across the bounding fault is well defined.

Thickness, boundaries, lithology, and facies

The Hog's Back Formation is 14.3 m thick at its type locality (Fig. 2.3) and thickens eastward to about 27 m in core from the GSC Russell Well (~ 40 km SE of Ottawa, Loc. 4). The formation disconformably overlies the Rockcliffe Formation and underlies, with apparent conformity, the Pamelia Formation of the lower Ottawa Group. The Rockcliffe - Hog's Back formational contact, exposed at two localities (Locs. 1 & 2), is marked by an erosional unconformity overlain by a coarse-grained, cross-bedded quartz arenite of irregular thickness (2 - 20 cm). The Hog's Back - Pamelia formational boundary shows no obvious disconformity, and carbonates of the former unit are overlain abruptly by a dark brown sandy shale of the basal Pamelia Formation (Figs. 2.3 and 2.4).

The Hog's Back Formation is divisible into two parts. The lower part is about 5.4 m thick at the type section and thickens eastward to 7.6 m at the Russell well (Loc. 4, Fig. 2.1). It consists predominantly of thinly laminated, burrowed, dark grey shale with subordinate, thin (< 10 cm), medium grey dolomitic lime-mudstone interbeds (Figs. 2.3 and 2.4). The shale and mudstone weather to greenish grey and rusty green-grey, respectively. Fine- to medium-grained quartz sandstone forms rare thin lenses to laminae. The base of the formation in the Ottawa region contains a prominent, coarse-grained quartz arenite bed, 2 -

Fig. 2.2 Geological mapping of the Prince of Wales Falls, Rideau River at Hog's Back Park, Ottawa. This is the type area fro the Hog's Back Formation. Block A exposes most of the formation and the lower contact with the Rockcliffe Formation. The upper contact with the Pamelia Formation is exposed in fault-block B which also exposes the basal unit of the Pamelia Formation. Correlation of the Hog's Back Formation is defined across the fault separating the two blocks (modified after Williams 1991).


Meter
0 20 40
N
W
E
S
Block A
Block B
Rideau River
Pamelia Fm
Upper calcareous dolostone of Hog's Back Fm
Lower shales of Hog's Back Fm
Rockcliffe Fm
Bedding attitude
Section location
Fault
Under-water fault-trace
Relative fault movement
Down-thrown side of a fault
Axis of an anticline
Hog's Back Rd
Mooney's Bay
Northing
5024250
5024150
444850
444950
Easting
445050

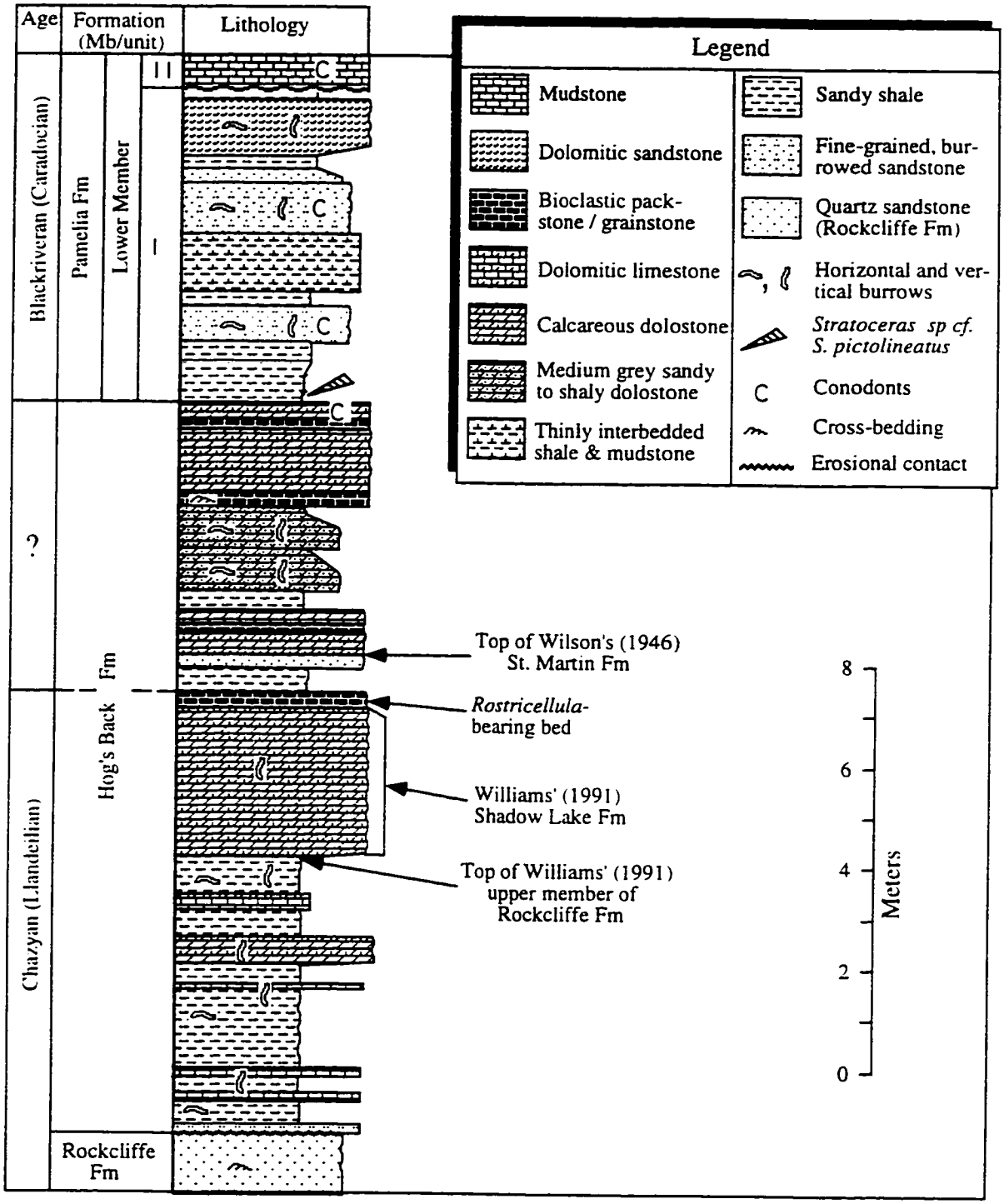
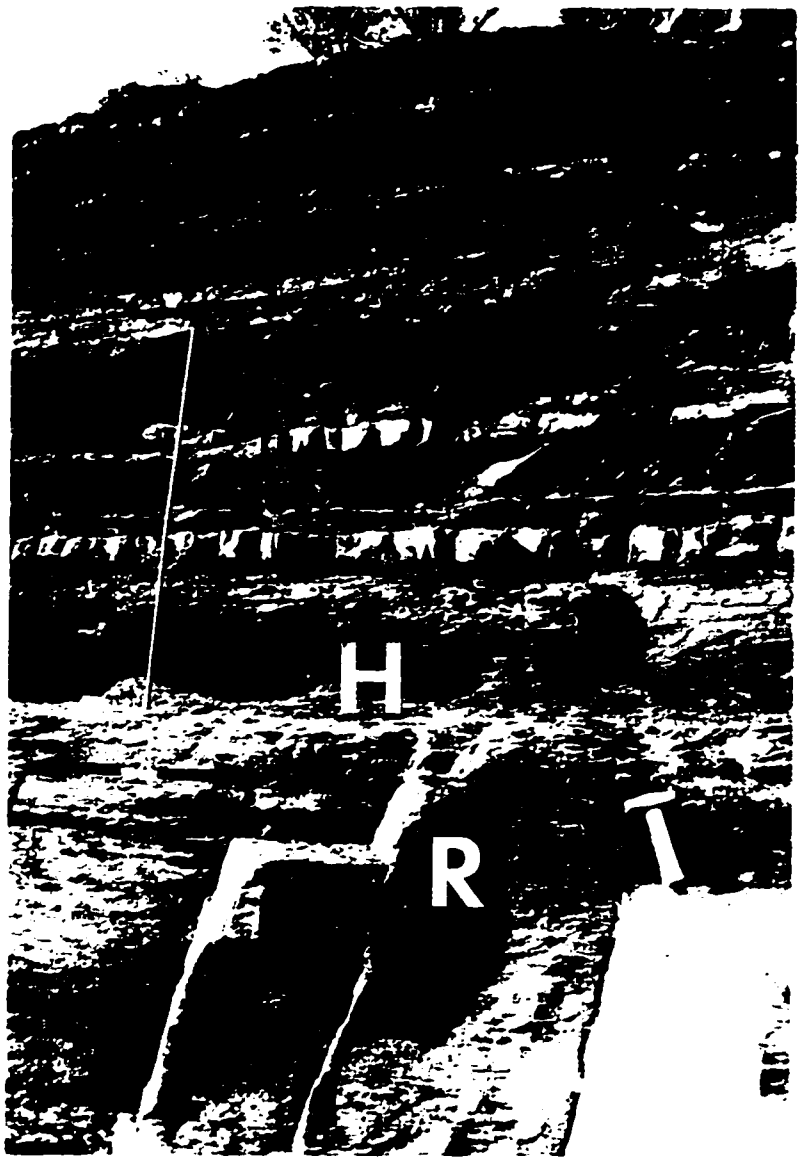


Fig. 2.3 Composite type section of the Hog's Back Fm. The age of the upper few meters of the formation remains uncertain. Correlations with the work of Wilson (1946) and Williams (1991) are also shown.

Fig. 2.4 The lower, shale-dominated part of the Hog's Back Formation is punctuated by thin lime mudstone beds (vertical arrows). The disconformable Rockcliffe (R) - Hog's Back (H) contact (along horizontal arrows) is preserved and exposed at this outcrop. The measuring stick is 1.2 m long (Loc. 1, Prince of Wales Falls, Ottawa).


H
R

20 cm thick. The quartz clasts of this basal bed are much coarser than quartz grains of the underlying Rockcliffe Formation. The basal quartz arenite bed of the Hog's Back Formation thickens eastward and correlates with a 56-cm thick bed of fine- to medium-grained sandstone, overlain by the thick shale, in the Russell well core (Loc. 4). The lower part of the formation contains rhythmic shallowing-upward units of (1) basal, thin, fine-grained silty sandstone; (2) shale; and (3) thin-bedded, planar to lenticular and locally nodular lime mudstone. Rhythmic bedding often contains only the latter two units. Sand- to pebble-sized phosphatic (collophane) grains occur at several horizons. Inclined and subvertical burrows (possibly *Psilonichnus* ichnofacies) and horizontal burrows, possibly *Planolites*, are present in the lime-mudstone and shale, respectively. Subvertical burrows appear to extend from the basal shale into the underlying sandstone. Wave ripple cross-lamination occurs within sand lenses and laminae within the shale.

The upper part of the Hog's Back Formation is about 8.9 m thick at the type section, and thickens to the east (e.g., 19.4 m at Loc. 4). It consists of thin to mostly thick beds (10-80 cm) of fine crystalline, greenish grey silty to sandy and-or calcareous dolostone that weathers to light brownish grey (Fig. 2.5). Other subordinate distinctive lithotypes include: (1) thin interbeds of coarse-grained, pinkish grey, bioclastic packstone and grainstone; (2) a few thin dark green shale interbed; and (3) two thick beds (~ 80 cm each) of medium grey, burrowed sandy to shaly dolostone, rich in phosphatic particles. Both of the latter lithologies contain horizontal burrows. The thin calcarenite beds show tabular cross bedding and local imbrication. A few calcite concretions occur in the lower part of this section, within thick-bedded calcareous dolomite. Rare intraskeletal gypsum crystals are preserved within bivalve shells in the packstone - grainstone lithofacies.

Fig. 2.5 The upper calcareous and sandy dolostone part of the Hog's Back Formation. More resistant, thin interbeds of bioclastic packstone to grainstone protrude from the outcrop (vertical arrows). The Hog's Back (H) - Pamelia (P) contact (horizontal arrows) is preserved in this fault-block (Block B, Fig. 2.2). Horizontal field of view is 17.3 m. Loc. 1: Prince of Wales Falls, Ottawa.

Characteristic fossils and geologic age

Macrofossils are generally uncommon in the Hog's Back Formation, except within the packstone - grainstone facies where elevated fossil abundance is matched by low diversity. Fragments of *Lingula* (brachiopod) and ostracodes are present in the lower shale. Thin sections from the upper, fine crystalline sandy and calcareous dolostone show a few bivalve and (phosphatic) linguloid fragments. Framework grains of skeletal packstone and grainstone interbeds, however, contain whole to fragmented shells of bivalves (~ 80%), ostracodes (~ 15%), and remaining fossil material composed of brachiopod, encrusting calcimicrobes, and pelmatozoan fragments. The brachiopod *Rostricellula plena* Hall (1847) occurs at one stratigraphic level, about 5 m below the upper contact of the formation (Fig. 2.3), forming a local brachiopod floatstone.

The lower two-thirds (~ 9.3 m) of the Hog's Back Formation contains fossils of Chazyan age, such as *Rostricellula plena* brachiopod (Raymond 1911; Wilson 1946; Hofmann 1963; Clark 1972a; Bolton et al. 1991). The basal siliciclastics of the overlying Pamelia Formation contain conodonts (Sami 1987; McCracken 1995) and an orthocone specimen [*Stratoceras* sp. cf. *S. pictolineatus* Foerste (Wilson 1961)] of Blackriveran (Caradocian) age. Therefore, the uppermost 5 m of the Hog's Back Formation at the type section, bracketed by the above-mentioned Chazyan and Blackriveran strata, has an uncertain age. A sample from the upper 20 cm of the formation, however, contains a conodont assemblage of *Curtognathus* sp., *Erismodus* sp., *Glyptoconus* sp., and *Phragmodus flexuosus* Moskalenko (McCracken 1995). Among this conodont fauna, *P. flexuosus* Moskalenko is the most biostratigraphically diagnostic form. It ranges from the base of the *Polyplognathus friendsvillensis* Zone to the mid-*Plectodina aculeata* Zone (Sweet 1984), and corresponds

to a Chazyan through early Blackriveran age (McCracken 1995). Previous work shows that *P. flexuosus* dominates the conodont fauna in beds correlative with the Hog's Back Formation, and are dated as Chazyan (Copeland et al. 1989; Bolton et al. 1991). In addition, the bulk of the Hog's Back Formation is correlative with limestones rich in *R. plena* brachiopod of Hofmann's (1963) section at Pointe Claire (Loc. 6). From available biostratigraphic data, it is likely that the entire Hog's Back Formation is of Chazy age, and the Chazyan - Blackriveran boundary may coincide with the Hog's Back - Pamelia formational contact.

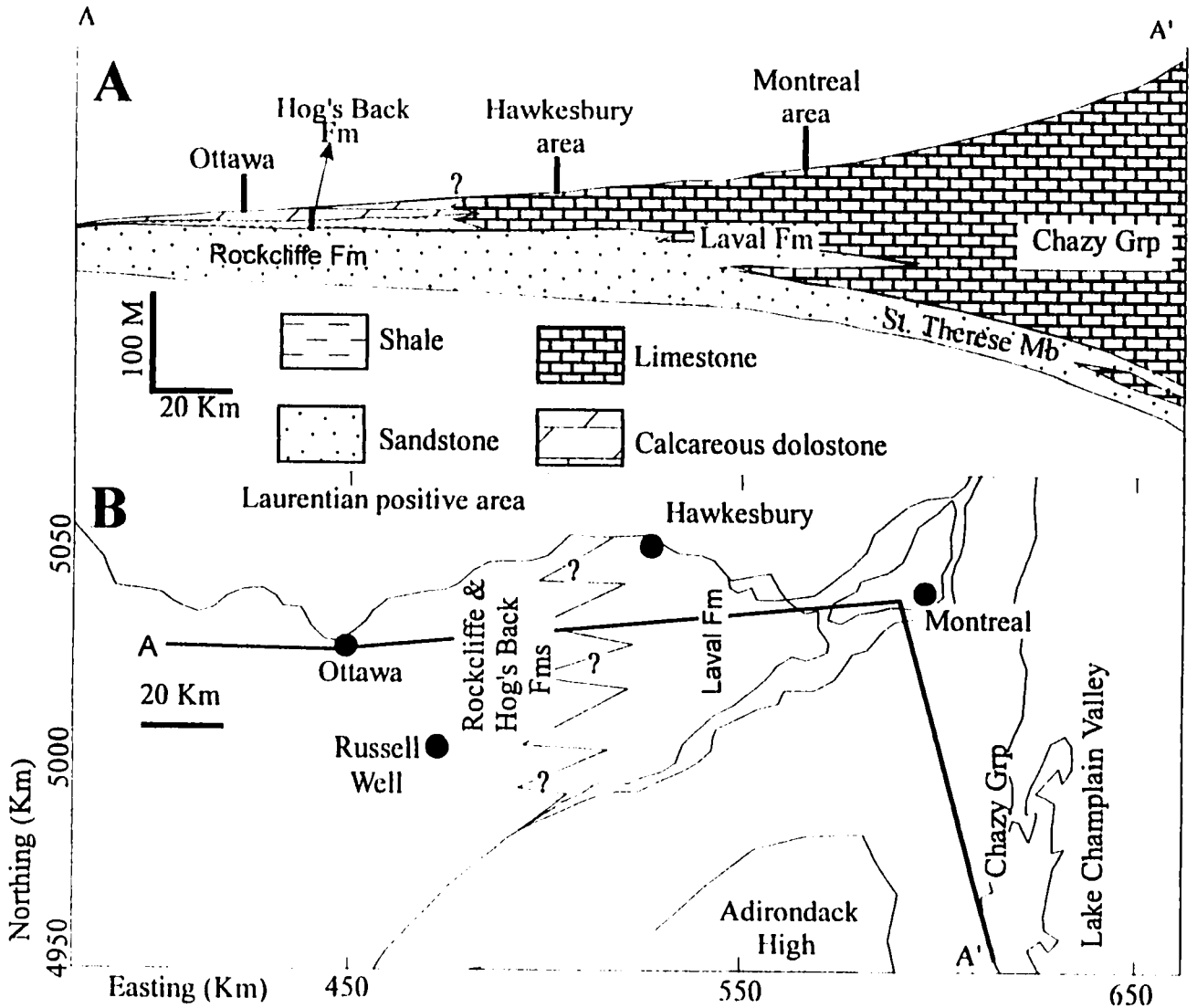
Correlation

Wilson (1946) placed the Rockcliffe - St. Martin boundary at the base of a 3 m thick covered interval that appears to correspond to recessive shales overlying sandstones. My correlation suggests that the lower boundary of the Hog's Back Formation corresponds to this same contact but includes a basal thin sandstone of possible local distribution. This contact lies *within* Williams' (1991) upper Rockcliffe Formation (Fig. 2.3). I place the contact between the lower and upper parts of the Hog's Back Formation equivalent to Williams' (1991) Rockcliffe - Shadow Lake formational boundary. Williams (1991, p. 80) defines this contact as a disconformity but I recognize no obvious disconformity. The upper boundary of the Hog's Back Formation lies about 5 m above the upper extent of the *Rostricellula*-bearing bed which Wilson (1946) used as a guide-fossil for the St. Martin formation, and about 9.4 m above the upper boundary of Williams' (1991) upper Rockcliffe Formation (Fig. 2.3).

By tracing the Hog's Back Formation from its type section through Russell County (Loc.4), there is an increase in thickness of the formation as well as in its carbonate content. I suggest that the formation correlates with the upper, carbonate-dominated Beaconsfield Member of the Laval Formation (Hofmann 1979) in the Montreal region. Given the correlation of the Laval Formation with the Chazy Group of the Lake Champlain Valley (Hofmann 1979, Fig. 2.6), the Hog's Back Formation likely correlates with the upper part of the Chazy Group of the Lake Champlain Valley (Fig. 2.6). The bioclastic packstone and grainstone beds within the upper part of the Hog's Back Formation also thicken eastward and correlate with similar grainstone facies that reaches thicknesses of up to 4.5 m near the Ontario and Quebec border (see Williams 1991). These calcarenites are very prominent in the Montreal area and form Hofmann's (1963) St. Martin facies or Clark's (1972a) St. Martin Member.

From correlation among several localities from Ottawa to Montreal (Fig. 2.7), dolostone beds that Hofmann (1963) considered to form the base of the overlying Pamelia Formation in southwestern Quebec appear to be correlative with the uppermost calcareous dolostone of the Hog's Back Formation. Thus, the basal part of the Pamelia Formation in the region of Montreal, as also found in the Ottawa area, Kingston and New York regions, contains siliciclastics (Salad Hersi and Dix 1995). From well data from southern Quebec, Roliff (1967) showed that basal Pamelia strata include siliciclastic interbeds. His lithologies are very similar to those mapped in the Ottawa region. One of Roliff's (1967) sections (well 68, pp. 589, 590) shows an angular unconformity at the Chazy - Blackriver contact. This implies that some local tectonics has occurred in the region prior to the Blackriveran deposition. In fact, Okulitch (1936) has already pointed out existence of a tectonic

Fig. 2.6 Regional correlation of the Chazyan rocks from Ottawa region through Montreal area to Lake Champlain Valley. Note that the base of the Hog's Back Formation and thicker carbonate strata to the east mark an episodic back-stepping of the shore line accompanied by a remarkable decrease in siliciclastic input (Rockcliffe Fm and St. Thérèse Mb of the Laval Fm) from the Canadian Shield (modified after Hofmann 1979).


A
A'
Ottawa
Hog's Back Fm
Hawkesbury area
Montreal area
Rockcliffe Fm
Laval Fm
Chazy Grp
St. Therese Mb
100 M
20 Km
Shale
Limestone
Sandstone
Calcareous dolostone
Laurentian positive area
B
Hawkesbury
Montreal
Ottawa
Russell Well
Rockcliffe & Hog's Back Fms
Laval Fm
Chazy Grp
Lake Champlain Valley
Adirondack High
20 Km
Northing (Km)
5050
5000
4950
Easting (Km)
450
550
650

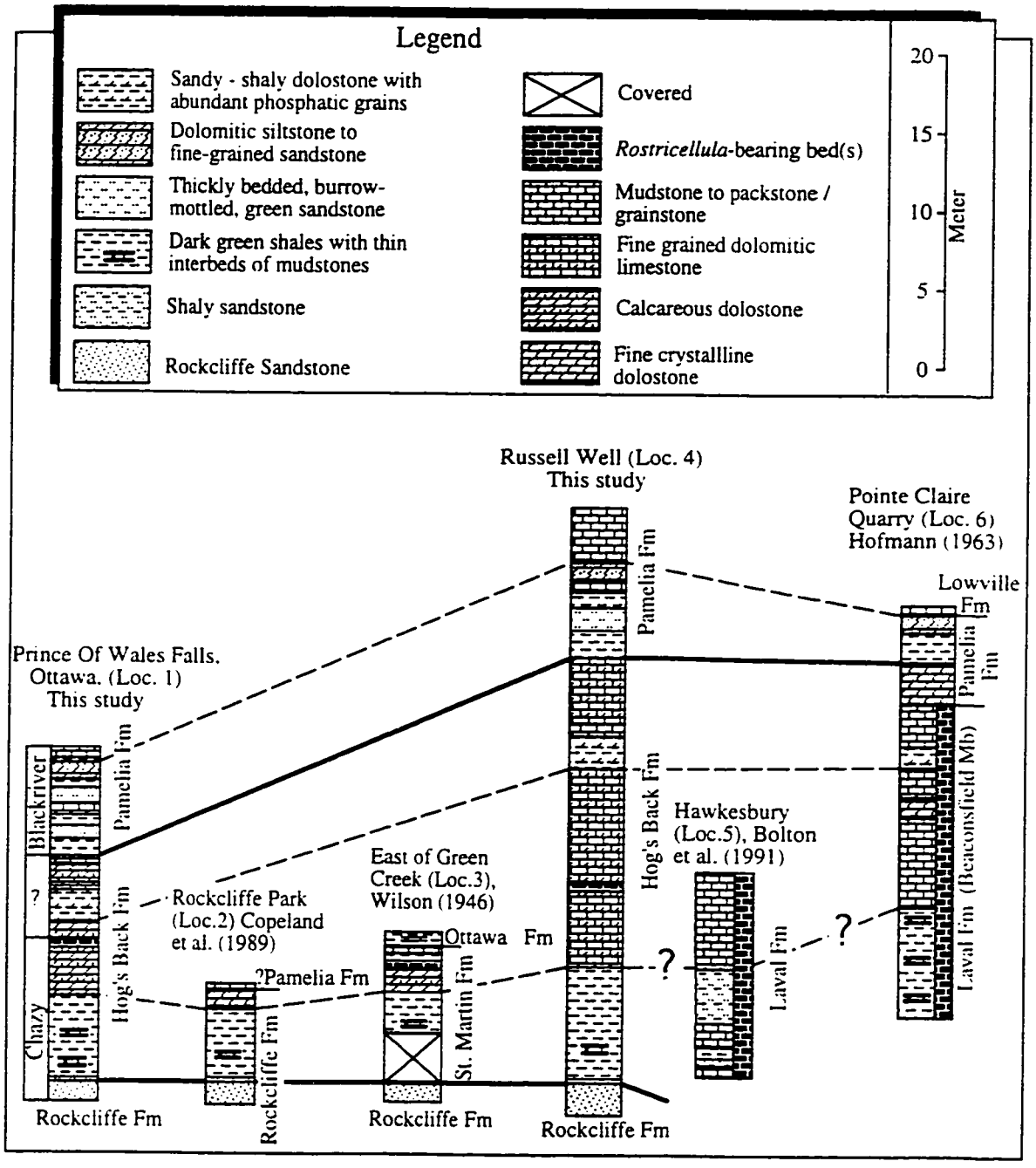


Fig. 2.7 Regional correlation chart of the late Chazyan rocks from Ottawa area eastward to Montreal area (Quebec). The formation or member names lying on the right side of each section are those proposed by their respective authors.

disturbance at the end of the Chazyan stage in the region of Montreal.

Progressive thinning of Chazyan (Llandeilian) strata from the type area of Lake Champlain Valley (New York), through the Montreal region, and into the Ottawa region is matched by westward thinning of the Hog's Back Formation within the Ottawa Embayment. Although previous work (e.g., Wilson 1946; Hofmann 1979; Troyer 1979; Copeland et al. 1989) recognized no rocks equivalent to the Hog's Back Formation west of Ottawa, sections measured by Wilson (1924) show that there may be shale similar to that in the lower part of the formation near Arnprior, about 50 km west of Ottawa. From these same sections, calcareous sandstone appears to be equivalent to the upper carbonate section of the Hog's Back Formation, and which contains some sandy dolostone beds. Chazyan rocks are not reported from south-central (Lake Simcoe area) and northern (Lake Huron area, Moose River Basin, Lake Timiskaming outlier) Ontario (see p. 995 of Johnson et al. 1992).

Depositional environment

The Rockcliffe and Hog's Back formations were deposited during a northwestward - advancing Middle Ordovician [Chazyan (Llandeilian)] transgression. Siliciclastic detritus (Rockcliffe and lower Hog's Back formations), eroded from Precambrian highs bordering the northern and western margins of the Chazyan shallow sea, dominate facies along the western sites of the basin, whereas carbonates could accumulate preferentially to the east (upper Laval Fm, Clark 1972; Hofmann 1979).

The Rockcliffe Formation contains wave-dominated estuarine or deltaic facies (Hofmann 1979). The basal unconformity and irregularly thick sandstone bed at the base of

the Hog's Back Formation may represent reworked Rockcliffe sediment that accumulated during the initial transgression. The energy at the depositional site was high during accumulation of the quartz arenite bed of the Hog's Back Formation. Thus, relatively finer particles within the reworked Rockcliffe sediments were sieved out.

The lower sandstone-shale-carbonate facies assemblage of the Hog's Back Formation characterizes peritidal conditions. This interpretation is supported by contrasting ichnofacies between the shale with horizontal burrows and limestone beds with subvertical to vertical burrows. This change may identify a changing response of biota to energy and likely water depth (Pemberton et al. 1992). Sand-size, terrigenous input probably occurred during short-term sea-level lowering or increased surface runoff. The thin lime-mudstone facies indicate short-term shutdown of siliciclastic input.

The upper, sparsely fossiliferous, fine crystalline calcareous dolostone facies likely identifies a highly restricted setting, possibly a sabkha environment. Gypsum crystals in intra-skeletal porosity (due to elevated salinity), calcite-filled nodules (due to replaced evaporite nodules) and rare fossils suggest local hypersaline conditions. However, the medium grey sandy and shaly dolostone beds with horizontal burrows may indicate subtidal deposits. Furthermore, very fossiliferous storm-deposited (?) packstone and grainstone beds reflect more "normal" salinity biofacies. Alternatively, these deposits may represent lowering of salinity, probably due to runoff increase, allowing short-lived pulses of productivity, with skeletal material subsequently reworked by waves or tidal currents. The regional facies change to more richly calcareous facies in the Laval Formation in the area of Montreal (Hofmann 1979) probably reflects less restricted (= normal salinity) conditions toward the basin's centre.

Significant stratigraphic boundaries

The Hog's Back Formation marks a unit that defines a transition from predominantly siliciclastic to carbonate sedimentation. Although a few sandstone units occur in the lower Ottawa Group, the flooding event marking the base of the Hog's Back Formation and another defining the base of the Ottawa Group characterize marked reduction of a once prominent terrigenous input in the Ottawa region, as represented by the earlier Rockcliffe Formation. Thus, the Hog's Back Formation preserves the history of basin-wide episodic back-stepping of the continental shoreline (Fig. 2.6). Flooding events bounding and defining this formation represent a mixed siliciclastic - carbonate genetic sequence (cf. Galloway 1989). Higher-order flooding events are identified by the very fossiliferous bioclastic packstone and grainstone that thicken eastward into the Montreal region, and the two medium grey sandy to shaly, burrowed dolomite beds in the upper part of the formation. However, upward-shallowing within the Hog's Back Formation may point to an overall progradation of the induced, new carbonate platform.

Conclusions

Chazyan (Llandeilian) rocks in the Ottawa Valley are redefined lithostratigraphically to include two formations, in ascending order: the Rockcliffe Formation (*sensu* Wilson 1946), and the newly proposed Hog's Back formation. The latter formation is overlain by basal siliciclastics of the Pamelia Formation [the lowest formation of the Blackriveran - Trentonian (Caradocian) Ottawa Group]. The Hog's Back Formation is 14.3 metres at its type section and thickens eastward, reaching about 27 m in a core from the Russell Well (~

40 km SE of Ottawa). The formation is divided into two parts. A lower part consists of a thin basal sandstone overlain by dark grey shales with thin lime mudstone and fine-grained sandstone interbeds. These sediments are arranged in a repetitive shallowing-upward pattern that accumulated within peritidal environments. The upper part consists of medium-bedded to thickly-bedded, fine crystalline, greenish grey, sandy to calcareous dolostone with thin interbeds of pinkish-grey bioclastic packstone and grainstone, and rare green shale. The upper part of the formation reflects deposition in hypersaline peritidal to possible sabkha environments. Bioclastic packstone and grainstone probably represent storm-reworked deposits with elevated fossil abundance and diversity resulting from lowered salinity.

Biostratigraphic data (macrofossils and conodonts) suggest that the Hog's Back Formation is Chazyan (Llandeilian) in age. Correlation east of Ottawa indicates that the Hog's Back Formation becomes more calcareous; the bioclastic limestones thicken eastward, and are equivalent to the calcarenites of the Beaconsfield Member of the Laval Formation in the Montreal region.

The stratigraphic boundaries of the Hog's Back Formation correspond to two regional flooding events. The base contains reworked Rockcliffe sediment during transgression. Flooding reduced terrigenous influx, and marks transition to the development of a subsequent carbonate platform. A shallowing-upward succession, characterized by a transition from siliciclastic to carbonate facies, in the Hog's Back Formation may reflect progradation of the induced stages of the platform. Termination of Hog's Back deposition was linked to a second prominent flooding event, marking the base of the Blackriveran - Trentonian Ottawa Group. The Hog's Back Formation, as defined by two prominent flooding events, appears to be best described as a genetic sequence (Galloway 1989).

CHAPTER THREE

LITHOSTRATIGRAPHY OF THE BLACKRIVERAN SUCCESSION IN THE OTTAWA EMBAYMENT

Introduction

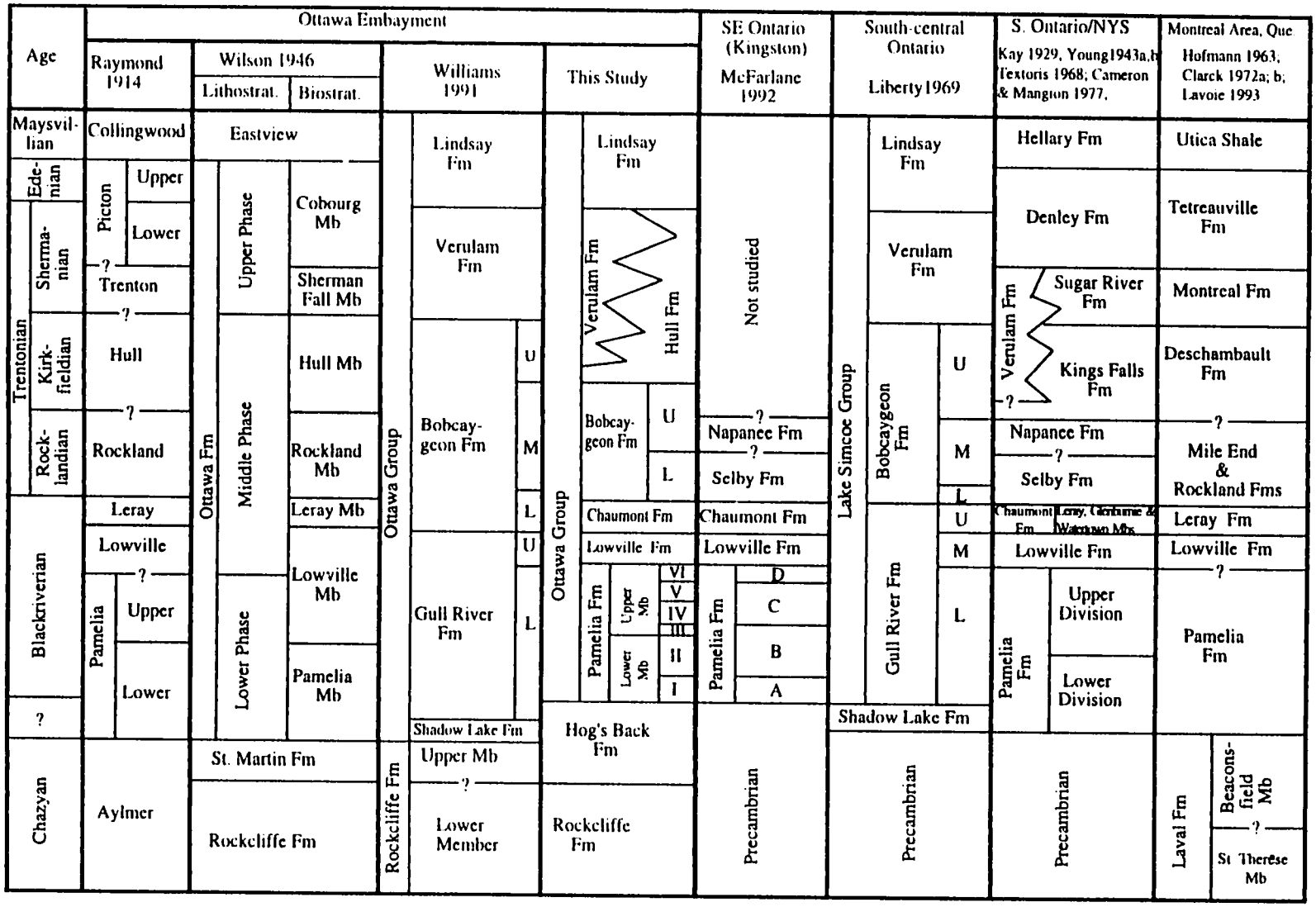
Blackriveran strata (lower Ottawa Group) in the Ottawa Embayment include three formations which are, in ascending order: Pamelia, Lowville and Chaumont. The lowest Blackriveran formation overlies the Chazyan Hog's Back Formation (see Chap. 2) and is overlain by the Trentonian Bobcaygeon Formation of the upper Ottawa Group (see Chap. 7).

As mentioned earlier (see Chap. 1), two stratigraphic nomenclatures have been adopted in the past for Blackriveran strata in the Ottawa Embayment. Like the work of Williams (1991), my work does not include the use of terms defined by faunal zonation (e.g.. Raymond 1914; Wilson 1946) for lithostratigraphic division (North American Commission on Stratigraphic Nomenclature 1983). However, I find difficulty in applying Liberty's (1967a, b; 1969) nomenclature for Blackriveran strata in the Ottawa Embayment. Liberty (1969) developed his new nomenclature after deciding that Blackriveran strata in the Lake Simcoe region are dissimilar to equivalent rocks in upstate New York. After mapping Blackriveran sections in the Lake Simcoe region [including Okulitch's (1939a) original type sections], Liberty (1969) concluded that stratigraphic terms Pamelia, Lowville and Chaumont (from upstate New York) could not be readily used as lithostratigraphic terms in south-central Ontario because equivalent rocks in the latter region all contained a "Lowville lithology". Liberty (1969, p. 22) emphasized that, "lithological correlation of [Lake Simcoe's] Gull River with Pamelia, Lowville and Chaumont units is not considered

possible". He proposed, instead, Shadow Lake and Gull River formations [modified after Okulitch (1939a)] for the Blackriveran strata of the Lake Simcoe region (see correlations in Fig. 3.1). Liberty's (1969) Gull River incorporates Okulitch's (1939a) upper Shadow Lake, Gull River and Moore Hill formations. Liberty (1967a) had extended his preliminary nomenclature to accommodate the upper Ordovician Ottawa [Formation] in the Ottawa Embayment.

My study demonstrates that lithologic attributes of Pamelia, Lowville and Chaumont formations *are* easily recognized in the Ottawa Embayment whereas definitions of the Shadow Lake and Gull River formations are not readily applicable. The Pamelia, Lowville and Chaumont rocks of the embayment do not all contain a "Lowville lithology" as suggested by Liberty (1969) for south-central Ontario, and correlations with the equivalent lithologies in New York State (Cushing 1908; Cushing et al. 1910; Kay 1929; Young 1943a; b; Fisher 1957; Cameron 1968; Textoris 1968; Ross 1970; Walker 1972; 1973; Cameron and Mangion 1977) as well as the Kingston area (Young 1943a; b; Cameron 1968; Peterson 1969; Cameron and Mangion 1977; McFarlane 1992) are convincing (Fig. 3.1). Lithostratigraphic correlations between the Ottawa Embayment and south-central Ontario, particularly Lake Simcoe area, can also be made.

Fig. 3.1 Chart showing various stratigraphic nomenclatures used for the Middle and Upper Ordovician succession in the Ottawa Embayment and its correlative strata in the neighbouring regions.


Age
Ottawa Embayment
Raymond 1914
Wilson 1946
Lithostrat.
Biostrat.
Williams 1991
This Study
SE Ontario (Kingston)
McFarlane 1992
South-central Ontario
Liberty 1969
S. Ontario/NYS
Kay 1929, Young 1943a,b; Textoris 1968; Cameron & Mangion 1977.
Montreal Area, Que.
Hofmann 1963; Clarck 1972a; b; Lavoie 1993
Maysvil-lian
Ede-nian
Sherma-nian
Kirk-fieldian
Rock-landian
Trentonian
Blackriverian
?
Chazyan
Collingwood
Picton
Upper
Lower
Trenton
Hull
Rockland
Leray
Lowville
Pamelia
Upper
Lower
Aylmer
Eastview
Ottawa Fm
Upper Phase
Cobourg Mb
Sherman Fall Mb
Middle Phase
Hull Mb
Rockland Mb
Leray Mb
Lowville Mb
Lower Phase
Pamelia Mb
St. Martin Fm
Rockcliffe Fm
Ottawa Group
Lindsay Fm
Verulam Fm
Bobcay-geon Fm
U
M
L
Gull River Fm
U
L
Shadow Lake Fm
Rockcliffe Fm
Upper Mb
?
Lower Member
Lindsay Fm
Verulam Fm
Hull Fm
Bobcay-geon Fm
U
L
Chaumont Fm
Lowville Fm
Pamelia Fm
Upper Mb
Lower Mb
VI
V
IV
III
II
I
Hog's Back Fm
Rockcliffe Fm
Not studied
?
Napanee Fm
?
Selby Fm
Chaumont Fm
Lowville Fm
Pamelia Fm
D
C
B
A
Precambrian
Lake Simcoe Group
Lindsay Fm
Verulam Fm
Bobcaygeon Fm
U
M
L
Gull River Fm
U
M
L
Shadow Lake Fm
Precambrian
Hellary Fm
Denley Fm
Verulam Fm
Sugar River Fm
Kings Falls Fm
?
Napanee Fm
?
Selby Fm
Chaumont Fm
Leray, Gananoque & Watertown Mbs
Lowville Fm
Pamelia Fm
Upper Division
Lower Division
Precambrian
Utica Shale
Tetreauville Fm
Montreal Fm
Deschambault Fm
?
Mile End & Rockland Fms
Leray Fm
Lowville Fm
?
Pamelia Fm
Laval Fm
Beacons-field Mb
?
St Therese Mb

Pamelia Formation

Origin

The Pamelia Formation, as proposed by Cushing et al. (1910), is a lithostratigraphic term. It contains a lower part which "has always a sandy base, followed by alternations of black limestone, blue limestone, and grey, somewhat magnesian limestone, often with shaly partings between the beds", and an upper part which contains "whitish, earthy limestone, with interbedded dove limestone, and grey magnesian limestone" (Cushing et al. 1910, p. 69). Later workers (e.g., Young 1943a; Textoris 1968; Walker 1972; 1973; Cameron & Mangion 1977) gave further details of the Pamelia Formation in the type area.

Walker (1973) has revised both the Pamelia and Lowville formations, and proposed a reference section along Roaring Brook in upstate New York. Walker's (1973) redefined formation boundaries are much different from other descriptions. For instance, Walker's (1973) Pamelia - Lowville boundary lies at about 10 metres below that documented by Textoris (1968). This places beds originally assigned to Pamelia (Cushing 1908; Cushing et al. 1910; Young 1943a; Textoris 1968) into the Lowville Formation. The Pamelia Formation recognized in the Ottawa Embayment is correlative with that described by Cushing et al. (1910), Young (1943a), and Textoris (1968).

Lithostratigraphy

In the Ottawa Embayment, the Pamelia Formation lies between the Chazyan Hog's Back Formation and the Blackriveran Lowville Formation. The lower boundary of the Pamelia Formation is also that of the Ottawa Group, and is well exposed at the Prince of

Wales Falls section, Ottawa (Loc. 20) as well as in cores (Locs. 5 & 41). The base is also poorly exposed at the Riverside road-cut (Loc. 16) in Ottawa. The lower boundary is characterized by an abrupt lithologic change from dolostone beds of the Hog's Back Formation (Salad Hersi & Dix 1997a; see Chap. 2) to dark brown to black sandy shale interbedded with thick, highly burrowed, greenish grey, fine grained sandstone and thin bioclastic mudstone and wackestone (Figs. 3.2, 3.3) . The Pamelia Formation has thick pure, calcareous and-or sandy dolostone to locally dolomitic sandstone beds (T-1 to T-6, Fig. 3.4) which occur repetitively throughout the formation. The upper boundary of the formation is placed at the upper surface of the highest prominent greenish, sandy and-or calcareous dolostone bed(s) (T-6) overlain by the limestone of the Lowville Formation (Figs. 3.4, 3.5).

The Pamelia Formation is about 42 m thick in the Ottawa area and increases, slightly, to about 43.5 m in the Russell well core (~40 km southeast of Ottawa, Loc. 41). The formation thins eastward and it is significantly reduced in thickness, to less than 3 m, in the region of Montreal, Quebec (Clark 1972a; b; Harland & Pickerill 1982; Hofmann 1963; Okulitch 1936; 1939b).

In the Ottawa Embayment, the formation is divided into two (Lower and Upper) members. These divisions are based on gross changes in lithology. The Lower Member has a thick (~ 6 m in the Ottawa area) basal sandstone and shale succession, with limestone interbeds, and is overlain by limestone and dolostone. Similarly, the Upper Member has a basal sandstone unit overlain by carbonate strata; the lower part of the carbonate succession is dominated by dolostone beds whereas the upper part is mainly limestone in composition (Fig. 3.5). There is no outcrop which exposes a continuous section of the Pamelia Formation. Nonetheless, mapped sections overlap one another and offer composite sections through the

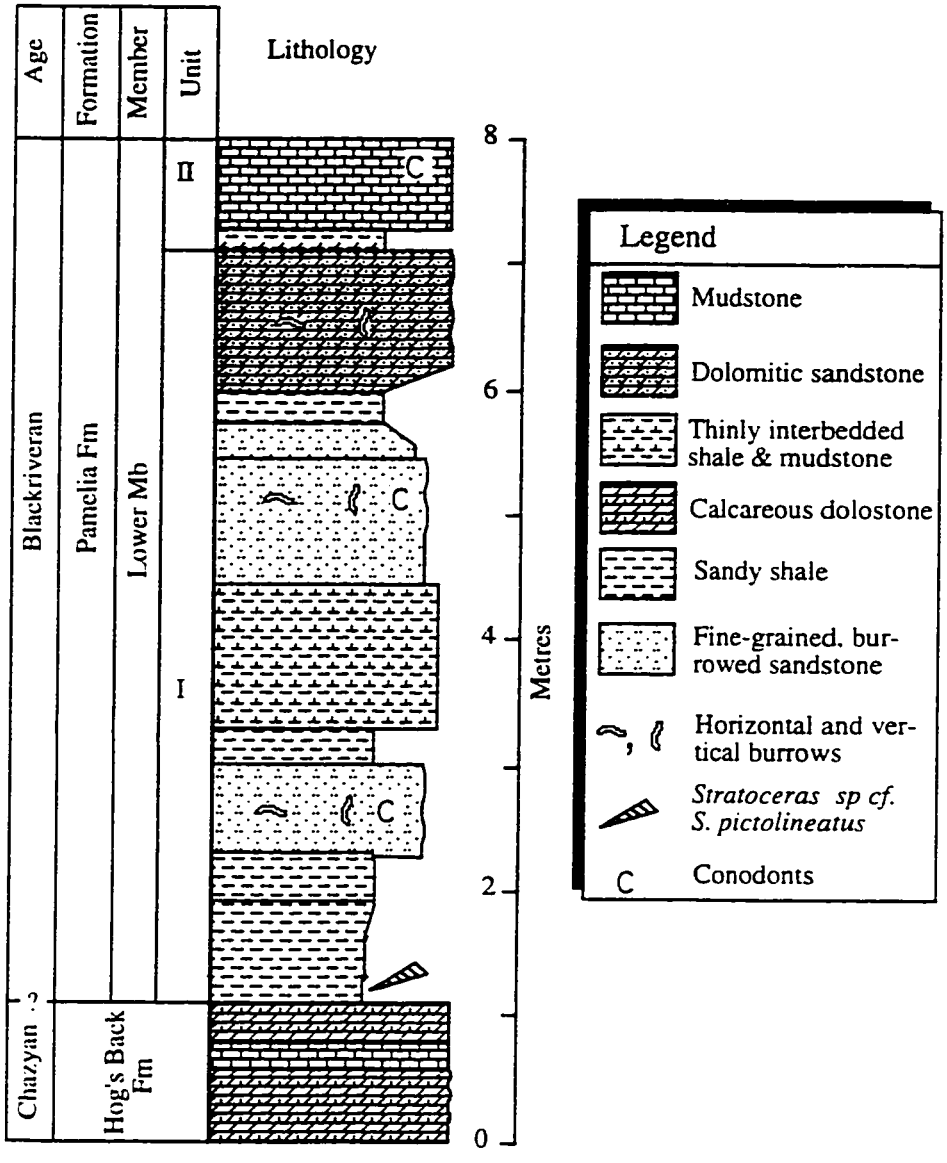


Fig. 3.2 Lower Pamelia section from Prince of Wales Falls at the Hog's Back Park, Ottawa.The contact between the Hog's Back and Pamelia formations is exposed at this locality.

Fig. 3.3 Hog's Back (H) - Pamelia (P) contact at Locality 20 (horizontal arrows). Basal unit (Unit I) of the Pamelia Formation is characterized by interbedded thick shale and sandstone beds. Note the apparent rhythmic character of bedding within this unit. Horizontal field of view is about 18 m. Loc. 20: Prince of Wales Falls, Ottawa.

Fig. 3.4 The Pamelia Formation is characterized by recurring intervals of sandstone, sandy to pure dolostone, (e.g., T-1). The upper boundary of the formation is placed at the upper surface of the highest sandy dolostone interval (T-6) in the stratigraphic column. The formation is here divided into Lower Member which consists of two units (Unit I & Unit II) and Upper Member which consists of four units (Units III to VI).

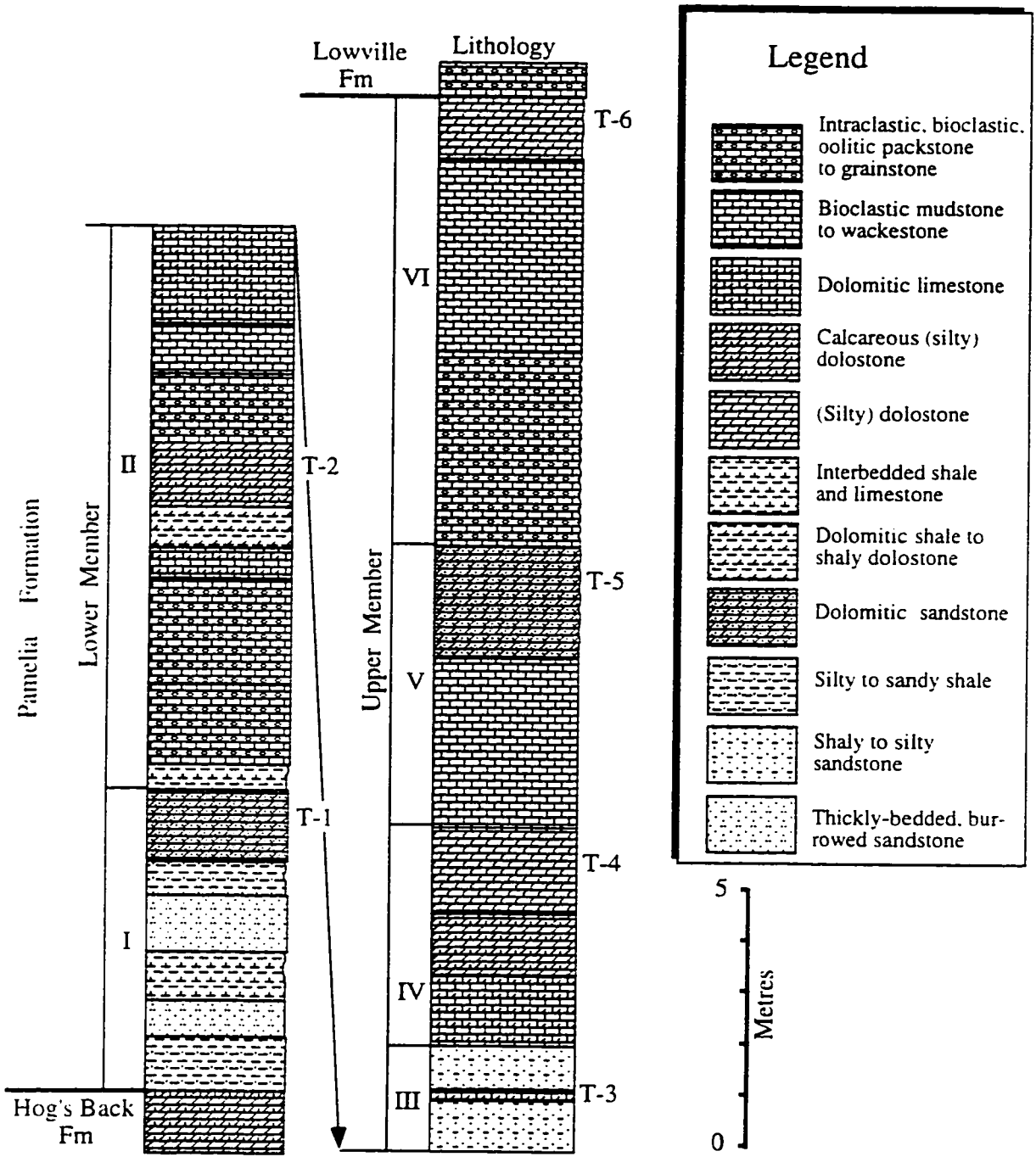

Lowville Fm
Lithology
T-6
T-5
T-4
T-3
T-2
T-1
VI
V
IV
III
II
I
Upper Member
Lower Member
Pamelia Formation
Hog's Back Fm
Legend
Intraclastic, bioclastic, oolitic packstone to grainstone
Bioclastic mudstone to wackestone
Dolomitic limestone
Calcareous (silty) dolostone
(Silty) dolostone
Interbedded shale and limestone
Dolomitic shale to shaly dolostone
Dolomitic sandstone
Silty to sandy shale
Shaly to silty sandstone
Thickly-bedded, burrowed sandstone
5
0
Metres

Fig. 3.5 Outcrop picture showing thick sandy dolostone bed that caps the Pamelia Formation. This sandy dolostone bed is the highest of recurring (sandy) dolostone units within the Pamelia Formation. The acid bottle is 5.5 cm long. Loc. 15: Frazer Duntile quarry, Ottawa.

formation (Fig. 3.6). In core from Locality 41 (GSC Russell well) a continuous section of the Pamelia Formation is recovered (see Appendix 1, Loc. 41). This allows a reliable examination of both temporal and lateral lithofacies distribution of the formation in the Ottawa Embayment.

The two members of the Pamelia Formation are divisible further into six lithostratigraphic units (units I to VI). These units are defined by differences in lithofacies and lithofacies associations. The sandy to calcareous dolostone and sandstone intervals (T-1 to T-6) of the Pamelia Formation are laterally extensive and, as will be shown, are used as key markers for both local (within Ottawa Embayment) and regional (Ottawa Embayment, Montreal, Lake Simcoe, Kingston and New York) correlations. These dolostone beds define an apparent rhythmic pattern.

Lower Member

The Lower Member of the Pamelia Formation includes two units, I and II. The lower Unit I is dominated by thick sandstone and shale beds with subordinate limestone interbeds. It shows some lateral lithologic variations (see below). Unit II is dominated by limestone with dolomite and shale interbeds. The thickness of the Lower Member is fairly constant (~ 18.5 m) throughout the study area (Figs. 3.7, 3.8).

Unit I

The base of this unit is the Hog's Back - Pamelia formational contact (Figs. 2.5, 3.2, 3.3). Among 8 localities at which the unit is exposed (Fig. 3.6), three sites (Locs. 20, 41 & 54) preserve a complete section of the unit, and yield an average thickness of 6.4 m. An

Fig. 3.6 Vertical stratigraphic ranges of the studied sections which contain Blackriveran strata. Arrows indicate that the section continues to that direction. Vertical dashed lines represent sections removed by faults. Loc. 1 = Braeside quarry, McNab; loc. 5 = Westport quarry + OGS well at the same locality; Loc. 10 = Moodie Dr. (Fallowfield) quarry, Nepean; Loc. 11 = Fallowfield quarry, Nepean; Loc. 12 = Houlahan quarry, Nepean, Loc. 14 = Iris Rd. Transitway at Highway 417, Ottawa, Loc. 15 = Frazer Duntile quarry, Carling Ave at Kirkwood Dr., Ottawa, Loc. 16 = Riverside Dr., Ottawa, Loc. 17 = Redeveloped quarry (Western Community) between Bourbon St. and Owl Dr., Ottawa, Loc. 18 = Plante Dr., Ottawa. Loc. 19 = McCarthy Rd., at Walkley Rd., Ottawa, Loc. 20 = Prince of Wales Falls, Ottawa. Loc. 21 = Hog's Back quarry (near Riverside Dr.), Loc. 22 = GSC Observatory well at Observatory Crescent, Ottawa, Loc. 24 = Scott Street Transitway (at & west of Tunny's Pasture), Ottawa, Loc. 27 = Beechwood Ave., Ottawa, Loc. 34 = Francon quarry (northern quarry), Blackburn Hamlet, Gloucester; Loc. 36 = St. Joseph Blvd., near Hart Rd, Gloucester; Loc. 39 = St. Joseph Blvd., ~ 300 m east of tenth Line, Orleans; Loc. 40 = Stewart quarry. Rockland; Loc. 41 = Russell well, Russell County; Loc. 41 = Embrun quarry, Embrun; Loc. 43 = St. Albert Station quarry, Finch; Loc. 44 = Cruickshank quarry, Winchester Springs; Loc. 45 = Cornwall quarry (Permanent Concrete), Cornwall; Loc. 46 = Cornwall quarry (Dibblee Construction Co.), Cornwall; Loc. 47 = Macleod quarry, Cornwall; Loc. 48 = Green Valley quarry, Lancaster.

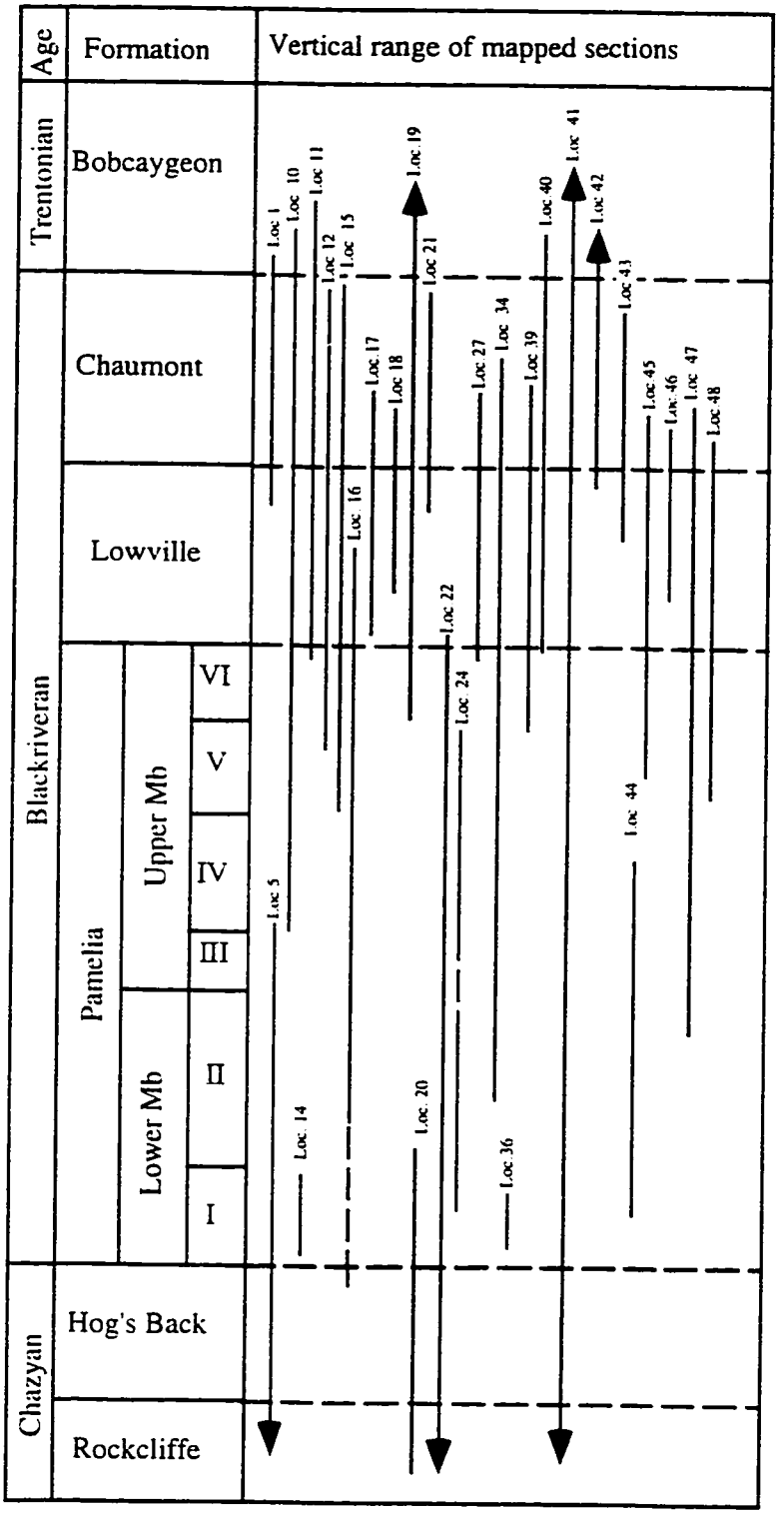
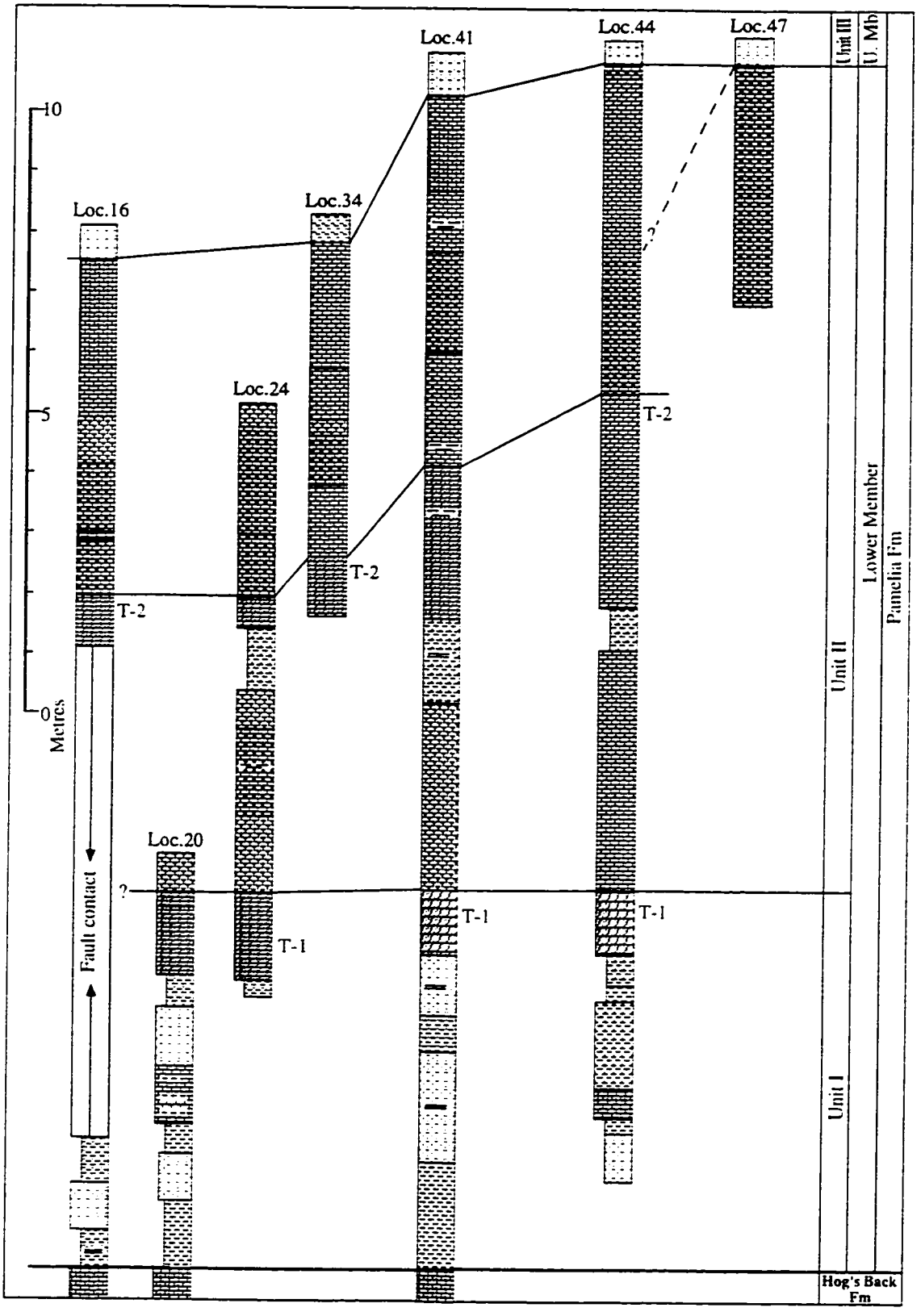

Age
Formation
Vertical range of mapped sections
Trentonian
Bobcaygeon
Blackriveran
Chaumont
Lowville
Pamelia
Upper Mb
Lower Mb
VI
V
IV
III
II
I
Chazyan
Hog's Back
Rockcliffe
Loc 1
Loc 10
Loc 11
Loc 12
Loc 15
Loc 16
Loc 17
Loc 18
Loc 19
Loc 21
Loc 22
Loc 24
Loc 27
Loc 34
Loc 36
Loc 39
Loc 40
Loc 41
Loc 42
Loc 43
Loc 44
Loc 45
Loc 46
Loc 47
Loc 48
Loc 5
Loc 14
Loc 20

Fig. 3.7 Correlations of selected seven sections which show the Lower Member of the Pamelia Formation. Note that thickness of Unit I is almost constant across the embayment. Unlike other localities in the embayment, Locality 47 shows bioclastic, oolitic grainstone to form the highest beds of the member. It appears that the erosional event, which occurred before deposition of Unit III (lowest unit of the Upper Member), probably removed dolomitic lime-mudstone and dolostone lithofacies which occurs at the upper part of the Lower Member in the other localities. The base of the formation is taken as a datum. Horizontal distance is not in scale. Locations shown include: Loc. 16: Riverside Dr., Ottawa; Loc. 20: Prince of Wales Falls, Ottawa; Loc. 24: Scott St. Transitway, Ottawa; Loc. 34: Francon quarry - North, Blackburn Hamlet, Gloucester; Loc. 41: Russell well, Russell County. Loc. 44: Cruickshank quarry, Winchester; Loc. 47: Macleod quarry, Cornwall.


Loc.16
Loc.34
Loc.41
Loc.44
Loc.47
Loc.24
Loc.20
10
5
0
Metres
T-2
T-2
T-2
T-1
T-1
T-1
?
?
Fault contact
Unit III
U. Mb
Lower Member
Pamelia Fm
Unit II
Unit I
Hog's Back Fm

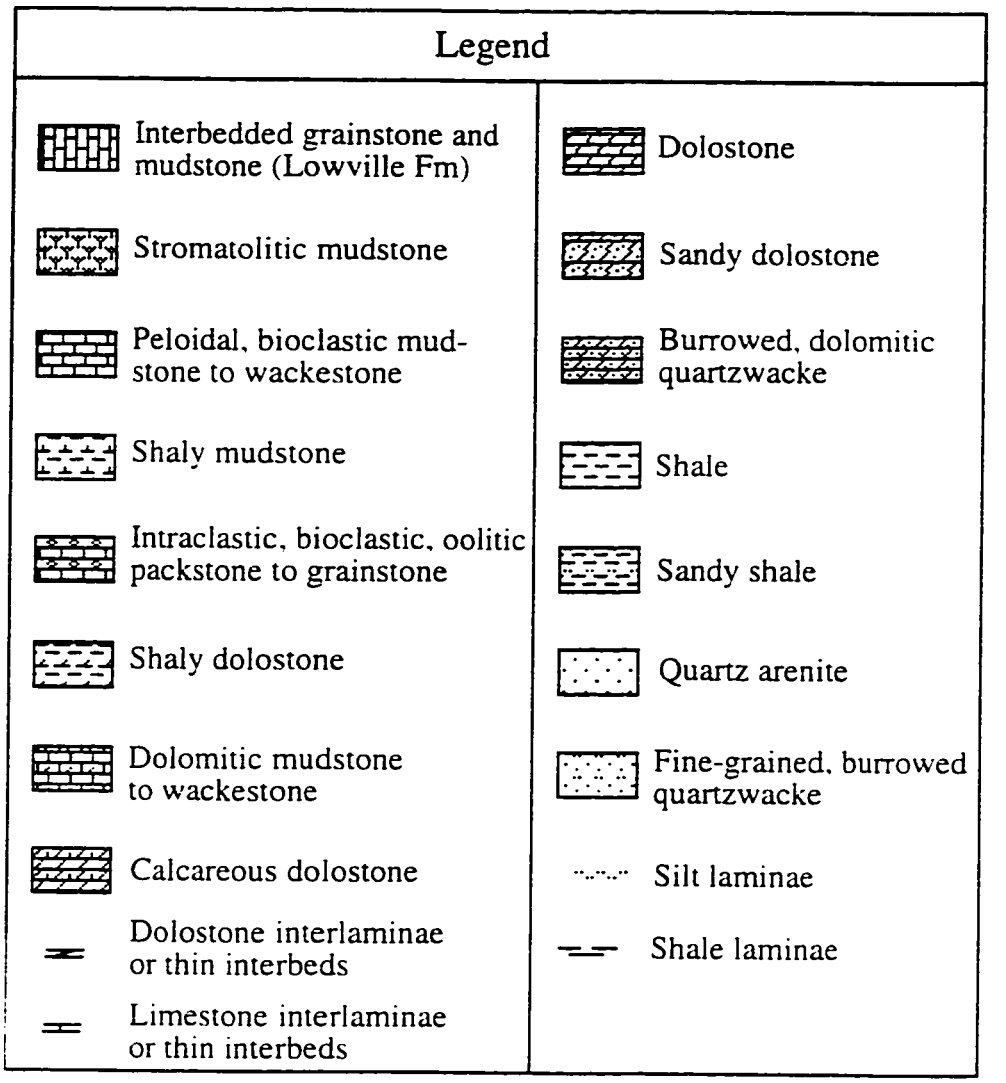


Fig. 3.8 Legend for Figures 3.7 and 3.13

isopach map of the unit constructed from data compiled from my work and previous work (e.g., Wilson 1924; Wilson 1990) shows that the thickness of the unit is almost uniform within the Ottawa Embayment (Fig. 3.9). The best outcrops occur at localities in Ottawa (Locs. 14, 20, 24 & 36) and most of the field descriptions are taken from these sections (see Appendix 1).

Unit I is lithologically dominated by intensely burrowed, green, fine to medium grained quartzwacke and medium to dark greenish black shale (Fig. 3.3). Interbeds of dark grey bioclastic (mainly ostracod) mudstone to packstone also occur. The mudstone lithofacies becomes microbially laminated in the eastern part of the embayment (e.g., Loc. 44). Rare bioclastic oolitic packstone is present. The various lithofacies of the unit are arranged in a repetitive (rhythmic) pattern: shale always forms the base of each rhythm, followed (gradationally or abruptly) by either highly burrowed sandstone or interbedded shale and mudstone - packstone, and succeeded by burrowed sandstone (Fig. 3.2).

The top of the unit is marked by a thick bed (up to 1.2 m, Locs. 20 & 24) of fine-grained dolomitic sandstone, and is equivalent to slightly sandy to pure, fine crystalline dolostone in the Morrisburg area (Loc. 44). This latter dolostone is characterized by medium to thick beds (18 to 57 cm, with total thickness of about 1.6 m). These beds are assigned to T-1 for correlation purposes (Fig. 3.7).

Unit I has generally a low fossil content, and characteristic fossils include ostracods (*Leperditia sp.*) present in the mudstone to packstone beds. Branching bryozoans are also locally present. An orthocone fossil (*Stratocera* sp. cf. *S. pictolineatus* Foerste) was collected a few centimetres above the base of the unit at Locality 20 (Salad Hersi & Dix 1995; 1997a). Two samples from thick sandstone beds at locality 20 gave a rare and poorly preserved

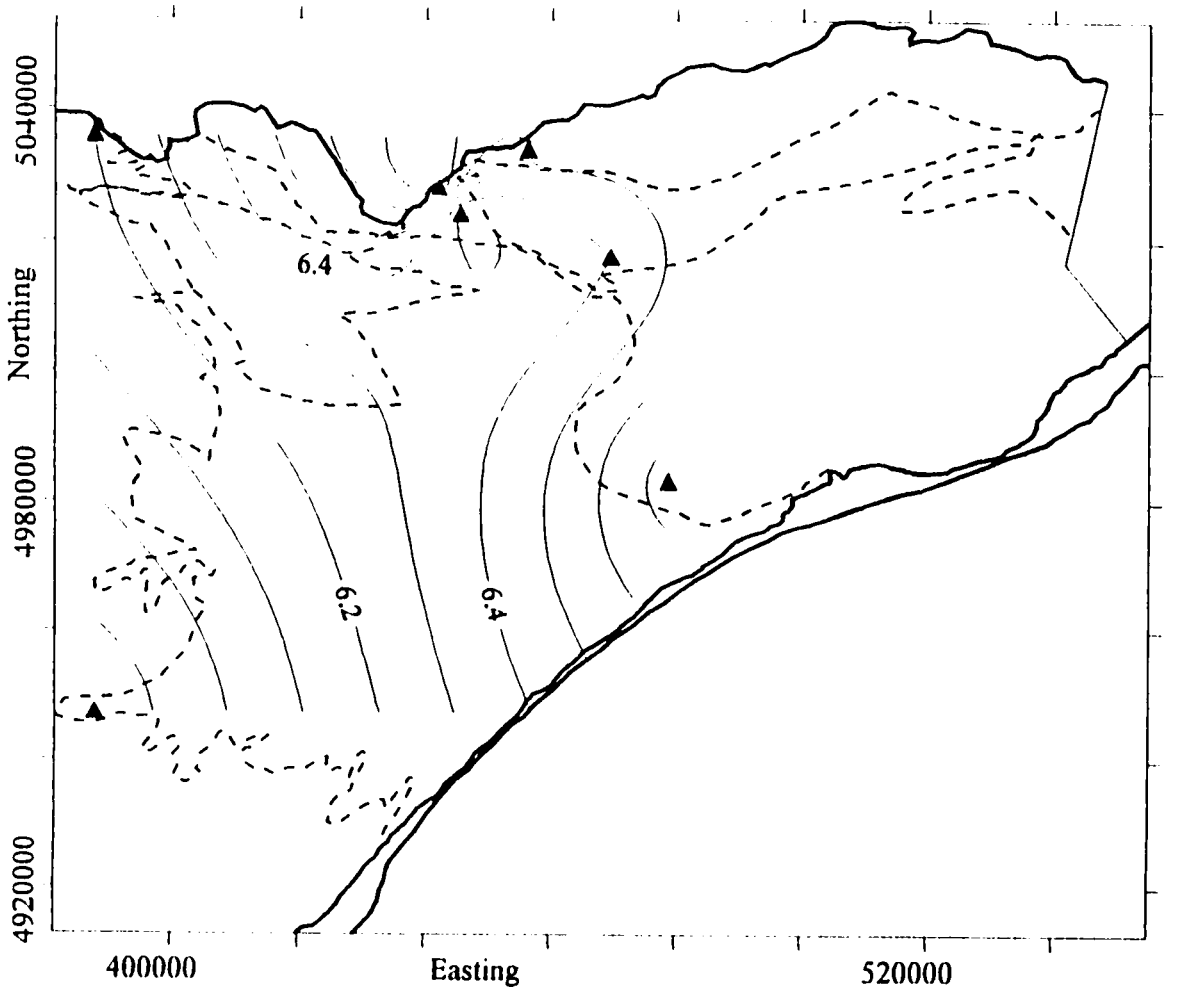


Fig. 3.9 Isopach map showing thickness variation of Unit I of the Lower Member of the Pamelia Formation within the Ottawa Embayment. The contours show wide spacing (gentle slope) and their intervals are 0.1 m. This suggests that the Ottawa Embayment was almost flat. Dashed lines are geologic boundaries (see Fig. 1.1 for details).

conodont fauna of *Erismodus* sp., *Phragmodus* sp. and *Curtognathus* sp. (McCracken, 1995). Horizontal (*Planolites* ichnofacies) burrows are common in the unit. Vertical (*Skolithos* ichnofacies) and U-shaped (*Arenicolites* ichnofacies) are also locally significant.

Unit II

In all localities, the sandstone to sandy dolostone (T-1) bed(s) at the top of Unit I is conformably overlain by thin to medium beds of stromatolitic to flat, microbially laminated mudstone interbedded with bioclastic and oolitic packstone and grainstone. The upper limit of the unit (i.e., upper boundary of the Lower Member) is exposed at six localities (Locs. 16, 22, 34, 41, 43 & 44). It is marked by a prominent erosional surface, in places by an obvious hardground (Fig. 3.10). The erosional pattern is apparently less developed in the Ottawa area (Locs. 16, 22 & 34) than in the eastern part of the embayment (Locs. 41, 44 & 47). This contact is also characterized by an abrupt lithologic change from dolomitic lime mudstone (Locs. 16, 22, 34, 41 & 43) or bioclastic oolitic grainstone (Loc. 44) to medium- to coarse-grained sandstone (at all localities) that forms the basal siliciclastic unit (Unit III) of the Upper Member of the Pamelia Formation.

Unit II has an average thickness of about 12.0 m, and increases slightly to the southeast (Figs. 3.7 & 3.8). This unit begins with stromatolitic mudstone and packstone overlain by thin to medium beds of bioclastic, oolitic packstone with shaly partings. Stromatolites show well pronounced laterally linked hemispheroids (LLH of Logan et al., 1964) in the Ottawa area (Fig. 3.11). In the Morrisburg area (Loc. 44), microbially laminated to thinly bedded mudstone with small isolated spheroidal structures (SS of Logan et al., 1964) occur in the lower part of the unit.

Fig. 3.10 An erosional contact separates the Lower Member from the Upper Member of the Pamelia Formation (Loc. 44). It is well developed in the eastern localities (e.g., Locs. 41, 44, and 47) than western localities (e.g., Locs. 34 and 16). Note the well developed erosional pattern with rip-up clasts (just right of the hammer). The basal sandstone unit (light-coloured) of the Upper Member of the Pamelia Formation occurs above this contact. The irregularity of the erosional surface is possibly enhanced by chemical dissolution. Hammer is 33 cm long. Loc. 44: Cruickshank quarry, Winchester.

Fig. 3.11 LLH type stromatolite of lime mudstone at the lower part of Unit II of the Pamelia Formation. The pencil is 15 cm iong. Loc. 24: Scott Transitway, Ottawa.

Dark brown, sandy dolomitic shale and greenish grey sandy dolostone (T-2, Fig. 3. 7) occur in the middle part of Unit II. The sandy dolostone becomes thicker and more dominant to the southeast where, for example, it dominates the section near Morrisburg (Loc. 44). Sandy dolostone of T-2 is succeeded by interbedded intraclastic, bioclastic, and oolitic packstone to grainstone and bioclastic (locally stromatolitic) mudstone.

The upper part of the unit is dominated by shaly, dolomitic lime mudstone in all localities except at Locality 47. At this latter locality, the shaly, dolomitic lime mudstone is apparently missing, and erosionally truncated bioclastic, oolitic grainstone is in contact with the overlying Upper Member of the Pamelia Formation.

Limestone beds of Unit II are generally dark to dark grey on fresh surfaces and weather to medium grey, whereas the dolostone beds are greenish grey and weather dull yellowish (orange) green. Sedimentary features include stromatolites (LLH type of Logan et al., 1964), microbial flat and wavy laminae, horizontal bedding, trough cross-bedding (Fig 3.12), scour channels, current ripple marks, mudcracks, flat-pebbles, hardgrounds and vertical burrows (*Skolithos* in the sandy dolostone lithofacies).

The unit is moderately fossiliferous. Characteristic fossils include stromatolites, ostracods (mostly *Leperditia* sp.), tabular serpulid worm colonies (along discrete layers), gastropods, bivalves, trilobites (e.g., *Bathyurus acutus* Raymond), rare crinoids and stromatoporoids.

Fig. 3.12 Oolitic, bioclastic grainstone lithofacies of Unit II, Pamelia Fm, showing trough and tabular cross-bedding, as well as planar bedding. The pencil is 15 cm long. Loc. 24: Scott Transitway, Ottawa.

Upper Member

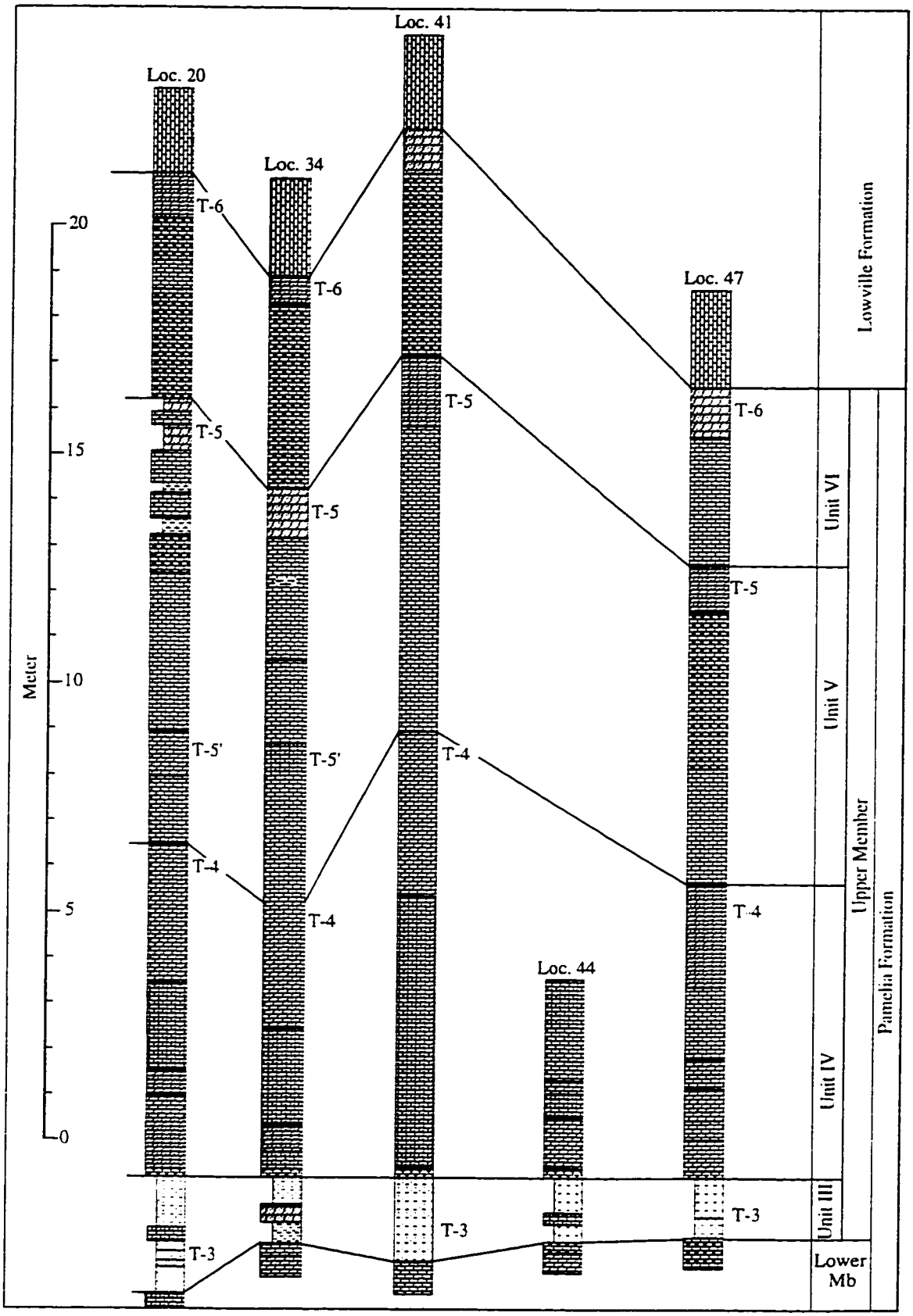
Seventeen localities expose partial or continuous sections (Fig. 3.6) through the Upper Member. The member has an almost constant thickness of about 24.7 m from Ottawa (Loc. 16) to Russell County (Loc. 41) but decreases to about 18 m in the Cornwall area (Loc. 47) (Figs. 3.8, 3.13). The lower boundary of the member is defined by the above mentioned erosional contact with the Lower Member of the formation. The upper boundary of the member is the Pamelia - Lowville formational contact. This contact is exposed at 12 localities (Fig. 3.6). It is placed at the upper surface of the highest (calcareous) dolostone to sandy (calcareous) dolostone bed(s) (T-6, Figs. 3.4, 3.5, & 3.13) in the succession.

The Upper Member consists stratigraphically of a basal siliciclastic unit (Unit III) followed by interbedded thick dolostone to sandy dolostone (Unit IV); thinly bedded, microbially laminated mudstone to wackestone with minor intraclastic rudstone interbeds (Unit V), and thin to thick beds of medium grained intraclastic, bioclastic and oolitic packstone to grainstone (Unit VI). Thick dolostone beds mark the top of the units IV, V, and VI (T-4, T-5, and T-6, respectively, Fig. 3.13). Detailed descriptions of these units are presented in the following subsections.

Unit III

This unit is represented by a relatively thin sandstone forming the base of the Upper Member of the Pamelia Formation. There are six localities (Locs. 16, 22, 34, 41, 43 & 44, Fig. 3.6) which provide continuous sections through the unit. The unit has a maximum thickness of about 3 m in the Ottawa region (Loc. 22), and thins eastward to about 1.2 m at Locality 47, near Cornwall (Fig. 3.14). At Locality 5 (near Westport), the unit is intensely

Fig. 3.13 Lithostratigraphic correlation of selected sections showing the Upper Member of the Pamelia Formation. The member is divided into four units (units III to VI). Unit III (also labelled as T-3) is dominated by sandstone. Other units are various limestone lithofacies, and each one is capped by sandy to pure dolostone beds (T-4 to T-6). The beds of T-5' are not laterally extensive. The base of Unit IV is taken as Datum. Horizontal distance is not in scale. See Fig. 3.8 for legend. Locations shown include: Loc. 20: Prince of Wales Falls, Ottawa; Loc. 34: Francon quarry - North, Blackburn Hamlet, Gloucester; Loc. 41: Russell well, Russell County, Loc. 44: Cruickshank quarry, Winchester; Loc. 47: Macleod quarry, Cornwall.


Loc. 20
Loc. 34
Loc. 41
Loc. 47
Loc. 44
Meter
20
15
10
5
0
T-6
T-5
T-5'
T-4
T-3
Lowville Formation
Unit VI
Unit V
Unit IV
Unit III
Upper Member
Lower Mb
Pamelia Formation

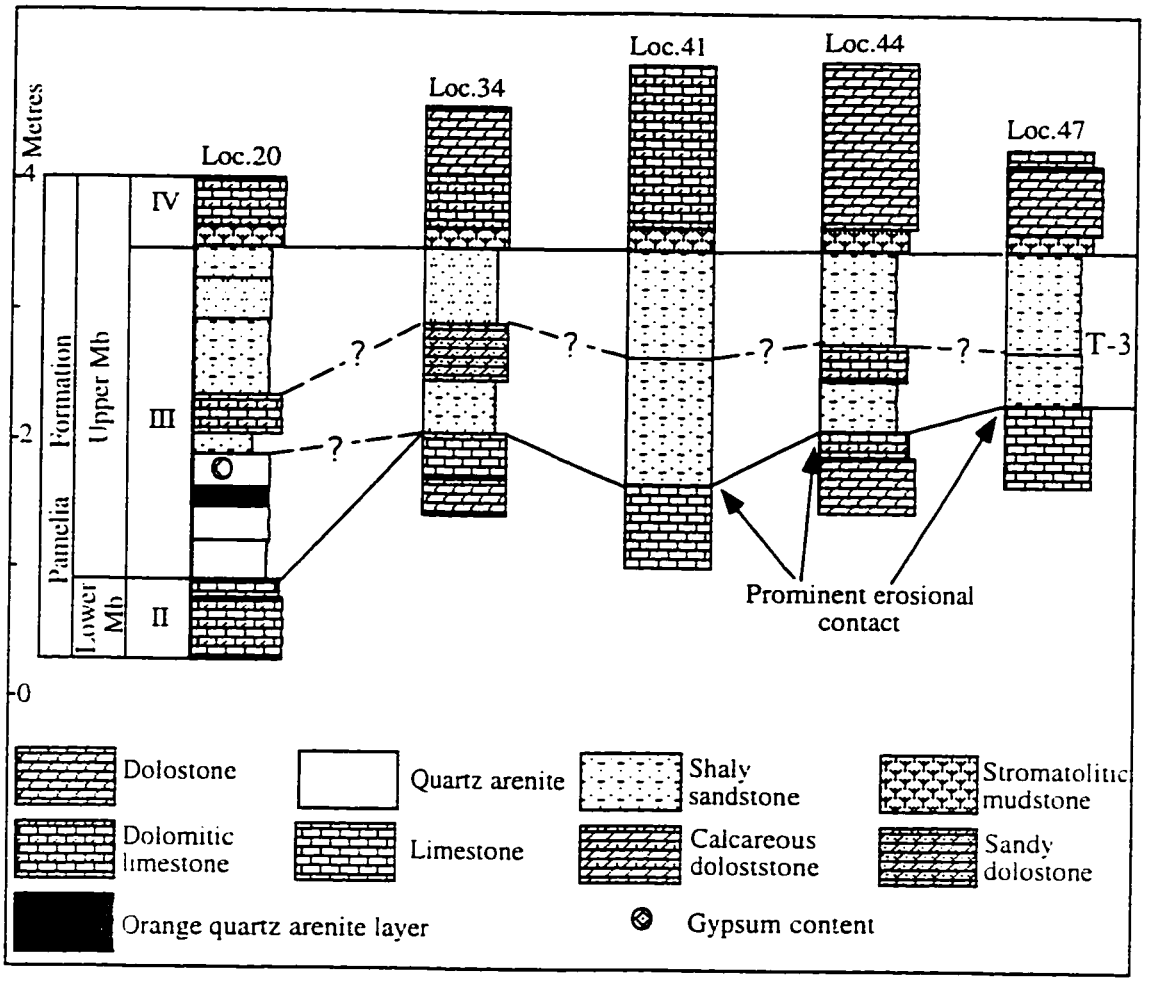


Fig. 3.14 Correlation of Unit III (the basal sandstone layer of the Upper Member of the Pamelia Fm) within the Ottawa Embayment. Note that a thin orange, quartz arenite layer lies within the unit at Locality 20. An erosional lower boundary for the unit is developed at eastern sections, and may correspond to the top of the gypsum-bearing bed above the orange layer (see the text for more discussion). See Fig. 3.6 for section names and locations.

weathered and poorly exposed, and its boundaries can not be satisfactorily mapped. It appears to have more carbonate interbeds compared to other localities in the Ottawa Embayment. The lower boundary, as discussed above, is defined by the erosional surface at the top of the underlying Unit II. The irregular erosional pattern of this surface (Fig. 3.10) suggests that beds just below the surface were well cemented and indurated prior to erosion and deposition of Unit III. Dolomitic limestone beds missing from the upper part of the Lower Member at locality 47 were probably removed during this erosional event. This suggests that there may have been development of an appreciable erosional vacuity before deposition of Unit III. The upper boundary of the unit is marked by an abrupt lithologic change from a lower dark green shaly sandstone to an overlying 15-cm-thick stromatolitic lime-mudstone, then followed by thick to medium beds of interbedded dolostone and limestone forming Unit IV (Fig. 3.14).

Unit III is lithologically dominated by laminated to thickly (<1 cm - 58 cm) bedded fine grained quartz wacke. A medium bed of sandy, dolomitic bioclastic mudstone to wackestone occurs in the middle of the unit at three localities (Fig. 3.14). In the Ottawa area, beds below the above-mentioned carbonate bed are dominated by thinly bedded quartz arenite lithofacies. Thin shale interbeds are also common in the unit, and become more abundant in eastern localities. The unit represents one of the six (dolomitic) sandstone and-or (sandy) dolostone intervals that characterize the Pamelia Formation, and is denoted as T-3 (Figs. 3.5 & 3.13). The sandstone and carbonate lithofacies are light greenish grey to medium green and weather to rusty yellowish green.

At one locality (Loc. 16) in the City of Ottawa, Unit III shows a distinct thin (17 cm thick) layer of orange-coloured, poorly sorted quartz arenite. Quartz grain-size distribution

is bimodal (coarser grains range from about 0.6 to 1 mm, and finer grains are about 0.1 mm in size), and grains are well-rounded with frosted surfaces. This sandstone layer is comparable with what Folk (1968) termed as "bimodal supermature sandstone"; sediment of aeolian origin, incorporated in shallow marine environment. Beds stratigraphically equivalent with this orange, quartz arenite layer, as well as the underlying beds of the lower part of the unit are missing at eastern and southeastern localities within the embayment (e.g., Locs. 34, 41, 44, & 47). The absence of the lower part of the unit from these localities is probably due to erosion which prevailed in these parts of the embayment, as manifested by the pronounced erosional contact between the unit and the underlying Unit II of the Lower Member of the Pamelia Formation. At Locality 47, the erosion appears to have been more intense than at any other studied locality. This is suggested not only by the missing lower part of Unit III but also a good portion of Unit II has been apparently eroded as well (Fig. 3.13).

In the Ottawa area (e.g., Loc. 16), the lower part of the unit (below the orange quartz arenite layer) is characterized by vertical (*Skolithos* sp.) burrows, gypsum (determined by X-ray diffraction), gypsum molds, and poorly developed (and deformed probably due to compaction) desiccation cracks. The upper part of the unit shows only vertical and horizontal (*Skolithos* sp. and *Planolites* sp., respectively) burrows. At other localities (Locs. 34, 41, 44, & 47), the unit is dominated by horizontal (*Planolites* sp.) burrows.

Fossils are generally rare in the unit. However, a few articulated and disarticulated ostracod carapaces, as well as broken bivalve and trilobite shells are recognized in thin section.

Unit IV

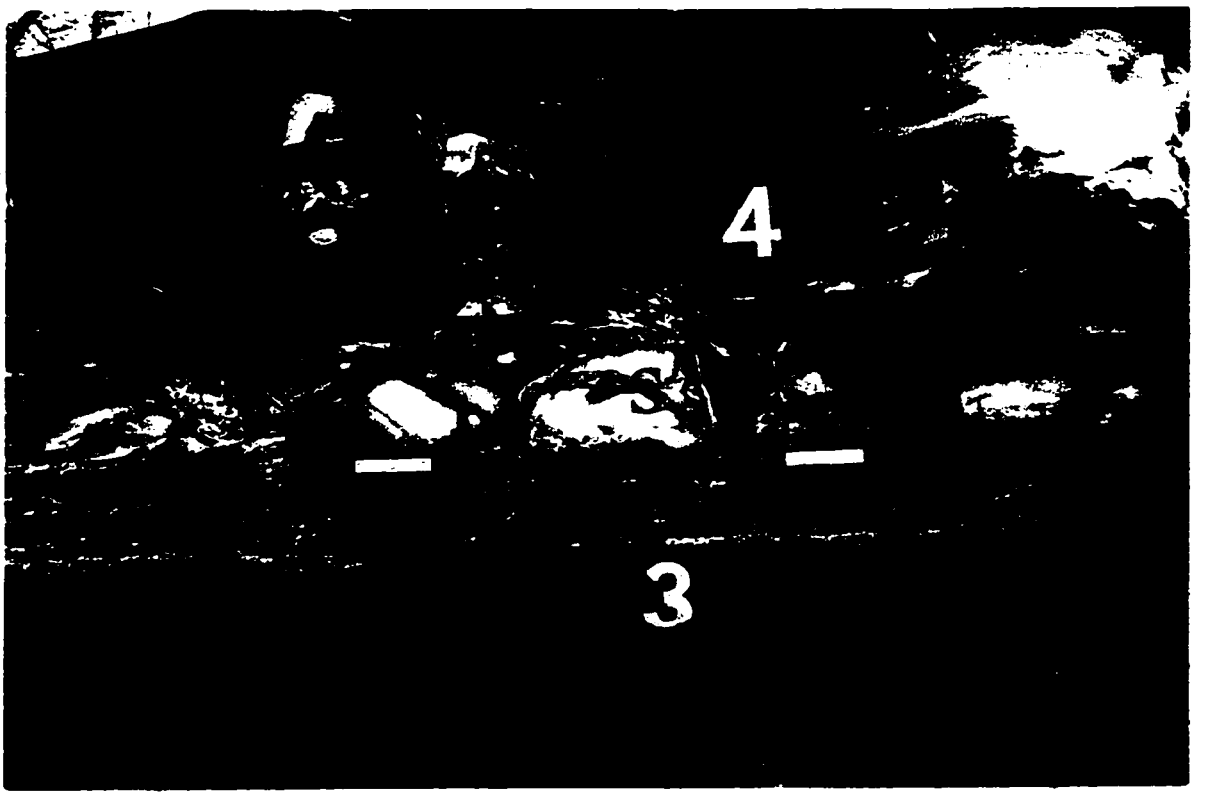
This unit has a maximum thickness of about 10 m in the Russell core (Loc. 41). It thins toward Ottawa (e.g., ~ 7.5 m at Riverside road-cut, Loc. 16) and Cornwall (e.g., ~ 5.8 m at Loc. 47) (Fig. 3.13). A stromatolitic mudstone bed (10 - 15 cm thick) occurs at the base of the unit (Fig 3.15). It is followed by medium to thick (15 - 95 cm thick) interbeds and-or interlaminae of intraclastic, peloidal, bioclastic mudstone to packstone, and fine crystalline, pure to sandy dolostone. The dolostone - limestone interbedding is well developed in localities southeast of Ottawa (e.g., Locs 44 & 47, Fig. 3.16), but in the Ottawa area (e.g., Locs. 16, 24, 34), the limestone becomes either slightly dolomitic showing irregular mottles of dolomite or is thinly interbedded to interlaminated with dolostone.

The upper half of Unit IV is exclusively formed by thickly bedded, fine crystalline pure to sandy dolostone (T-4, Fig. 3.13) with minor fine grained sandstone and shale interlaminae. These dolostone beds contain calcite and celestite nodules, subvertical (possibly *Psilonichnus* sp.) burrows, and mudcracks. The latter are well developed in the thin siltstone laminae interbedded with the thick dolostone beds. Petrographic analysis show that in many cases the vertical burrows contain more quartz grains than the rest of their host rock (see Chap. 4). Pyrite crystals are present throughout the dolostone beds. Fresh and weathered surfaces of the dolostone beds are medium greenish grey and buff whereas those of the mudstone and packstone beds are medium to dark brownish grey and light (bluish) grey, respectively.

Other common sedimentary structures in the unit include hardground surfaces with irregular boring, fenestral (birdseye) texture, thin shaly partings, stylolites, and thin microbial laminations. Bioclasts in the unit are concentrated in the limestone lithofacies and include

Fig. 3.15 Unit III (3) - Unit IV (4) contact (along horizontal bars) at Locality 44. The contact is characterized by a lithologic change from lower (locally shaly) quartzwacke arenite overlain by a 12 to 15 cm thick bed of stromatolitic lime-mudstone (s) in all localities. The stromatolitic bed is usually followed by interbedded limestone and dolostone lithofacies. The pencil is 15 cm long. Loc. 44: Cruickshank quarry, Winchester.

Fig. 3.16 The picture shows the upper part of Unit II (lower dark beds), all of Unit III (first light grey unit, s), and the lower part of Unit IV (everything above unit s). A stromatolitic bed at the base of Unit IV is developed here as thin, horizontal microbially laminated mudstone (m). Distinct peloidal and bioclastic mudstone to packstone (l) and dolostone (d) interbeds occur in the lower part of Unit IV. Horizontal field of view is about 10 m. Loc. 47: Macleod quarry, Cornwall.


4
3

m

heads of *Tetradium* corals, ostracods, bivalves, gastropods, trilobites, *Solenopora* algae, brachiopods and bryozoa (*Parasopora* sp). The dolostone beds locally contain rare ostracod carapaces and bivalve shells.

Unit V

Unit V has its maximum thickness of about 9.5 m at the Francon (northern) Quarry (Loc. 34) at the eastern outskirts of Ottawa. It thins both westward (e.g., ~ 6 m at Loc. 10) and eastward (e.g., 6.8 m at Loc. 47) from Ottawa (Fig. 3.13). The unit consists of interbedded peloidal, bioclastic wackestone and packstone, microbially laminated (< 1 cm) to thinly bedded (<5 cm) mudstone, thin to medium (~ 5 to 20) bedded bioclastic, intraclastic packstone to rudstone, and (locally) bryozoan bafflestone. Thinly laminated, dark brown to black shale is generally present in the unit but is most common in the upper part. About the lower two-thirds of the unit is characterized by repetitive subunits which consist of packstone and thinly laminated mudstone. The latter is locally associated with intraclastic packstone to rudstone lithofacies. Intraclasts are poorly sorted, and form mostly flat-pebble breccia (Fig. 3.17). The upper one-third of the unit is dominated by bryozoan bafflestone (Locs. 24 & 34) and bioclastic and-or oolitic packstone to grainstone (e.g., Locs 10, 16, 39, 47). Medium to thick (30 - 40 cm) calcareous shale is locally interbedded with these beds. Limestone in the unit at all localities has a medium (brownish) grey colour on its fresh surface and weathers to light (bluish) grey. Shale is black and weathers black to dark green.

The uppermost part of the unit contains dolomitic sandstone to sandy dolostone beds (T-5, Fig. 3.13) with (locally) thin mudstone interlaminae. The base of T-5 is marked by a prominent erosional surface at Locality 34 (Francon northern quarry, Blackburn Humlet,

Fig. 3.17 Thinly laminated intraclastic mudstone (a) interbedded with intraclastic (flat-pebble breccia) rudstone to floatstone (b) (Unit V). The breccia show little current- or wave-reworking, and appears to have resulted from desiccation cracks forming thin mudchips. Some desiccation cracks are still preserved (arrow) in the rock and define boundaries of the mudchip breccia. The coin is about 2 cm in diameter. Loc. 24: Scott Transitway, Ottawa.

Gloucester). This is followed by a quartz-rich carbonate paleosol layer with *in situ* brecciation (Plate 3.18a) resulting in "hybrid arenite" (*sensu* Zuffa 1980) (Locs. 10 & 34). The latter is succeeded by interbedded sandy dolostone and dolomitic mudstone. In other localities, the beds of T-5 are either dominated by dolomitic sandstone locally interbedded at the lower part with thinly interlaminated mudstone and quartz-rich packstone (Locs. 15 & 16) or sandy (with quartz grains up to 30%) dolostone (Locs. 41 & 47). At Locality 16, gypsum molds now filled by blocky calcite cement, occur in a thin mudstone layer (Fig. 3.18b). The beds of T-5 are usually greyish green on a fresh surfaces and weather to buff (dull orange) colour.

The unit is moderately fossiliferous, and recognized fossils include gastropods, bivalves, ostracods, *Tetradium* corals, serpulids, bryozoans and trilobites.

Birdseye texture due to fenestral fabric, flat to wavy microbial laminations, mudcracks, hardground surfaces, and stylolites are common sedimentary structures in the unit. Horizontal burrows are present in certain shale layers at the upper part of the unit. Pyrite crystals are locally abundant along horizontally burrowed surfaces filling burrows.

Unit VI

This unit shows minor thickness variation, 4.5 m average, with a maximum thickness of 5.5 m at Locality 16 (Ottawa) and minimum of 3.1 m at Locality 48 (near Cornwall). The upper boundary of the unit is the top of the Pamelia Formation, and the upper surface of a sandy dolostone interval (T-6, Figs. 3.5, 3.13). This sandy dolostone is the last occurrence of the six dolomitic sandstone and sandy to pure dolostone intervals (T-1 to T-6) that occur in the Pamelia Formation. It weathers to buff green. The beds of T-6 have an average

Fig. 3.18a Thin section photomicrograph from a paleosol layer at the top of Unit V. The section is dominated by intraclasts (dark grains) resulted from *in situ* brecciation (arrow), and detrital quartz grains (q). Scale bar is 770 μm. Loc. 34: Francon quarry - North, Blackburn Hamlet, Gloucester.

Fig. 3.18b Thin section photomicrograph from mudstone with evaporite molds now filled by calcite (Unit V). The sample represented by this photo is from a layer correlative with the paleosol bed mentioned in Fig. 3.18a. The upper part of the picture shows laminated calcareous sandstone (comparable with the hybrid arenite of Zuffa 1980); a lithofacies often seen in this stratigraphic interval. Scale bar is 1160 μm. Loc. 16: Riverside Dr., Ottawa.

a

thickness of about 1 metre and range from 65 cm to 180 cm.

Unit VI consists of interbedded intraclastic, bioclastic, oolitic packstone and grainstone, and bioclastic mudstone and wackestone. The packstone and grainstone generally dominate the lower part of the unit and grade up into mudstone to wackestone lithofacies. These limestone beds show a dark (locally brownish) grey colour on their fresh surfaces, and weather to dark to medium grey. Intraclasts in the packstone lithofacies are made up of grey lime mudstone which weathers to light grey and-or greenish dolo-mudstone which weathers to dull orange. Thin interbeds to interlaminae of black (sometimes dark green) shale are present throughout the unit.

Packstone and grainstone lithofacies in this unit contain cross-lamination, scour surfaces, stylolites, normal grading, and wave and current ripple marks. Mudstone and wackestone, and (to some extent) the sandy dolostone, possess microbial laminations. Other sedimentary structures in the unit include "birdseye texture" due to calcite precipitation in bivalve-sheltered pores (mostly in the oolitic packstone and grainstone), scour surfaces, vertical and horizontal burrows, irregular shaly partings and mudcracks.

The unit is moderately fossiliferous, and fossils include bivalves (*Cyrtodonta* sp.), gastropods, *Solenopora*, trilobites, serpulids, ostracods, orthocones and bryozoans. These fossils are generally fragmented and abraded. Certain shells are filled by dark-coloured micrite that differs from the micrite-matrix of the packstone facies.

Lowville Formation

Origin

Clarke and Schuchert (1899) initially proposed the Lowville Limestone as a time-stratigraphic term for what earlier workers (e.g. Emmons 1840) called "Birdseye limestone". Cushing (1908) and Cushing et al. (1910) have described the Lowville formation from a lithostratigraphic basis. Cushing et al's (1910) Lowville formation consists of two members: Lowville limestone and Leray limestone. The former consists of dove-grey, fine-grained limestone intercalated with subcrystalline dark to black limestone, oolitic limestone, and-or white-weathered shaly limestone. The Leray limestone overlies the Lowville Limestone member, and consists of "dark grey to black, heavily bedded, dove limestone, with layers of black chert nodules" (p. 86). Cushing et al. (1910) noted that the two members were separated by an unconformity. Kay (1929) proposed that the Leray Limestone is lithologically more related to the Chaumont Formation rather than Lowville Formation. Thus, the Lowville Formation, as revised by Kay (1929), is restricted to the lower member (Lowville limestone) of Cushing et al's (1910) original definition. This redefinition is widely accepted by subsequent researchers (e.g., Kay 1937; Young 1943a; Fisher 1957; Textoris 1968; Ross 1970; Walker 1972; 1973).

Lithostratigraphy

In the Ottawa Embayment, the Lowville Formation conformably overlies the Pamelia Formation and is overlain by the Chaumont Formation. The Lowville Formation is exposed in 23 sections, of which 14 display complete successions (Fig. 3.6). The formation has an

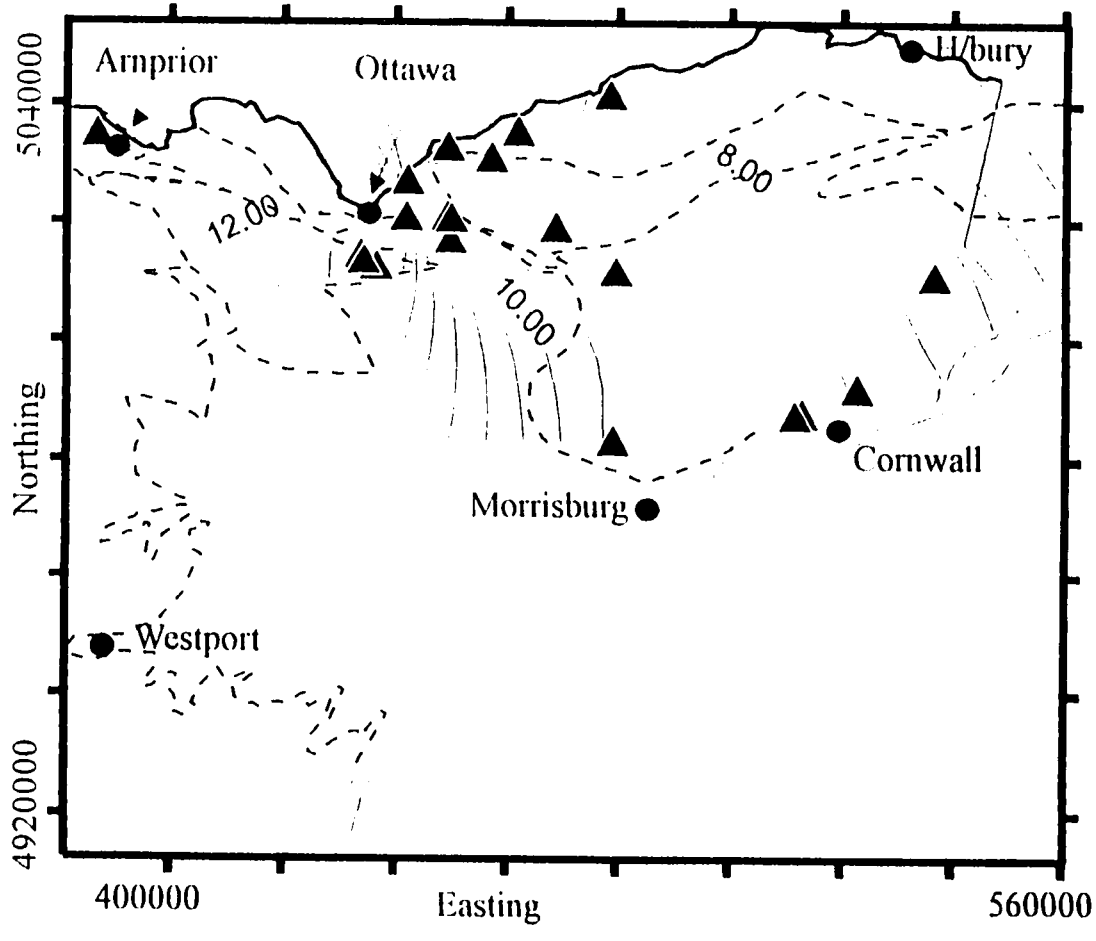
average thickness of 10 metres, and generally thins eastward, northward and westward from the Ottawa area (Fig. 3.19).

The lower boundary of the formation is marked by the occurrence of any of the several Lowville lithofacies units (see below) overlying the thick sandy dolostone bed(s) that cap(s) the Pamelia Formation. However, intraclastic, bioclastic and-or oolitic packstone and grainstone usually form the basal part of the Lowville Formation. The upper boundary of the formation is characterized by a paraconformable to disconformable surface. The highest beds of the formation are either truncated (Fig. 3.20a) or show a rubbly texture (Fig. 3.20b) that suggests erosional and-or hardground development (Salad Hersi & Dix 1994). The boundary also describes a sharp lithologic change from thin to medium beds of any of the Lowville lithofacies units (usually dove-grey *Tetradium*-rich mudstone, wackestone to local bafflestone) to very thick-bedded, intensively burrowed, fine-grained bioclastic, peloidal mudstone to packstone of the Chaumont Formation (Fig. 3.20c).

The Lowville Formation is lithologically complex and can be grouped into two broad categories: (1) a grainy lithofacies, that accumulated under highly agitated environments (sand shoals); and, (2) a muddy lithofacies, that accumulated under relatively lower energy environments (calm inter-shoal depressions and lagoons). Unlike the Pamelia Formation, the Lowville Formation is apparently free of sandstone and dolomite beds. However, sand- to silt- size, subangular to subrounded quartz grains as well as isolated dolomite rhombohedral crystals (Dolomite II and Dolomite III generations, see Chap. 6) are present locally, and recognized in thin section. Thinly bedded to laminated black shale is common throughout the formation.

The grainy lithofacies is characterized by fine to coarse grained, medium to dark

Fig. 3.19 Isopach map showing thickness variation of the Lowville formation with the Ottawa Embayment. The formation is its maximum thickness to the south of Ottawa and decreases eastward. Data from the Montreal are (Harland and Pickerill 1982) have been used also for the reconstruction of this isopach map. The Lowville Formation thins to about 5 m in the Montreal region. Contour intervals are in metres. Dashed lines are geologic boundaries (see Fig. 1.1 for details).


Arnprior
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Cornwall
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Northing
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Easting
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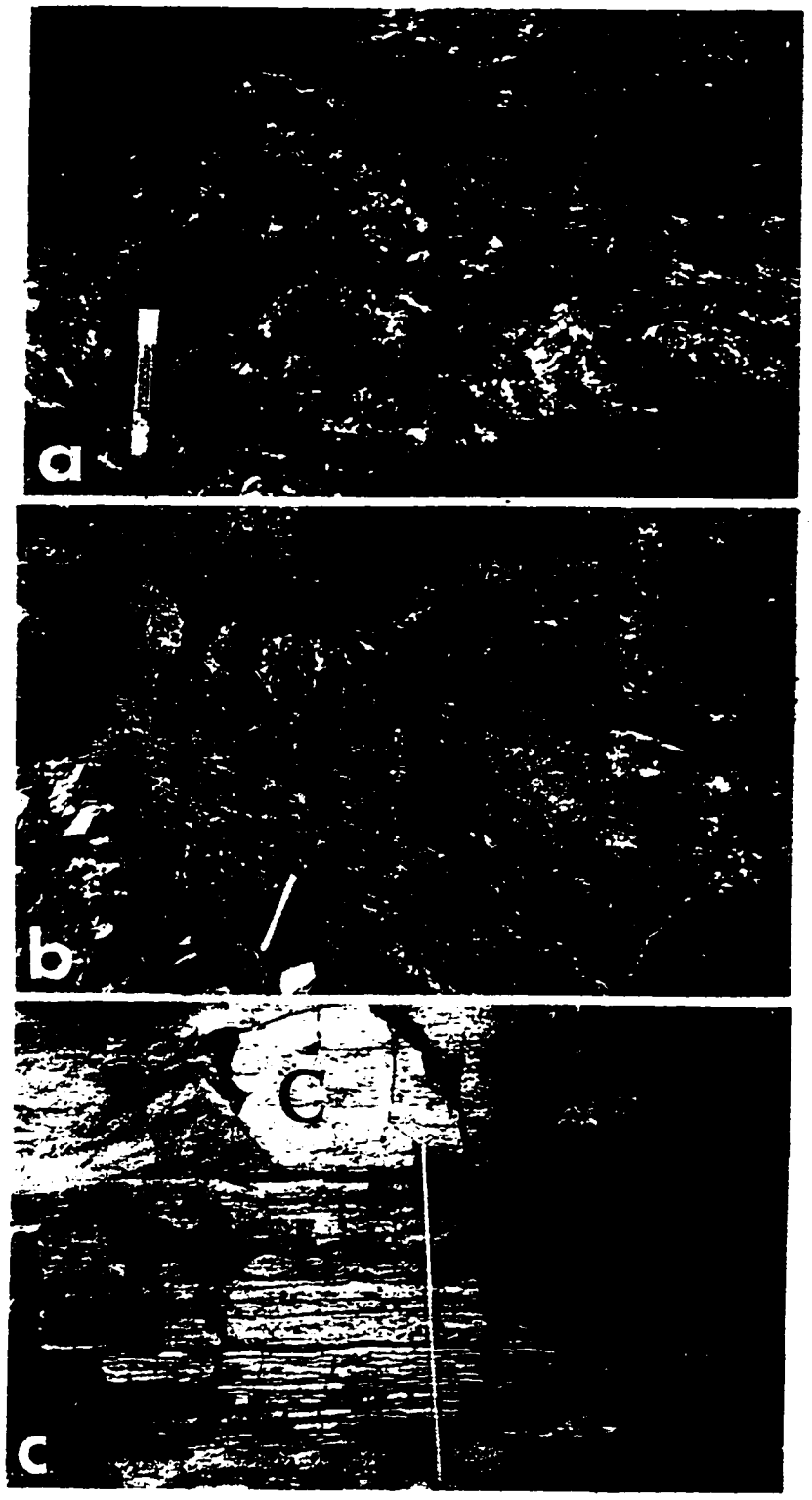
Fig. 3.20a Lowville (L) - Chaumont (C) contact (arrows) defined by an erosional surface. Note the truncation of the Tetradium corals. The marker pen is 14 cm long. Loc. 43: St. Albert Station quarry, Finch Township, Stormont County.

Fig. 3.20b Lowville (L) - Chaumont (C) contact (arrows) defined by Lowville beds with rubbly texture overlain by thick beds of the Chaumont Formation. Hammer is 25 cm long. Loc. 46: Cornwall quarry, Cornwall.

Fig. 3.20c Lowville (L) - Chaumont (C) contact (arrows) defined by sharp, planar contact with no obvious erosional or rubbly texture. Measuring stick is 1.2 m Long. Loc. 15: Farzer Duntile quarry, Ottawa.


a
b
c

brownish grey, intraclastic, bioclastic, peloidal and oolitic packstone to grainstone. The facies weathers light to medium brownish grey. Bioclast composition is dominated by bivalves, bryozoans and trilobites. Gastropods, serpulids, crinoids, *Tetradium* corals, *Solenopora* algae, ostracods and orthocones are also found. All shell material is reworked and usually abraded. Fine-sand to pebble-size intraclasts of mudstone or dolostone origin are often present. Beds are commonly medium thick (15 cm average) but range from thin (2 cm) to thick (45 cm). Tabular cross bedding and laminations, wave and current ripple marks, scoured surfaces, stylolites, normal grading, birdseye texture (due to calcite precipitation in bivalve-sheltered pores), overturned *Tetradium* heads, lenticular bedding (Fig. 3.21), and shaly partings are common sedimentary structures. Bioclastic, peloidal mudstone to packstone mounds and lenses are locally abundant within the grainy lithofacies.

The muddy lithofacies unit consists of light to medium (brownish) grey bioclastic (peloidal) wackestone, floatstone to bafflestone, and mudstone. The facies weathers light (somewhat bluish) grey. It is equivalent to the dove grey "lithographic to sublithographic limestone" of previous workers (e.g., Wilson 1946; Kay 1942; Steele-Petrovich 1984). *Tetradium* corals, both *in situ* and as broken fragments, are the dominant fossils. Other bioclasts include, in volumetrically decreasing importance; bryozoans, bivalves, trilobites *Solenopora*, ostracods, orthocones, crinoids, gastropods and serpulid worm tubes. Thin beds (<10 cm) are predominant within the muddy lithofacies, but medium beds (10-30 cm) are also common. Thick beds (up to 70 cm) are rare. Sedimentary structures include common shaly partings, planar to wavy bed contacts, rubbly texture, horizontal burrows (*Planolites* ichnofacies) and subvertical calcite tubes (*Phytopsis tubulosa* of Raymond 1931). The latter developed from molds of *Tetradium* corals subsequently refilled by calcite spar.

Fig. 3.21 The Lowville Formation is characterized by oolitic and bioclastic packstone and grainstone interbedded with bioclastic (mostly *Tetradium* corals) mudstone to bafflestone. This picture (Loc. 48) shows thin to medium beds of the packstone - grainstone lithofacies with overturned *Tetradium* corals (c), lenticular bedding (arrow), and small bioclastic, peloidal packstone mounds (m). Note that beds of packstone - grainstone facies drape the mounds as well as the overturned coral colony. Thin shale interlaminae are also present. The field note-book is 18.5 cm long. Loc. 43: St. Albert Station quarry, Finch Township, Stormont County.

The two dominant lithofacies units in the Lowville Formation are often interbedded, and show preferential stacking from the grainy lithofacies to the muddy lithofacies (see Chap. 5). However, the grainy lithofacies dominates in about the lower two-third of the formation whereas the muddy lithologic unit becomes dominant in the upper one-third.

Chaumont Formation

Origin

The Chaumont Formation was initially proposed by Kay (1929) from rock exposures at the Chaumont Bay, Jefferson County, New York State. The unit includes "beds younger than Lowville and older than Rockland" (Kay 1929, p. 664). Kay's Chaumont Formation contained three members which are, in ascending order: Leray, Glenburnie, and Watertown members. The Leray Member has its type section at the Township of Leray, Jefferson County New York State, and consists of thickly bedded, fine-grained, cherty limestone. The Glenburnie Member, which has its type section at a locality near the village of Glenburnie, Kingston Township, Frontenac County, Ontario, consists of very fossiliferous, shaly limestone, about 70 cm thick. The Watertown Member has its type section near the village of Watertown, Jefferson County, New York State, and consists of thickly bedded fine- to medium-grained limestone. The Watertown limestone was originally proposed by Cushing et al. (1910) for a 13-foot (~ 4 m)-thick, massive limestone that overlies their Leray limestone (or their upper member of the Lowville Formation). It contained a lower 6-foot ledge of thickly bedded fine- to medium-grained limestone overlain by a 7-foot ledge of similar lithology. The latter was commonly known as "the seven-tier" by quarry operators

(for more details see Cushing et al. 1910; Young 1943b).

Kay (1929) later recognized that the Leray limestone of Cushing et al. (1910) was lithologically more related with the Watertown limestone than with the Lowville lithology, but the two are locally separated by the Glenburnie shaly limestone. Therefore, Kay (1929) combined the three units under the same name, Chaumont Formation. The Glenburnie Member is not recognized outside of its type area, and the other two members form the bulk of the formation. Where the Glenburnie shaly limestone is absent, the Leray and the Watertown members are not distinguishable lithologically. In fact, Young (1943b) acknowledges that, "When many sections of the upper Black River beds have been studied, the value of the term "Chaumont" becomes apparent" (p. 210).

Lithostratigraphy

In the Ottawa Embayment, the Chaumont Formation disconformably overlies the Lowville Formation (Salad Hersi and Dix 1994) and underlies Trentonian strata, referred to here as the Bobcaygeon Formation. Twenty-one localities offer partial to complete sections through the formation (Fig. 3.6). The formation has its maximum thickness (about 20.5 m) in the Russell core (Loc. 41), and thins both eastward and westward from that locality (Figs. 3.22, 3.23) with a minimum thickness of 2.3 m at Locality 1 (Braeside quarry, ~ 50 km west of Ottawa, see Appendix 1, section 1).

The lower boundary of the formation is placed at the base of thickly bedded limestone which succeeds the relatively thinner beds of the Lowville Formation (Fig. 3.20c). This boundary has been already described in the Lowville Formation section. The upper boundary of the Chaumont Formation is defined by an interbedding nature with the overlying

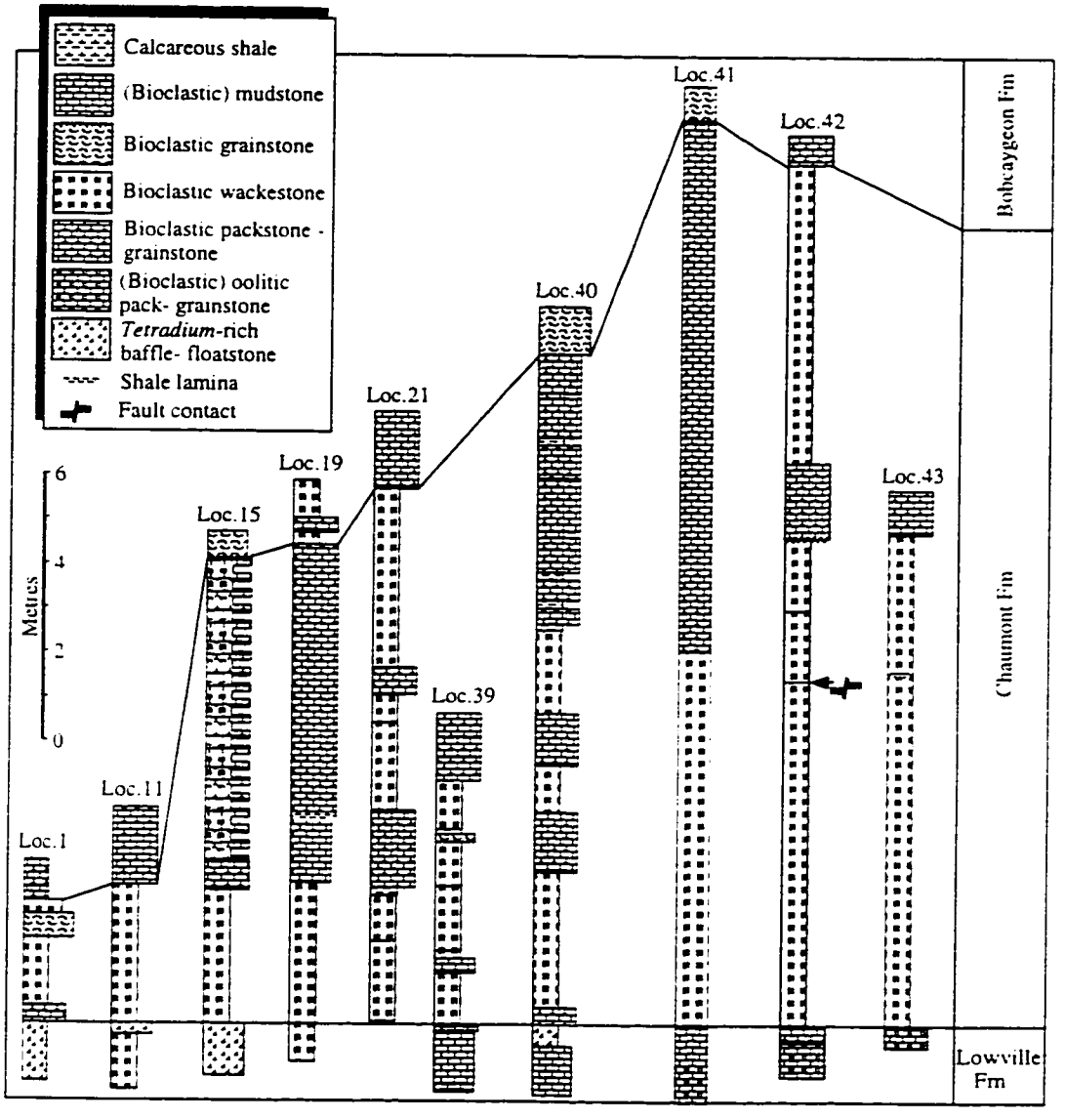


Fig. 3.22 Correlation of the Chaumont Formation within the Ottawa Embayment. Note that the thickness of the formation changes significantly southeastward (i.e., to the right). See Figs. 1.1, 1.6, and 3.6 for section names and locations.

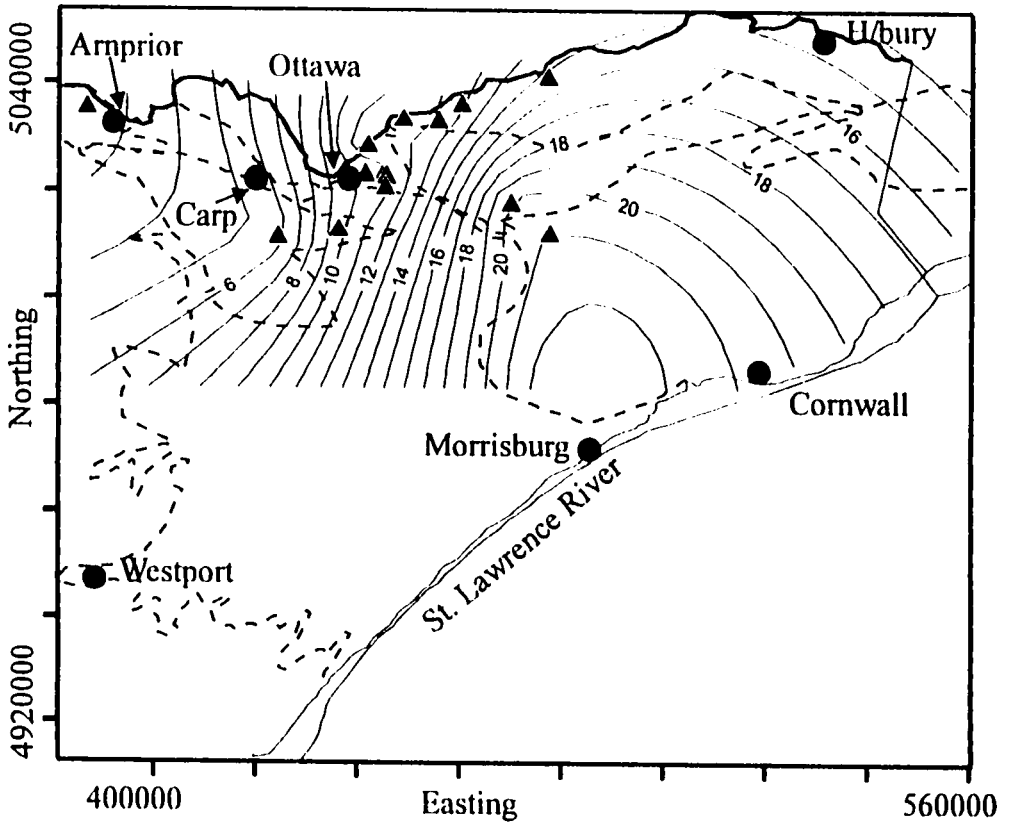


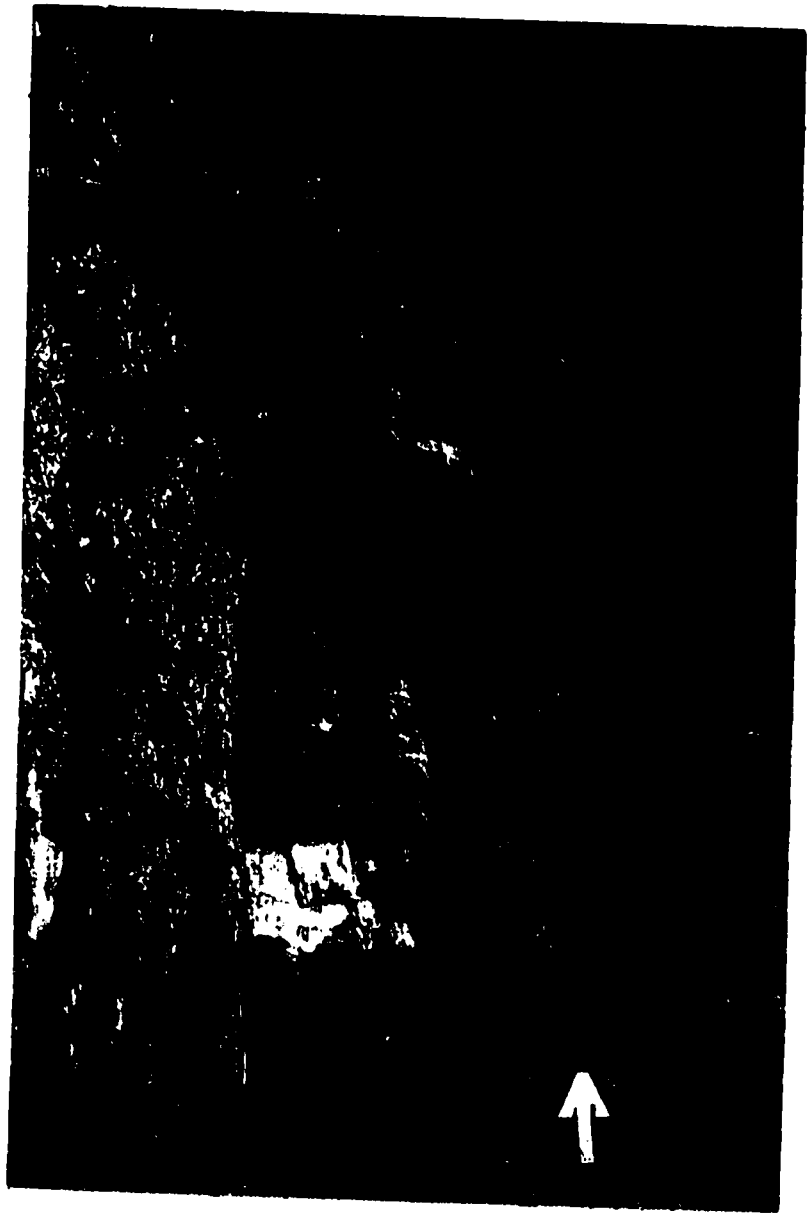
Fig. 3.23 Isopach map showing thickness variation of the Chaumont Formation within the Ottawa Embayment. The formation is characterized by a pronounced thicknening east of Ottawa. Note the potential general NE-SW trend of increased thickness. Contour intervals are in metres. Dashed lines are geologic boundaries (see Fig. 1.1 for details).

Bobcaygeon Formation. The contact between the two formations is arbitrarily put at the top of the highest, thick, burrow-mottled, bioclastic, peloidal wackestone to packstone of the Chaumont Formation succeeded by medium to thinly bedded, coarse to medium grained, bioclastic grainstone to packstone of the Bobcaygeon Formation. Bioclastic grainstone facies may locally occur within the Chaumont Formation (see below) but is not volumetrically significant.

The Chaumont Formation is lithologically dominated by medium to very thick (20 to >100 cm, mostly thick, Fig. 3.24), medium to dark brownish grey, fine- to medium-grained bioclastic mudstone, wackestone and packstone. The very thick beds (> 1 m) generally dominate the lower part of the formation. Grain size of bioclasts tends to increase westward from Ottawa area to Braeside (Loc. 1) as well as upward from the base of the formation. Increase in grain size to the west is accompanied by a gradual decrease in matrix (fine-grained wackestone and packstone in the Ottawa area grades to medium- to coarse-grained packstone and grainstone facies in western localities, e.g., Locs. 1, 8, and 11), and increased abundance of high-energy sedimentary structures. This lateral change produces a substantial lithologic change such that the unique Chaumont lithology, typical to the east, is no longer recognized (e.g., Locs. 1, 8, 9 & 11). These coarse-grained sediments occurring in western localities were also recognized by Barnes (1964; 1967, Calcarenite shoal facies) as well as Williams (1991, Unit B of his lower member of the Bobcaygeon Fm). My work places these beds into the lower part of a revised Bobcaygeon Formation (see Chap. 7).

Two other minor lithologies of the Chaumont Formation include calcareous shale to shaly wackestone, and coarse-grained bioclastic grainstone to rudstone. The calcareous shale is thinly bedded (1 to 7 cm) with few (mostly brachiopod) fossils. The shaly wackestone is

Fig. 3.24 Thickly-bedded, bioclastic, peloidal wackestone to packstone of the Chaumont Formation. Barnes's (1964; 1967) Chaumont - Rockland contact, which corresponds to the Blackriveran - Trentonian (Rocklandian Stage) boundary is shown by the arrow. Horizontal field of view is about 13.5 m. Loc. 40: Rockland quarry, Rockland, Clarence Township, Russell County.



usually medium bedded (12 to 15 cm thick, e.g., Loc. 40). Bioclastic grainstone to rudstone beds are characterized by local concentrations of coarse-grained shells (mostly brachiopods and crinoids) and minor intraclasts. These beds are generally thin to medium (10 - 15 cm) thickness, but may locally be as much as 55 cm thick (e.g., Loc. 1). The calcareous shale to shaly wackestone, and grainstone to rudstone lithologies form rare interbeds within the above-mentioned predominant lithology of the formation. These minor lithofacies occur in few sections and cannot be mapped from one outcrop to another.

Thin (< 1 cm) irregular shaly partings are common throughout the formation. Where the thick beds of the formation are weathered, they flake along these shaly partings, and form thinner (3 - 30 cm thick) irregular beds. Unlike its equivalent in upstate New York and south-eastern Ontario (Young 1943b), the Chaumont Formation in the Ottawa Embayment seldom contains chert nodules. However, silicified bioclasts and authigenic quartz crystals are seen in thin section.

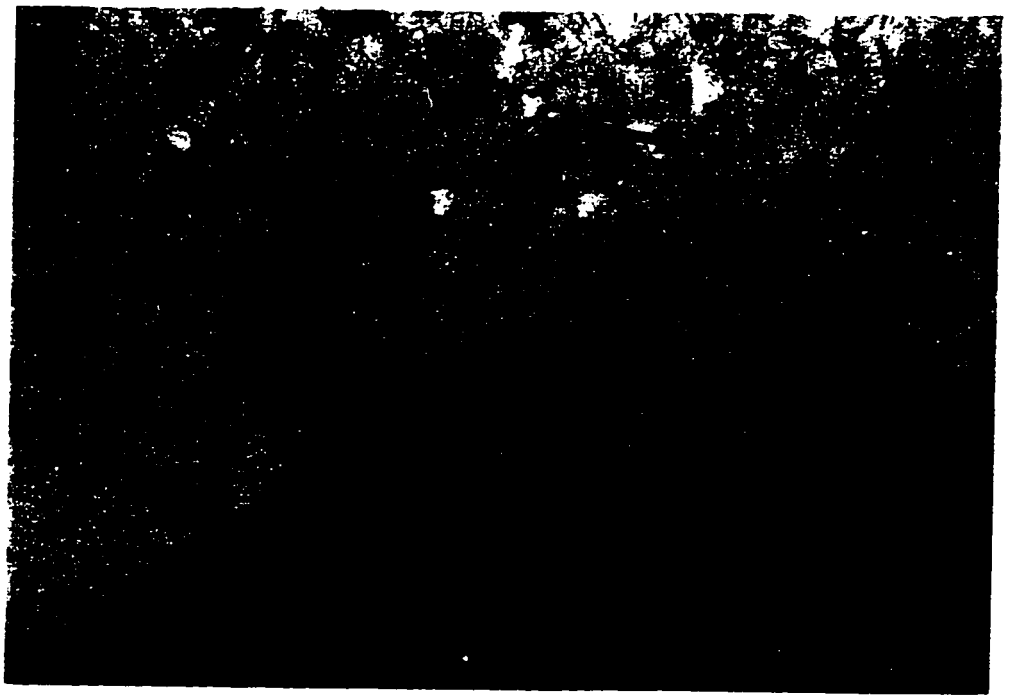
Horizontal and dendroid burrows, stylolites and hardground surfaces are common in the formation. Burrow-fills are sometimes dolomitized, and give the formation a mottled appearance (Fig. 3.25). Cross laminations are locally present in bioclastic packstone. This lithology contains less burrows than the mudstone and wackestone lithofacies.

Lithostratigraphic correlations of the Blackriveran strata

Previous work within the Ottawa Embayment

Raymond (1914) subdivided the Blackriveran succession in the Ottawa Valley using faunal zonation, and applied the Pamelia, Lowville and Leray formations. Raymond's

Fig. 3.25 The Chaumont Formation is characterized by thickly bedded, highly burrowed bioclastic, peloidal wackestone to packstone. The burrows give a mottled appearance to the formation. Black chert (which is abundant in equivalent beds in upstate New York) is rarely present (arrow) in the formation. The picture is taken from near the base of the formatiion. The pencil is about 14 cm long. Loc. 19: McArthy road (at Walkley), Ottawa.



Pamelia formation contains a 33.5 m (115 ft) thick succession which overlies upper Chazyan rocks and underlies a 4.5-metre (15 ft) thick, *Tetradium*-bearing Lowville "Formation". It appears that Raymond's Lowville correlates with the upper, fine grained, bioclastic (mostly *Tetradium* corals), mudstone to bafflestone of the Lowville Formation of my study. The Lowville - Leray boundary of Raymond (1914) is correlative with my Lowville - Chaumont contact.

Wilson (1932) gave Pamelia a member status within the Black River Formation and placed its lower boundary arbitrarily within three or four feet above Chazyan rocks bearing the brachiopod *Rostricellula plena* (previously known as *Camarotoechia plena* Hall). This biostratigraphically defined boundary lies within the upper Hog's Back Formation (see Chap. 2). Wilson's (1932) Pamelia - Lowville boundary is also arbitrarily placed at the base of "the first bed of the fine-grained lithographic limestone which shows *Tetradium* producing the birdseye effect characteristic of the Lowville" (p. 137). Calcite replacement of *Tetradium* corals is probably what Wilson (1932) refers to as "birdseye". The first beds which show this "birdseye" character occur at the lower part of Unit IV (in the Ottawa area) of the Pamelia Formation. Therefore, Wilson's Lowville Formation is probably correlative with units IV, V, and VI of the Pamelia Formation and the Lowville Formation of my study. This is supported by the fact that Wilson (1932) notes that, above the Pamelia - Lowville contact, "there are one or two layers of the more impure limestone which still retain the small dolomitic inclusions, but they soon disappear and the *Tetradium cellulosum* beds predominate" (p. 137). It can be inferred from this statement that Wilson's (1932) Lowville rocks include dolomitic limestone that may correspond to the dolostone and dolomitic limestone intervals in the Upper Member of the Pamelia Formation. Her *Tetradium*-

dominated beds may correspond to the Lowville Formation of my study.

Barnes (1964, 1967) examined the stratigraphy of the Blackriveran and lower Trentonian strata in the Ottawa Valley. He adopted Wilson's (1932) boundaries of Pamelia and Lowville formations. Barnes (1964, 1967) presented a detailed study of the Chaumont Formation. His work is based on both lithofacies and conodont analysis of the Chaumont and lower Rockland formations. Barnes's (1964, 1967) Chaumont - Rockland boundary is based either on lithologic changes (localities west of Carp) or on conodont faunal changes (localities east of Carp). In the area east of Carp, Barnes (1967) defined the Chaumont - Rockland boundary to occur between beds carrying "Chaumont" conodont fauna and beds carrying "Rockland" conodont fauna (p. 235, his Fig. 14). Barnes's (1964, 1967) Chaumont Formation contains two facies. In the area east of Carp (~ 30 km west of Ottawa, Fig. 1.1), his Chaumont Formation consists of thickly bedded, highly burrowed, bioclastic peloidal wackestone to packstone (poorly washed fossiliferous pelmicrite) with irregular, interlacing shale partings. Barnes (1964; 1967) calls this lithology "Ottawa type calcarenites". These calcarenites thin westward from Carp and are commonly overlain by cross stratified, coarser grained bioclastic packstone to grainstone that Barnes calls "calcirudite shoal facies" of the Rockland Formation. Barnes (1967) states that, "When traced eastward, the calcirudites (of the Rockland Formation) wedge out in the vicinity of Carp and the *entire* (Rockland) formation is then "Ottawa type" calcarenites which are *similar* to those of the underlying Chaumont" (p. 215, italics and words in brackets are mine). Due to these lithologic similarities in the region east of Carp, Barnes (1967) suggests, "that the Chaumont and Rockland should be best regarded as members of one formation" (p. 212).

The Chaumont Formation, as defined in my work, is correlative *only* with Barnes'

"Ottawa type calcarenites". This implies that my Chaumont correlates with Barnes' Chaumont Formation in his western localities but to the east (or east of Carp), my definition of Chaumont contains Barnes' Chaumont *and* lower Rockland formations (Fig. 3.26). Using Barnes conodont data, my correlation suggests that the Chaumont Formation is diachronous at its upper boundary; the Blackriveran - Rocklandian boundary occurs within the Chaumont Formation in the eastern localities (e.g., Loc. 40, the well known Stewart quarry), whereas in western localities (west of Carp), the boundary may lie above the Chaumont Formation (Fig. 3.26).

Sawford (1972) divided the Blackriveran to lower Trentonian strata in the Ottawa Valley into five informal units, in ascending order, I to V. The lowest unit (I) unconformably overlies the Rockcliffe Formation, and consists of two facies: (1) basal terrigenous clastics; and, (2) dolomitic mudstone and intraclastic (?lime) mudstone (dolomitic micrite and intramicrite) which overly the former lithology. Minor oolitic grainstone and domal stromatolites also occur near the base of the unit. Units II and III of Sawford (1972) consist of bioclastic (including bivalves, serpulids and *Tetradium* corals) packstone, and oolitic limestone. These are followed by unit IV which contains bioclastic and peloidal mudstone and-or wackestone (fossiliferous micrites and pelmicrites). The highest unit V consists of peloidal, intraclastic, bioclastic grainstone. Sawford (1972) equated his Unit I with the Pamelia Formation; units II and III with the Lowville Formation; Unit IV with the Chaumont Formation of the New York region; and, Unit V with the lower part of the Bobcaygeon Formation of the Lake Simcoe region. Correlation of Sawford's subdivision with my work is shown in Figure 3.27.

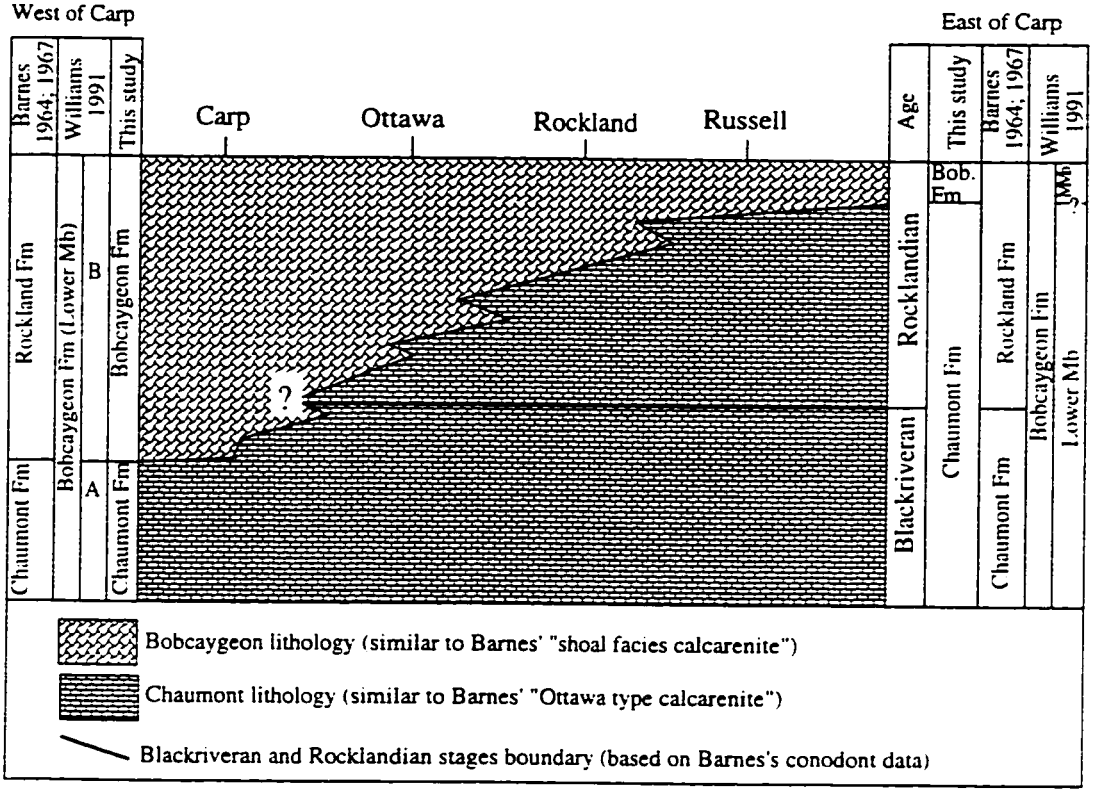


Fig. 3.26 Chaumont - Bobcaygeon relationship as defined in this study, and correlations with previous work of Barnes (1964; 1967) and Williams 1991).

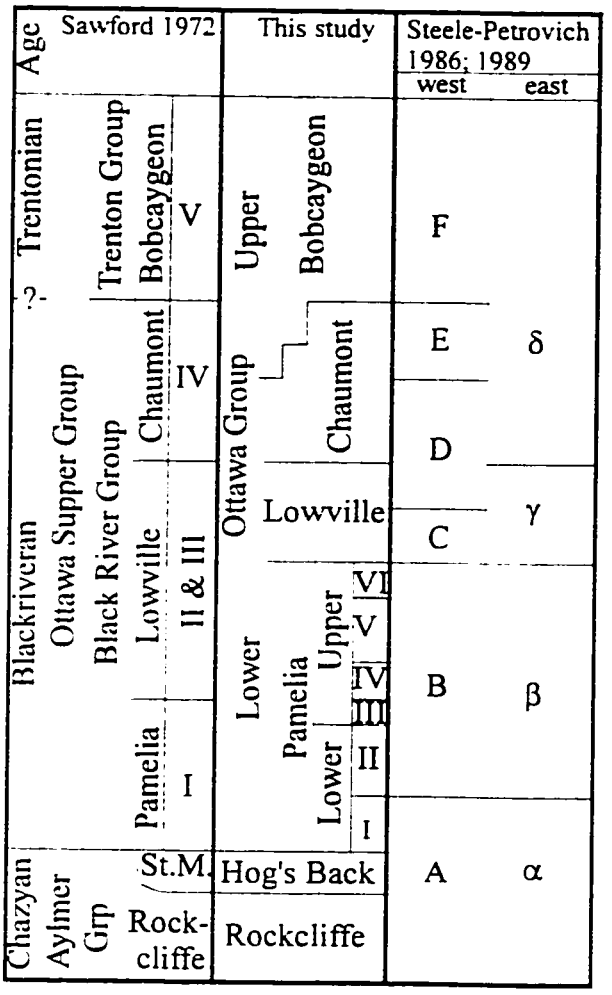


Fig. 3.27 Chart showing correlation of my study with th4e work of Sawford (1972) and Steele-Petrovich (1986, 1989).

Steele-Petrovich (1984; 1986; 1989) studied stratigraphic attributes of the Blackriveran and lower Trentonian succession in the Ottawa Valley. She reported that lithologic variations occur within the Blackriveran - Trentonian succession in the Ottawa Valley, and proposed different informal lithologic units for strata occurring west and east of the Ottawa City. Her proposed units and their correlation with my work are shown in Figure 3.27. Steele-Petrovich (1989) suggests that the St. Martin "formation" is absent at the Transitway section in Ottawa (Loc. 24 of my work), and indicates that the Rockcliffe Formation (her Unit α) is directly overlain by the Pamelia Formation (her Unit β). This interpretation is also supported by Donaldson (1985) as well as Boggs (1989). My work recognizes that the siliciclastic beds beneath the stromatolitic limestone at that locality, which Steele-Petrovich recognizes as Rockcliffe Formation, are the uppermost dolomitic sandstone (T-1) of Unit I of the Pamelia Formation. In addition, sections from Torbolton and Fitzroy areas (~ 40 km west of Ottawa) redrawn from Wilson (1924) and correlated with sections in the Ottawa area (Fig. 3.28) suggest lateral facies changes but, nonetheless, successive deposition from Rockcliffe through Hog's Back to Pamelia formations. Although the correlation appears to be straight forward (e.g., three stromatolitic layers present in correlative intervals in the Pamelia Formation at the sections from both localities), Wilson (1924) reports Chazyan fossils (*Rostricellula* sp.) in what appears to be Pamelia strata. Unless these fossils are misidentified or reworked into the Pamelia Formation, two problems arise from the correlation shown in Figure 3.28: (1) the section at Torbolton is Chazyan and, therefore, the stratigraphy of the Chazy strata in the region should be reconsidered; or (2) the Pamelia Formation is diachronous and becomes older westward from Ottawa (Dix et al. 1997a). But if the fossils are misidentified or reworked into the Pamelia Formation, the

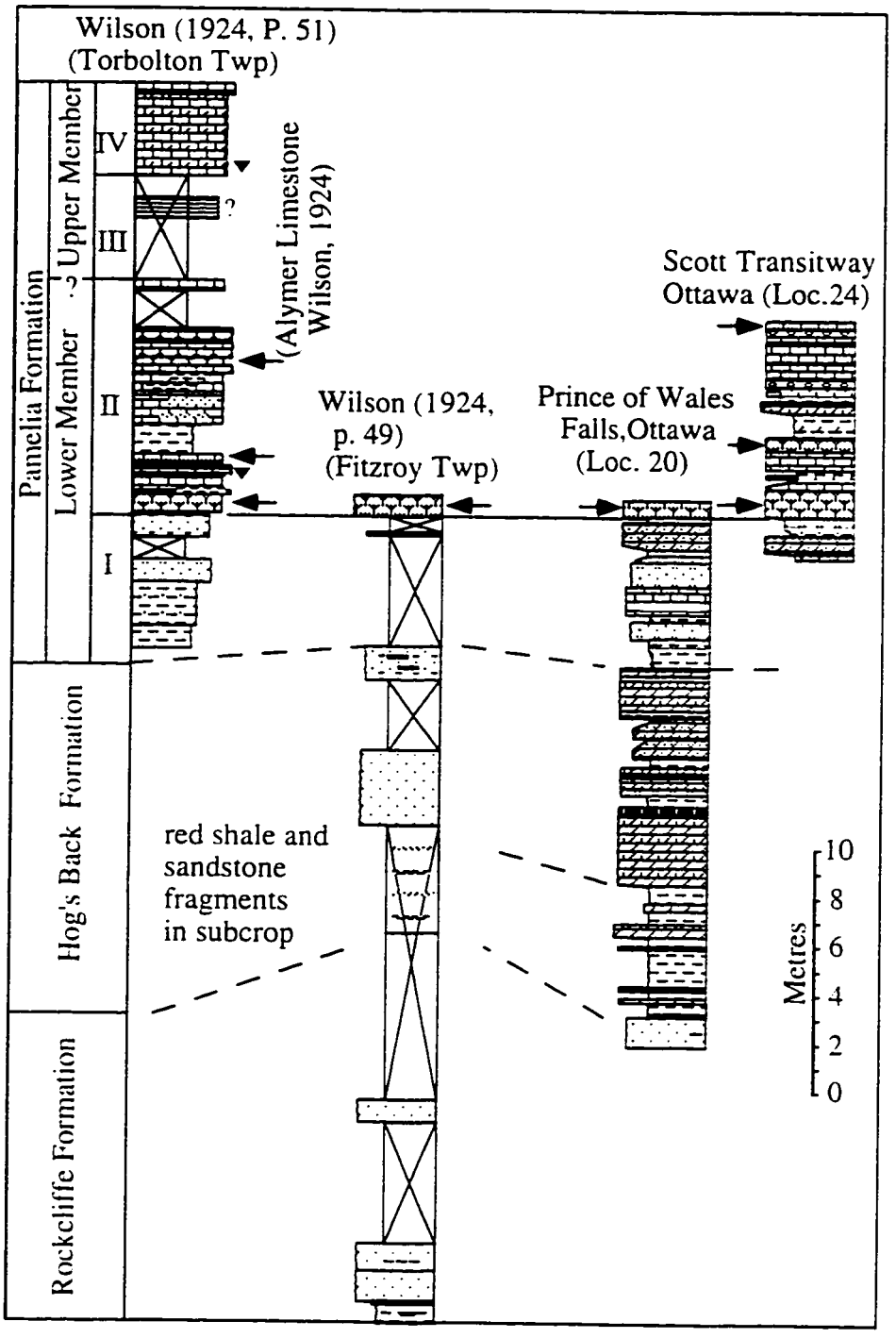


Fig. 3.28 Correlation of two sections (Locs. 20 and 24) with two sections from the Fitzroy - Torbolton area (~ 40 west of Ottawa, M.E. Wilson 1924). The correlation suggests that beds equivalent to the Hog's Back Formation occur in these western localities. This challenges the traditionally accepted stratigraphy (e.g., A.E. Wilson 1946; Sawford 1972; Steele-Petrovich 1989) that St. Martin formation (partially equivalent to the Hog's Back Fm) does not occur west of Ottawa. See figures 2.3 and 3.8 for legend. Lithology of thin beds marked with question mark at Wilson's Torbolton section is not mentioned. Small filled triangles at the same section indicate beds with *Rostricellula plena* brachiopod. Arrows indicate extensive Stromatolitic intervals which are traciable from Ottawa to the Fitzroy - Torbolton area.

correlation shown in Figure 3.28 is correct, and therefore, it is unlikely that Wilson's (1946) St. Martin formation (part of my Hog's Back Fm) is missing from localities west of Ottawa as reported by Wilson (1946) and Steele-Petrovich (1989).

The most recent work in the Ottawa Embayment is that of Williams (1991). Rocks that I consider to be of Pamelia and Lowville affinity are correlative with the lower and upper members of Williams' (1991) Gull River Formation, respectively. However, an incongruence exists at the positioning of the lower boundary of the Ottawa Group (i.e., lower boundary of my Pamelia or Shadow Lake of Williams). Williams' (1991) Shadow Lake Formation and the lowest 5 meters of his Gull River Formation are placed in my Hog's Back Formation (Fig. 2.3). Existence of Shadow Lake Formation in the Ottawa Embayment is discussed in Chapter 2, and further details are also given in this chapter (see below).

Williams' (1991) Gull River Formation is overlain by the Bobcaygeon Formation. He divided his Bobcaygeon Formation into three (lower, middle and upper) members. The lower member consists of lithologically homogeneous, fine grained bioclastic mudstone to packstone in the eastern part of the Ottawa Valley. In the western part of the valley, Williams (1991) subdivides the lower member into a lower unit (A) that is lithologically similar to the lower member in the eastern localities, and an upper unit (B) which consists of medium to coarse grained bioclastic packstone to grainstone [similar to Barnes's (1964, 1967) calcarenite shoal facies of the Rockland Formation]. The Chaumont Formation, as described in my study, is correlative with the lower member of Williams' (1991) Bobcaygeon Formation in the eastern part and unit A of the western part of the Ottawa Valley (Fig. 3.26).

New York State

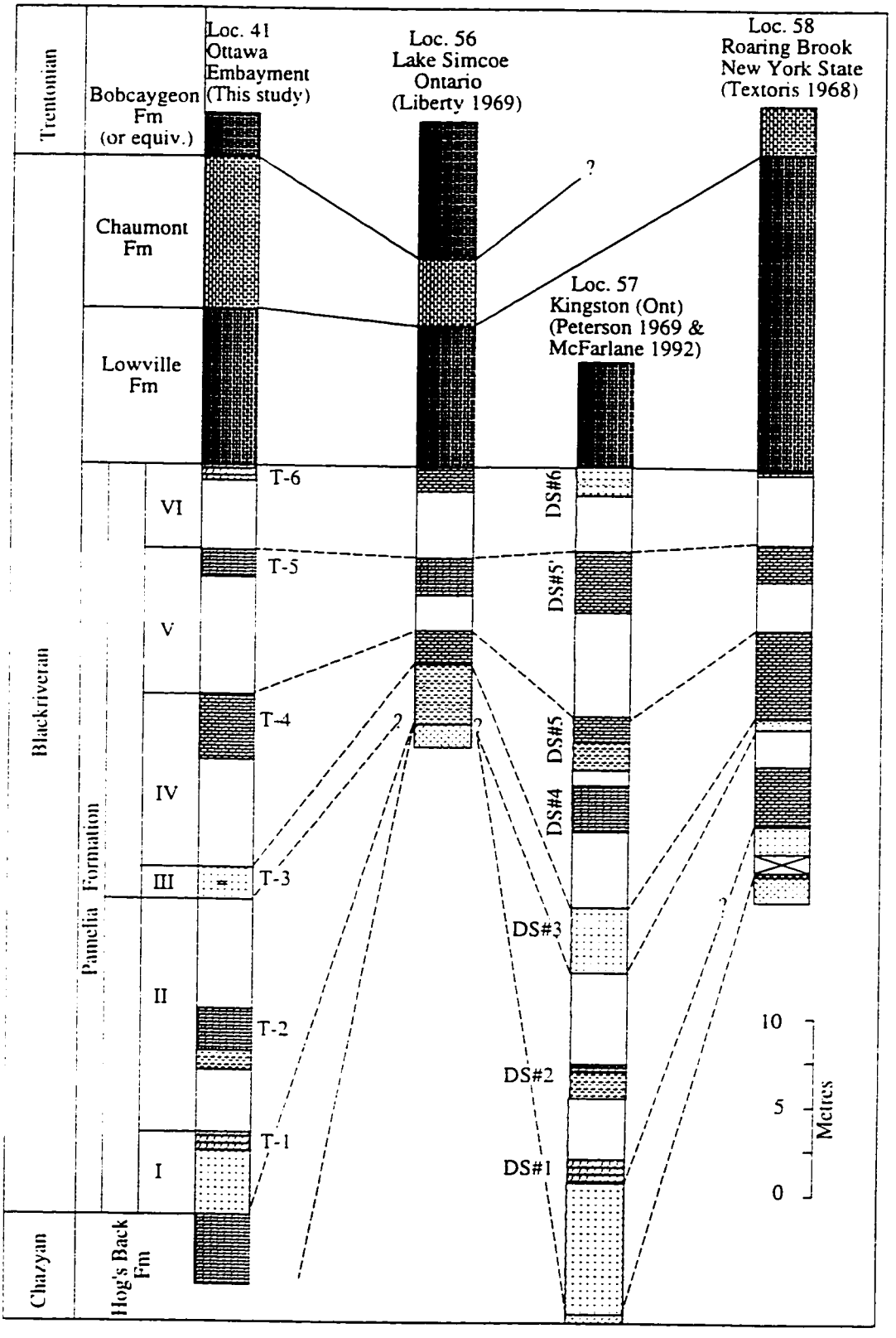
The Blackriveran strata in upstate New York consist of Pamelia, Lowville and Chaumont formations (Young 1943a; b; Textoris 1968; Walker 1973). The Pamelia Formation has a total thickness of about 46 m (150 ft) and includes two lithologic divisions. The lower division is about 21.5 m (70 ft) and consists of a basal unit dominated by conglomerate and sandstone. These siliciclastics are overlain by interbeds of dark grey to black, oolitic, bioclastic grainstone, packstone, lime mudstone, and sandy or calcareous shale and dolostone (Cushing et al. 1910; Young 1943a; Textoris 1968). The lower division of Pamelia in upstate New York is correlated with the Lower Member of Pamelia in the Ottawa Embayment. Young (1943a) observed that the basal siliciclastics of the Pamelia Formation show thickness and lithologic variations. He indicates that these differences "are partly due to the fact that the observed outcrops do not all have the same relation to the original Pamelia shore-line of any one time" (p. 153). This conclusion suggests correlation between the basal siliciclastics of the Pamelia Formation between New York and Ottawa.

Young (1943a) documents that the Pamelia Formation in New York thins eastward and westward from the type locality of Stone Mills, Jefferson County, New York. He also notes that it is always the lower division which thins and pinches out laterally. For instance, a section along Roaring Brook exposes only about 8 meters (26 ft) of the lower division. This is overlain by about 15 m (50 ft) of the upper division (Young 1943a, p. 147). Textoris (1968) who mapped the same section along Roaring Brook shows that above the 8-meter level of the section, there is a 20-30 cm thick unit of shale, siltstone, and sandstone followed by thick dolomite and dolomitic limestone interbeds containing *Tetradium* corals and calcite nodules. It is interpreted here that the 20-30 cm thick terrigenous unit is probably correlative

with the basal siliciclastics of the Upper Member (or T-3) of the Pamelia Formation in the Ottawa Embayment (Fig. 3.29). The Upper Member of Pamelia in the Ottawa Embayment is correlated with the upper division of the Pamelia Formation in the New York State (Fig. 3.1). The latter is about 24.5 m (80 ft) thick. It contains interbeds of thick, fine crystalline dolostone and peloidal, intraclastic, bioclastic mudstone to wackestone (Young 1943a; Textoris 1968). Like Unit IV of the Upper Member of Pamelia Formation in the Ottawa Embayment, thick-bedded dolostone dominates the lower part of the division. By comparing Textoris' (1968) section from Roaring Brook with Walker's (1973) from the same locality, it appears that Walker (1973) placed the upper boundary of his Pamelia Formation at the top of these thick dolostone beds. Thick-bedded dolostone in the New York region is correlated with the dolostone of T-4 in the Ottawa Embayment. Dolostone intervals correlative with T-5 and T-6 are also present in the upper division of Pamelia along Roaring Brook (Fig. 3.29).

The Lowville Formation in the Ottawa Embayment is correlative with that in upstate New York (Figs. 3.1, 3.29). The formation is about 10 m thick at its type section at Lowville, New York (Young 1943a). In the type area, the formation consists of two distinct lithologies: (1) thinly bedded, oolitic, intraclastic and shaly limestone; and (2) light to medium grey (dove grey) fine grained, bioclastic (mostly *Tetradium* corals) mudstone (Young 1943a). Like the Ottawa Embayment, the two lithologies are generally interbedded, but the former lithofacies dominates the lower part of the formation, whereas the latter dominates the upper part. The lower contact of the Lowville Formation in New York area is placed at the base of an intraclastic, bioclastic (?oolitic) limestone bed (Cushing et al. 1910; Young 1943a). Although there is no unequivocal correlation of lithology between the two regions, two points of evidence suggest their correlation: (1) The Lowville Formation does not contain

Fig. 3.29 Regional correlation of the Blackriveran strata. Note that the sandstone, sandy dolostone, and dolostone intervals of the Pamelia Formation can be traced into adjacent regions. Missing intervals (e.g., the lower 3 dolostone intervals missing from the Lake Simcoe are, and the lowest dolostone interval missing from the Roaring Brook section of New York) are attributed to diachronous advancement of the Trentonian transgression.


Trentonian
Blackriveran
Chazyan
Bobcaygeon Fm (or equiv.)
Chaumont Fm
Lowville Fm
Pamelia Formation
Hog's Back Fm
VI
V
IV
III
II
I
Loc. 41 Ottawa Embayment (This study)
Loc. 56 Lake Simcoe Ontario (Liberty 1969)
Loc. 57 Kingston (Ont) (Peterson 1969 & McFarlane 1992)
Loc. 58 Roaring Brook New York State (Textoris 1968)
T-6
T-5
T-4
T-3
T-2
T-1
DS#6
DS#5'
DS#5
DS#4
DS#3
DS#2
DS#1
?
10
5
0
Metres

(sandy) dolostone in either region such that beds of this latter lithology belong to the Pamelia Formation; and (2) the sandy dolostone beds which form the uppermost strata of the Pamelia Formation in the Ottawa Embayment (T-6) are usually overlain by intraclastic, bioclastic, oolitic packstone and grainstone. These observations suggest that the intraclastic limestone at the base of the Lowville Formation in New York area is correlative with the intraclastic, bioclastic, oolitic packstone and grainstone overlying the upper sandy dolostone (T-6) of the Pamelia Formation in the Ottawa Embayment. A similar conclusion can be drawn from Cushing et al.s' (1910) observation of the equivalent boundary traced into the Kingston (Ontario) region. Cushing et al. (1910) report that, "The upper dove limestones [of the Pamelia Formation] of the New York section are here [Kingston] capped by thin bedded, earthy, shaly layers, weathering yellow [dolostone usually weathers dull yellow], above which the Lowville comes, with its basal conglomerate. The division plane between the two formations (Pamelia and Lowville) is therefore much easier of recognition than on the New York side" (p. 77, words in brackets are mine).

As mentioned above, the Chaumont Formation in upstate New York consists of three members: Leray, local Glenburnie, and Watertown, in ascending order (Kay 1929; Young 1943b).

My definition of the Chaumont Formation in the Ottawa Embayment identifies a correlation with the Leray and Watertown members of the formation in New York (Kay 1929; Young 1943b) (Figs. 3.1, 3.29). However, there is much less authigenic silica in the Ottawa region. Calcareous shale within the formation in the Ottawa Embayment may be equivalent to thin metabentonite beds in upstate New York, and reported to occur in Glenburnie Member of southern Ontario (Kay 1930; Young 1943b). The diachronous nature

of the upper boundary of the Chaumont Formation in the Ottawa Embayment (see above) is not reported from that of the New York state. Therefore, correlation of the upper boundaries of the formation between the two regions is not known.

Kingston, Ontario

The Blackriveran stratigraphy of the region around Kingston has been subdivided into Pamelia, Lowville and Chaumont formations (Young 1943a). Cameron and Mangion (1977) replaced Chaumont with Watertown due to use of the word "Chaumontian" as a stage name. Peterson (1969), using well and outcrop data, studied the stratigraphy and sedimentology of the Blackriveran strata in the Kingston area. He divided the strata into five informal units which include, in ascending order: (1) Basal clastics; (2) Lower Limestone; (3) Cycle I; (4) Cycle II; and (5) Cycle III. There are several sandy dolostone intervals present in the lower four units.

McFarlane (1992) has also documented detailed lithofacies and biofacies descriptions of the Blackriveran succession in Kingston and environs. He adopted the formational nomenclature of the Blackriveran strata in the New York State (i.e., Pamelia, Lowville & Chaumont). McFarlane (1992) divided the Pamelia Formation into four members (A through D) each one being capped by a siliciclastic-rich dolosiltite sublithofacies. The first two members form the lower Pamelia: A-member consists of a basal conglomerate and arkosic sandstone that grades up into interbedded black and red weathering shale and green dolosiltite; B-member is a heterogeneous mixture of lithofacies consisting of stromatolites, cryptomicrobial laminite, mudstone, as well as oolitic and bioclastic packstone and grainstone. The two members are separated by a green dolosiltite layer (DS#1). The B-

member has a siliciclastic-rich dolosiltite layer in its middle (DS#2), and another one defines its top (DS#3). The upper Pamelia Formation in the Kingston area includes two members, C and D. The C-member consists of interbedded dolostone and lime mudstone. Two thick terrigenous-rich dolosiltites (DS#4 & DS#5) occur in the middle portion of the member. There is also mudcracked, thinly laminated to massive dolomitic mudstone layer at the top of the member shown in McFarlane's (1992) stratigraphic sections. This layer (which I assigned as DS#5' for correlation purposes, see Fig. 3.29, section 57) is correlative with a shaly dolostone in Peterson's (1969) section 4. McFarlane's (1992) D member consists mainly of mudstone and wackestone that grade to bioclastic, intraclastic packstone to grainstone. This member is capped by the last siliciclastic-bearing dolosiltite (DS#6) recognized by McFarlane (1992).

The Pamelia Formation is overlain by the Lowville Formation in the Kingston region (Cushing et al. 1910; Young, 1943a; McFarlane, 1992). The latter is 18 m thick and consists of thin to medium interbeds of oolitic, intraclastic packstone to grainstone, microbially laminated mudstone, bioclastic peloidal floatstone, mudstone, wackestone and packstone, and thin-bedded black shale (McFarlane 1992). The Lowville Formation is succeeded by the Chaumont Formation (Cushing et al. 1910; Young 1943a; b; McFarlane 1992). The latter is 8 m thick and comprises medium to very thick beds of "prominently burrow-mottled and locally fossiliferous peloid wackestone to packstone" (McFarlane 1992, p. 30).

General lithologic attributes and facies associations of the Blackriveran formations in the Kingston area permit a reliable correlation with their counterparts in the Ottawa Embayment. Figure 3.29, Kingston section, shows Peterson's well-section 4 (Loc. 57) incorporated with McFarlane's subdivisions and correlated with sections from other regions

[Ottawa Embayment (Loc.41), upstate New York (Loc. 58) and Lake Simcoe (Loc. 56)]. The Lower Member of Pamelia Formation in the Ottawa Valley is lithostratigraphically correlative with McFarlane's (1992) lower two members (A & B), and Peterson's (1969) Basal Siliciclastics and Lower Limestone units. The Upper Member of the Pamelia Formation (my study) is correlative with McFarlane's C- and D-members, and Peterson's (1969) Cycle I and Cycle II units in the Kingston region. Terrigenous-dominated intervals (e.g., T-1) in the Pamelia Formation of the Ottawa Embayment are correlative with McFarlane's (1992) beds of dolosiltite and sandy - shaly dolostone intervals of Peterson (1969) . The sandstone unit at the base of the Upper Member (Unit III) of the Pamelia formation in the Ottawa Embayment is correlative with DS#3 of McFarlane (1992). This correlation also shows that McFarlane's (1992) DS#4 and DS#5, combined, are correlative with the thick-bedded dolostone of T-4 whereas his beds that I assigned to as DS#5' correlate with T-5 of the Pamelia Formation in the Ottawa Embayment (Fig. 3.29). The Lowville and Chaumont formations in the Kingston region, as defined by McFarlane (1992) are correlative with the my Lowville and Chaumont formations in the Ottawa Embayment, respectively (Fig. 3.29). These two formations are also correlative with the lower and upper parts of Peterson's (1969) Cycle III unit, respectively.

Montreal area

Blackriveran strata in the region of Montreal consist of three formations: Pamelia, Lowville and Leray (Okulitch 1936; 1939a; b; Clark 1972a; b; Harland and Pickerill 1982). The Pamelia Formation consists of 2.5 to 7 m thick strata of lower bioturbated shaly beds overlain by "massive or finely parallel-laminated pale bluish grey to greenish dolomites"

(Harland and Pickerill 1982, p. 141). Admixture of high percentage of quartz grains, desiccation cracks and intraclastic horizons are common. The overlying Lowville Formation is about 5 metres thick, and it is dominated by thinly bedded (argillaceous) mudstone. Subordinate peloidal, intraclastic and oolitic limestone are also present (Harland and Pickerill 1982). The Lowville is gradationally overlain by the Leray Formation. The latter consists of 4 to 7 m thick succession of "massive, thick or thin bedded, dark grey, highly bioturbated micritic limestones with thin shale interbeds and irregular shaly partings" (Harland and Pickerill 1982, p. 141). Thin, cross-bedded, bioclastic grainstone beds and lenses are occasionally present. The bioclasts in the latter beds or lenses are dominated by brachiopods, bryozoans, gastropods, and pelmatozoan fragments. Other fossils in the formation include: corals, stromatoporoids and orthocones (Harland and Pickerill 1982).

The three Blackriveran formations in the Montreal region are correlated with the Pamelia, Lowville and Chaumont formations in the Ottawa Embayment, respectively. Lithologic and thickness differences in the Pamelia Formation between the two regions may be explained by two possible scenarios. (1) The Montreal area was a paleotopographic high, with no deposition during most of Pamelian deposition in the Ottawa Embayment. If correct, basin-fill thickness reflects gradual eastward onlap of a basin margin (Fig. 3.30). The base of the formation is diachronous, and the thin Pamelia Formation in the Montreal area correlates with the uppermost part of the Pamelia Formation in the Ottawa Embayment. (2) The Pamelia section in the Montreal area is a condensed section which is temporally correlative with all or most of the section preserved in the Ottawa Embayment (Fig. 3.31). Lateral thinning might be due to decreased accommodation space in the Montreal area related to lower subsidence rate compared to the rest of the embayment, or relative uplift of

Fig. 3.30 This figure shows one possible correlation of Pamelia Formation between the Ottawa and Montreal regions. The thickness of the formation is significantly reduced toward Montreal and is dominated by shale and dolostone lithofacies. This correlation shows that eastward progressive filling of the basin reached the Montreal region later, and the dolostone facies at St. Vincent de Paul quarry is temporally correlative with the uppermost sandy dolostone unit (T-6) in the Ottawa area.

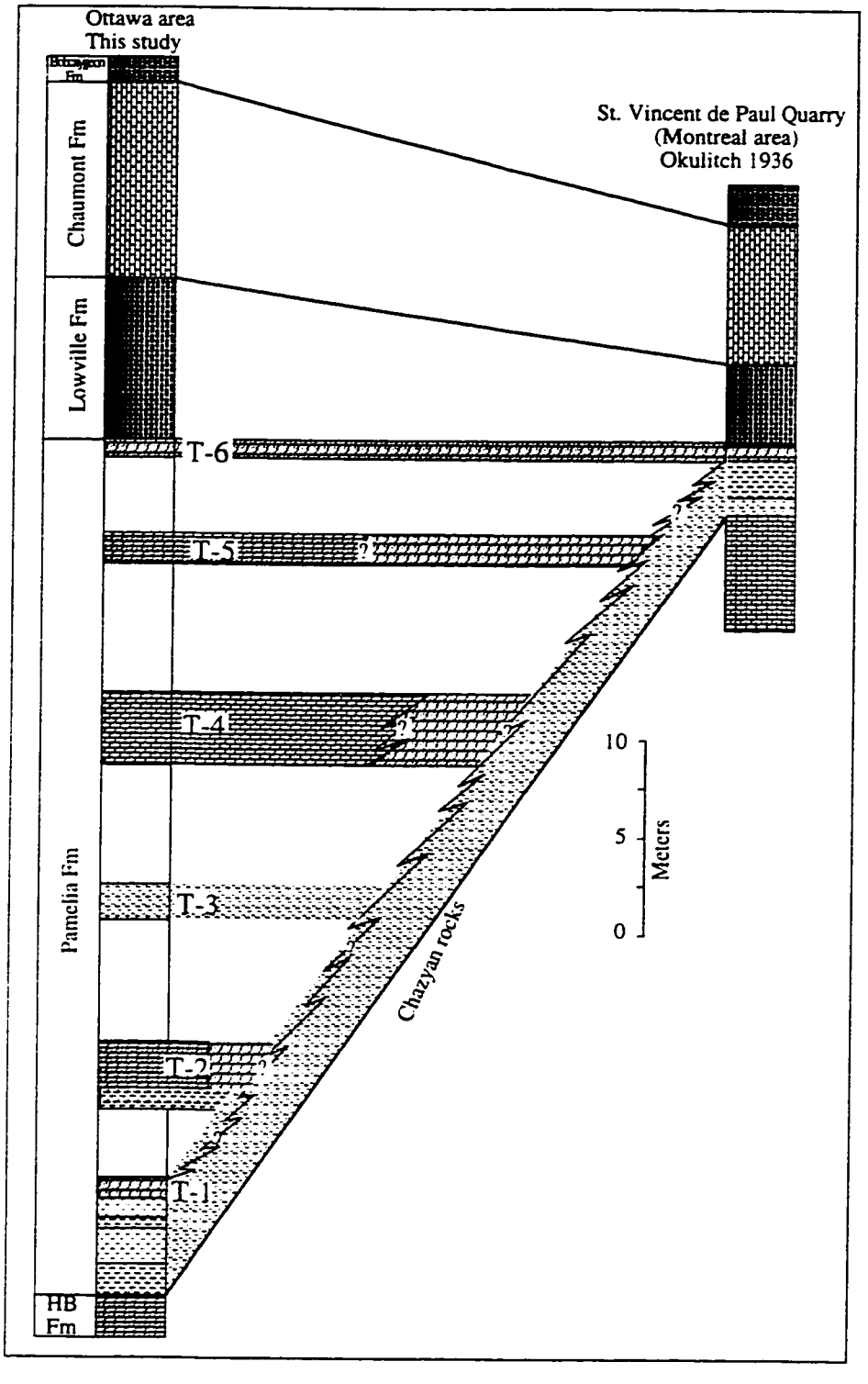
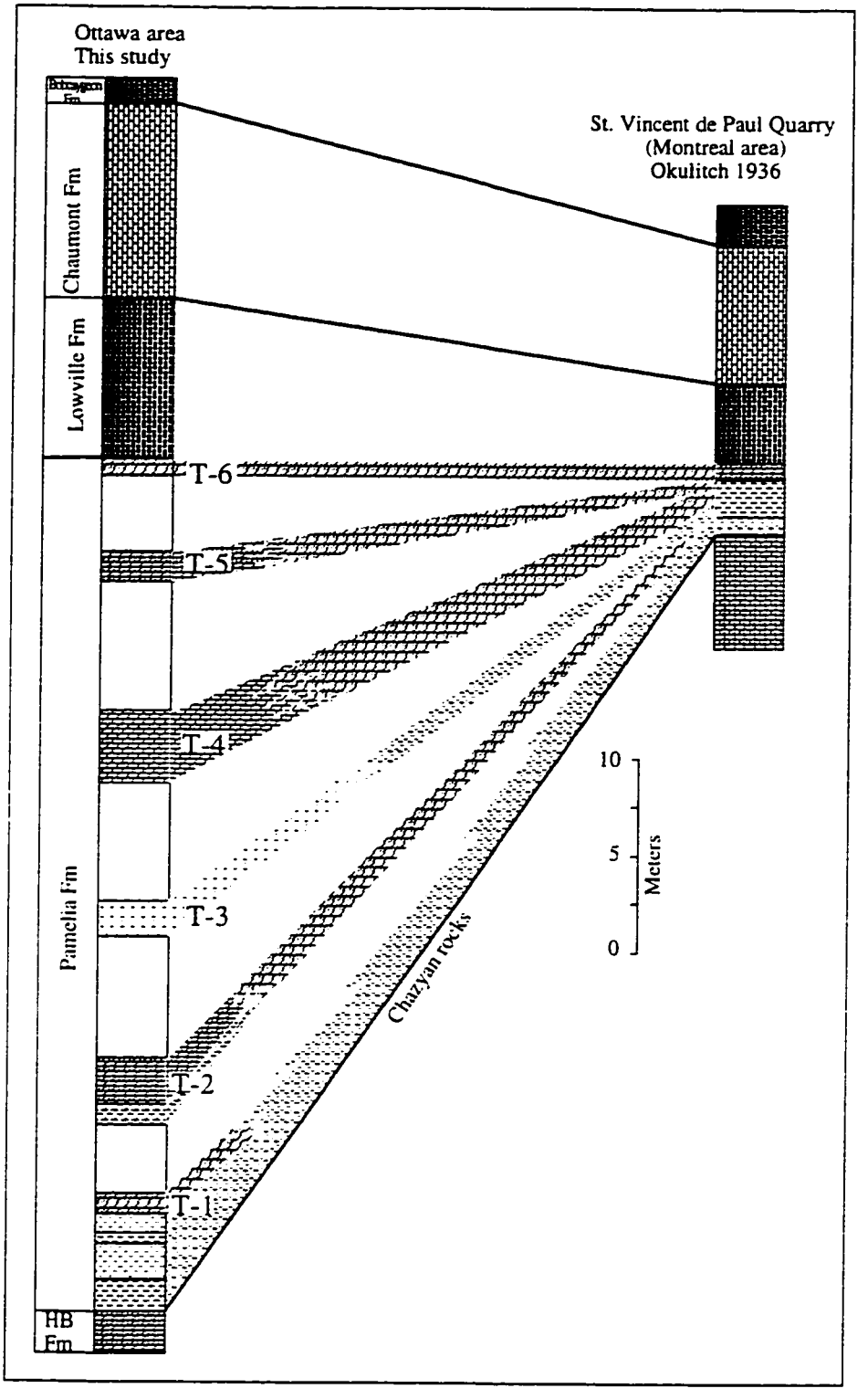

Ottawa area
This study
Chaumont Fm
Lowville Fm
Pamelia Fm
HB Fm
T-6
T-5
T-4
T-3
T-2
T-1
St. Vincent de Paul Quarry
(Montreal area)
Okulitch 1936
Chazyan rocks
10
5
0
Meters

Fig. 3.31 This figure shows an alternative correlation of the Pamelia Formation between the Ottawa and Montreal regions. Here the Montreal section is a condensed section equivalent to the entire Pamelia Formation in the Ottawa area. See text for explanation.


Ottawa area
This study
St. Vincent de Paul Quarry
(Montreal area)
Okulitch 1936
Chaumont Fm
Lowville Fm
Pamelia Fm
HB Fm
T-6
T-5
T-4
T-3
T-2
T-1
Chazyan rocks
10
5
0
Meters

basement blocks in the Montreal region. Either solution explains the greater facies restriction preserved in the region (Hofmann 1972).

Lake Simcoe Region

Young (1943a) has clearly shown that the Blackriveran strata in the region southwest of the Adirondack Massif thins westward and eastward away from the type area of New York. This thinning is at the expense of the lower strata of the succession (Young 1943a). The gradual loss of the lower Blackriveran beds is enhanced as higher beds progressively overlap older basement rocks (Young 1943a; Peterson 1969; Noor 1989; Melchin et al. 1994). Therefore it is not surprising that in the region of Lake Simcoe, lying northwest of the type localities, relatively thin Blackriveran strata are preserved.

From re-examination of Liberty's (1969) type sections in the Lake Simcoe area (pers. observation) I make two observations. (1) Carbonate rocks lithologically correlative with the Lower Member of the Pamelia Formation in the Ottawa Embayment are not represented in the Lake Simcoe region. (2) Interbedded fine crystalline dolostone and mudstone are lithologically similar to the Upper Member of the Pamelia Formation. These observations suggest that the Shadow Lake Formation is, at least partially, correlative with the sandstone facies (Unit III) at the base of the Upper Member of Pamelia Formation in the Ottawa Embayment and its correlatives in the other regions (Fig. 3.29). The units IV, V, and VI of my Pamelia Formation are correlative with Liberty's (1969) Lower Gull River (including submembers A_1, A_2, A_3, & A_4); my Lowville Formation is correlative with his Middle Gull River (including submembers B_1 & B_2); and, my redefined Chaumont is correlative with his Upper Gull River Formation (including submember B_3).

Does the Shadow Lake Formation occur in the Ottawa Embayment?

The Shadow Lake Formation was initially proposed by Okulitch (1939a) for the siliciclastic and dolomitic beds which occur at the base of the Blackriveran succession in the Lake Simcoe area. Liberty (1969) revised Okulitch's type sections and modified the upper boundary of the original Shadow Lake Formation. The revised formation, at its type area, consists of red, green and brown beds of arkosic conglomerate and sandstone which grade into interbedded calcareous, dolomitic sandstone and shale (Liberty 1969; Mukherji 1969; Noor 1989; Melchin et al. 1994; also pers. observations).

The formation is interpreted sedimentologically as a combination of regolith, alluvial and-or deltaic sediments reworked by the advancing Taconian Sea (Melchin et al. 1994). Conodont fauna suggest the formation becomes younger to the northwest direction, implying gradual inundation of an irregular paleotopography (Schopf 1966; Barnes et al. 1981; Noor 1989; Melchin et al. 1994). Therefore, it can be generally concluded that the Shadow Lake Formation is a diachronous unit which is chronostratigraphically equivalent to part of the Pamelia Formation. For the latter unit, siliciclastic-rich intervals represent interfingering of siliciclastics transported seaward during relative lowering of sea level.

The earliest work which applied the term Shadow Lake Formation to the Ottawa Embayment is that of Williams and Telford (1986). They suggested that the formation is 2.5 to 2.8 m of "silty to sandy dolostone, with shaly partings and thin interbeds of quartz sandstone" (p. 9). They correlated it with the Pamelia Formation of New York State. Williams (1991) later provided more detailed descriptions of sections exposing the formation. One of his sections is at Prince of Wales Falls, Ottawa (see Appendix 1, Loc 20). My study finds that the exposed rocks considered to be Shadow Lake Formation by Williams

(1991) are lithologically different from the original description (*sensu* Liberty 1969) and occur at a different stratigraphic level than proposed by Williams (1991). In contrast to the lithology of the Shadow Lake Formation, the correlative interval of rocks at Prince of Wales Falls, Ottawa, consists of thin to (mostly) thick beds of greenish grey, weathering to light green, fine crystalline dolostone to calcareous dolostone. Quartz and phosphatic grains are disseminated throughout. It is overlain by lithologically similar dolostone containing minor interbeds of thin to medium coarse grained bioclastic packstone to grainstone. These packstone / grainstone interbeds carry the well known Chazyan brachiopod of *Rostricellula plena*. These carbonate rocks belong to the Hog's Back Formation, and are correlated with the upper Laval Formation in the Montreal region (see Chap. 2 for more details).

CHAPTER FOUR

LITHOFACIES DESCRIPTION OF THE BLACKRIVERAN SUCCESSION IN THE OTTAWA EMBAYMENT

Introduction

Eleven lithofacies are recognized in Blackriveran strata of the Ottawa Embayment. These lithofacies are grouped under two divisions: (1) terrigenous-dominated lithofacies (TLF1 to TLF3); and, (2) carbonate-dominated lithofacies (CLF1 to CLF8). Field characteristics, petrographic attributes and depositional environments of these lithofacies are summarized in Table 4.1. Lithofacies associations within the Pamelia and Lowville formations define shallowing-upward patterns, and produce stacked rhythmic successions. Such rhythmic sedimentation is not recognized for the Chaumont Formation; instead the whole formation appears to shallow upwards. Description of lithofacies, their stratigraphic distribution, and interpretation of depositional environments are addressed in this chapter. Lithofacies descriptions and interpretations are based on both field and laboratory analyses of rock texture, grain types, fossil content, sedimentary structures, diagenetic features and lithofacies associations. The carbonate lithofacies are also compared with Flügel's (1982) Standard Microfacies (SMF) classification.

Quartzwacke lithofacies (TLF1)

Description

This lithofacies is made up of medium to very thickly bedded (20 - 110 cm), fine grained quartzwacke (Figs. 3.3, 4.1). Bedding is commonly well defined. The quartzwacke lithofacies is greenish grey on fresh surfaces and weathers a greenish buff colour. The

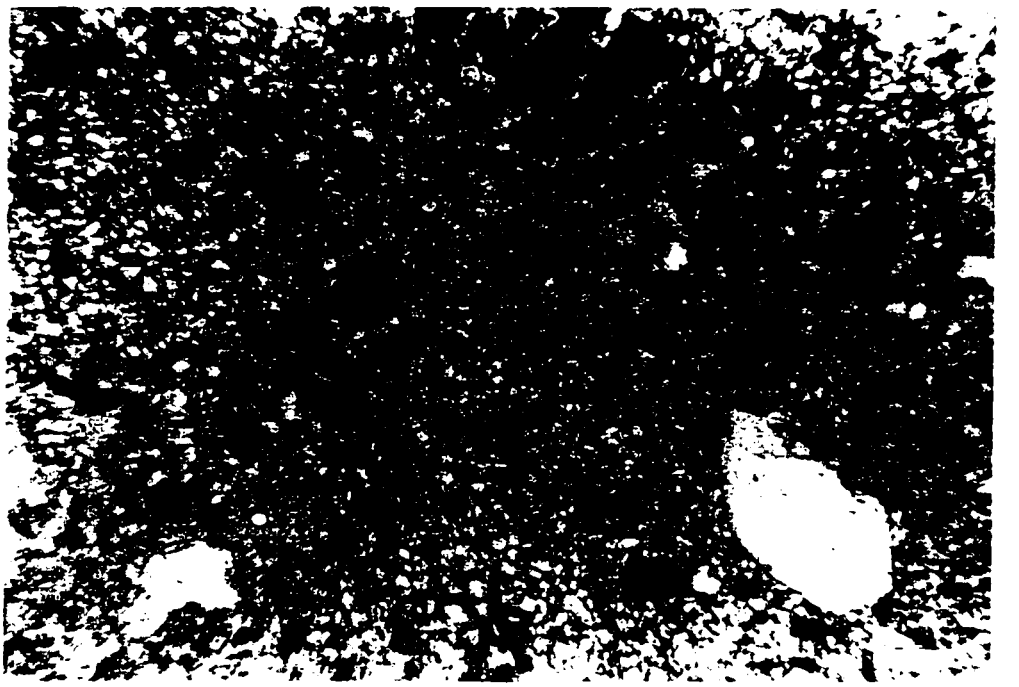
Table 4.1 This table shows field characteristics and petrographic attributes of the eleven lithofacies recognized to constitute the Blackriveran strata of the Ottawa Embayment. These lithofacies include three terrigenous-dominated (TLF) and eight carbonate-dominated (CLF) facies.

Lithofacies	Lithology	Bedding (cm)	Colour	Sedimentary structures	Characteristic fossils	Depositional environment
TLF1	Quartzwacke: fine grained, phosphatic detritus is present.	20 - 110	f.s. = greenish grey, w.s. = greenish buff.	Intense horizontal burrows (*Planolites*) vertical & U-shaped burrows at the top of beds.	Ostracodes (rare), poorly preserved conodont fauna: *Erismodus sp.*, *Phragmodus Sp.*, and *Curtognathus sp.*	Subtidal to intertidal.
TLF2	Quartz arenite: bimodal.	0.5 - 5	f.s. = light greenish to brownish grey, w.s. = light greenish grey.	Mudcracks, evaporite molds, vertical burrows (*Skolithos sp.*).	Poor. Ostracod and trilobite fragments.	Intertidal.
TLF3	Shale: locally sandy, calcareous or dolomitic shale.	<1 - 10	Black to dark grey	Horizontal burrows, mudcracks (local).	Ostracods, bryozoans, brachiobods and orthocones.	Subtidal to supratidal.
CLF1	Dolostone: fine crystalline dolomite, pure, sandy and-or calcareous.	20 - 95	f.s. = greenish grey, w.s. = buff (green).	Mudcracks, microbial lamination, hard-ground, evaporite molds, vertical to subvertical burrows, birdseye (fenestral), calcite & celestite nodules, collabse-breccia.	Ostracod, and *Lingula* brachiopod fragments.	Supratidal to upper intertidal of sabkha.
CLF2	Microbialite: laminated peloidal mudstone and stromatolitic mudstone to (oolitic, bioclastic) packstone.	< 1 - 5	f.s. = Dark to medium grey, w.s. = light grey.	Flat and wavy laminations, LLH and SH stromatolites, flat-pebble breccia, mudcracks.	Ostracods, bivalves, gastropods, serpulids, calcareous algae, crinoids.	Intertidal flat cut by tidal channels.
CLF3	Intraclstic (flat-pebble breccia) packstone to rudstone.	4 - 20	f.s. = medium brownish grey, w.s. = light (dove) grey.	Mudcracks, vertical to subvertical burrows, birdseye (fenestral) texture, stylolites, poor sorting, interaclasts locally show internal laminations.	Rare ostracods.	Intertidal to supratidal flat.
CLF4	Bioclastic mudstone to wackestone.	<1 - 20	f.s. = light (dove) grey to medium brownish grey, w.s. = whitish to light brown. grey.	Fenestral fabric, horizontal burrows, mudcracks (rare), stylolites, flat-pebble breccia (local).	Ostracods, *Tetradium* corals, gastropods, bivalves, crinoids, bryozoans, trilobites, *Solenopora* algae, orthocones.	Open (subtidal to locally intertidal) lagoon.

Lithofacies	Lithology	Bedding (cm)	Colour	Sedimentary structures	Characteristic fossils	Depositional environment
CLF5	Bioclastic floatstone to bafflestone	3 - 15	f.s. = medium to dark grey, w.s. = light grey	Horizontal burrows, rubbly texture (where shale laminae are abundant), radial branching of the *Tetradium* corals.	*Tetradium* corals, ostracods, bivalves, gastropods, trilobites, *Solenopora* algae, bryozoans, orthocones.	Subtidal lagoon - wave & current baffle zone.
CLF6	Bioclastic packstone to grainstone	2 - 40	f.s. = medium to dark brownish grey, w.s. = med. brownish grey	Planar and cross-bedding, current and wave ripple marks, scours, planar and irregular shaly partings, vertical and horizontal burrows, geopetal fill.	Bivalves, ostracods, trilobites, *Tetradium* corals, bryozoans, serpulids, gastropods, brachiopods, calcareous algae, *Solenopora*, crinoids, orthocones.	Shallow subtidal to intertidal sand bars.
CLF7	Oolitic packstone to grainstone	5 - 40	f.s. = dark brownish grey, w.s. = medium (brownish) grey	Planar bedding, tabular and trough cross-bedding, wave and current ripple marks, scour surfaces, imbrication, normal grading, fenestral fabric.	Bivalves (*Cyrtodonta* sp.), ostracods, trilobites, *Tetradium* corals, bryozoans, serpulids, gastropods, crinoids, orthocones.	Subtidal ooid shoals and sandflats.
CLF8	Bioclastic, peloidal wackestone to packstone	20 - > 100	f.s. = medium to dark grey, w.s. = medium grey	Intense horizontal burrows creating mottled appearence, irregular shaly partings, hardground and stylolitic bed contacts.	Tabulate and solitary corals, brachiopods, orthocones, crinoids, bryozoans, bivalves, ostracods, gastropods, trilobites.	Subtidal, below wave-base.

Table 4.1 cont.

Fig. 4.1 Quartzwacke lithofacies is characterized by fine-grained quartz grains. Phosphatic grains (dark grains) are also locally abundant. Unit I of the Pamelia Fm, Prince of Wales Falls, ottawa. Scale bar is 200 μm.



lithofacies is intensely burrowed. Most of the burrows are horizontal (*Planolites* sp., Fig. 4.2a), but there are also vertical (*Skolithos* sp.) and U-shaped (*Arenicolites* and *Diplocraterion*) burrows (Fig. 4.2b). The vertical and U-shaped burrows are usually present at the top of the beds, suspend downward from the bedding surfaces, and filled by relatively darker sediments rich in phosphatic (?collophane) grains. Although phosphatic debris (silt- to pebble-size) is disseminated throughout the quartzwacke lithofacies, it is usually more concentrated in the upper parts of the beds (Fig. 4.2b). The burrows produce a densely packed three-dimensional network comparable with ichnofabric index C-5 of Bottjer and Droser (1994). They generally obliterate most of the previously existing sedimentary structures. Internal thin laminations are preserved in certain beds. The framework is dominated by angular to subrounded, moderate to well sorted, quartz grains of fine-sand size. Minor feldspathic grains are also present. Silt-size quartz grains and clay form the matrix. This lithofacies is primarily cemented by dolomite, although calcite may locally be present. Bioclasts are generally absent except for rare ostracod fragments. This lithofacies contains a poorly preserved conodont fauna of *Erismodus* sp., *Phragmodus* sp., and *Curtognathus* sp. (McCracken, 1995).

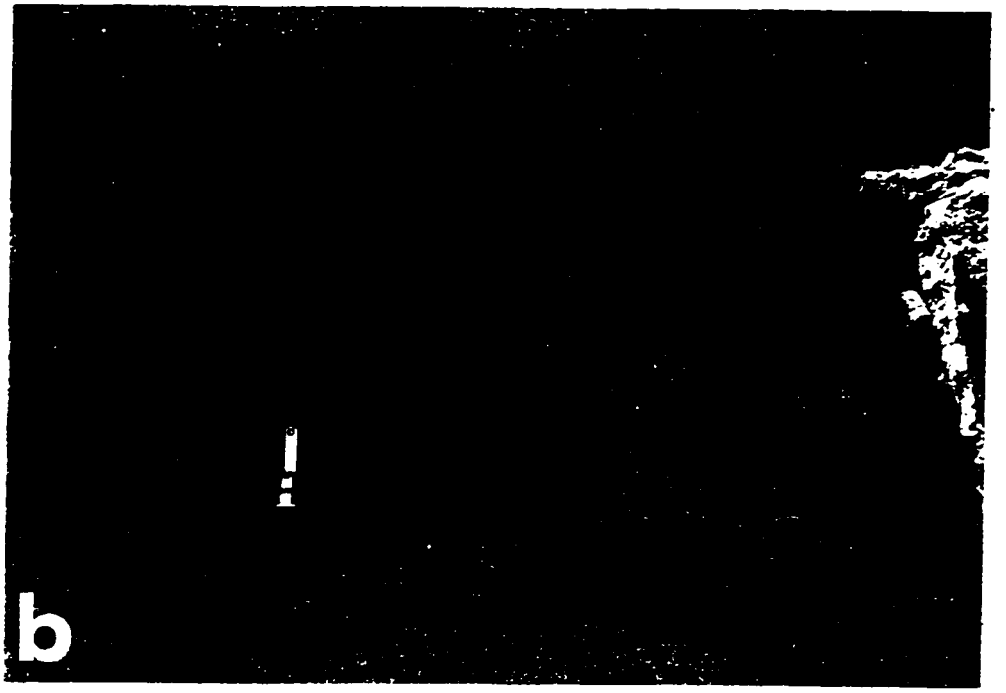
Stratigraphic distribution

This lithofacies occurs in Unit I and Unit III of the Pamelia Formation. In unit I, the lithofacies forms three thick beds separated by shale and limestone in the Ottawa area (e.g., Loc. 20). Conodont fauna were recovered at locality 20. The lithofacies can be traced in three widely separated areas (Ottawa area: Locs. 14, 20, & 22; Russell County: Loc. 41; and

Fig. 4.2a Extensive horizontal burrows (*Planolites*) preserved in the quartzwacke lithofacies, Unit I of the Pamelia Fm at Loc. 36 (St. Joseph Blvd, Gloucester). The burrows destroy previous (if any) sedimentary structures. The coin is 2.3 cm in diameter.

Fig. 4.2b Other burrows present in the quartzwacke lithofacies include Diplocraterion (d) and Skolithos (s). Note that these burrows are filled by dark sediments, concentrated in the upper part of the bed, and suspend downward from the bedding surface. Extensive horizontal burrows (tiny mottles) dominate the lower parts of the beds. Unit I of the Pamelia Fm at Loc. 14 (Iris Rd at Highway 417, Ottawa).The pencil is 15 cm long.

a


b

Winchester - Morrisburg area: Loc. 44) within the Ottawa Embayment.

Quartzwacke lithofacies is also recognized to occur in the basal siliciclastics of the Upper Member of the Pamelia Formation (Unit III). The lithofacies forms the upper half of the unit at Locality 16 (Riverside drive road-cut, Ottawa), and is predominant throughout the unit in all other mapped sections.

Interpretation

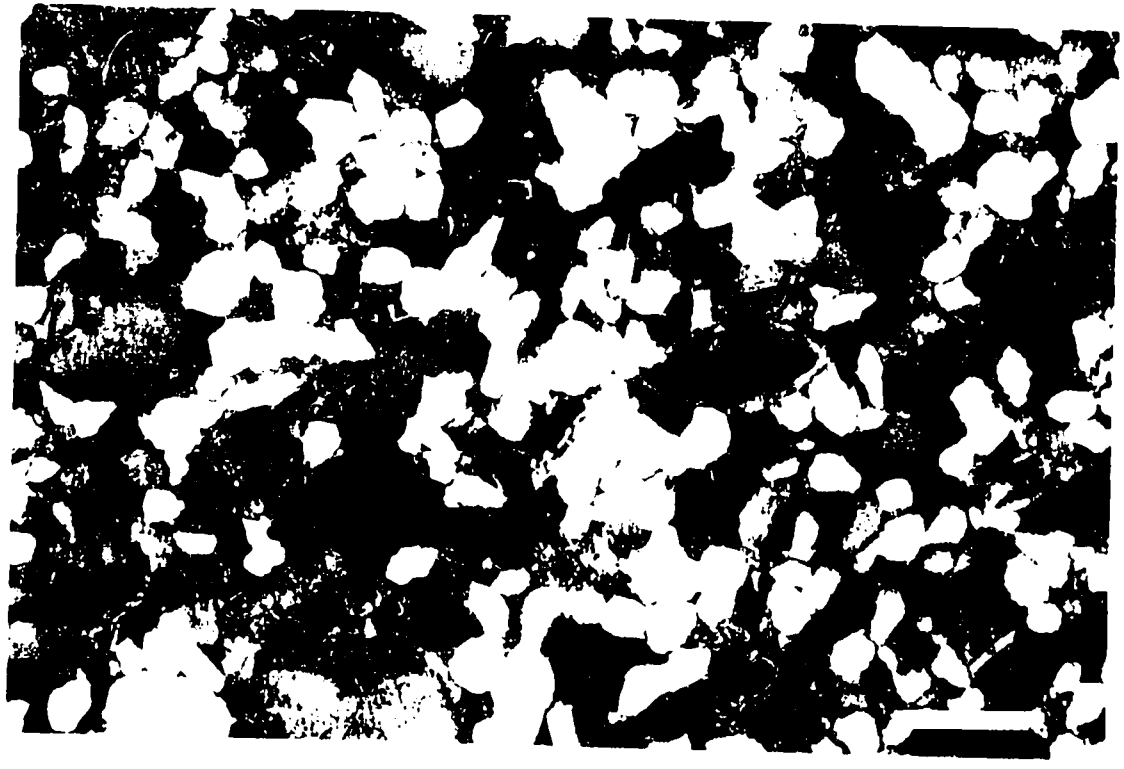
Absence of bedding in the lithofacies is due to intensive, thorough biogenic reworking of the sediment. This has produced a densely packed burrow network similar to *Ophiomorpha* ichnofabric of Bottjer and Droser (1994). This type of ichnofabric is interpreted to have formed in a nearshore depositional site of moderate energy (Bottjer and Droser 1994; Pemberton et al. 1992). The energy of the depositional environment was increased locally as suggested by the various *Glossifungites* ichnofacies (e.g., *Arenicolites* and *Diplocraterion*, Pemberton et al, 1992) concentrated in the upper parts the beds. Concentrations of phosphatic grains may reflect reduced sedimentation rates. The overall depositional environment can be regarded as a moderately-agitated, sand-dominated shallow subtidal to lower intertidal setting.

Quartz arenite lithofacies (TLF2)

Description

This lithofacies consists of laminated to thinly bedded (~ 0.5 - 5 cm), bimodal quartz arenite (Fig. 4.3). It has a light greenish to brownish grey colour, and weathers light (buff)

Fig. 4.3 Thin section photomicrograph of the quartz arenite lithofacies (TLF2). Note the bimodal as well as the subangular to subrounded nature of the quartz grains. Unit III of the Pamelia Fm at Riverside Dr., Ottawa. Scale bar is 500 μm.



green to light grey. Some beds show internal laminations. Thin shale beds commonly occur within the unit. The lithofacies also contains a 17-cm thick, orange, bimodal quartz arenite, comparable to what Folk (1968) called "bimodal supermature sandstone". The coarser quartz grains have frosted surfaces.

The framework grains of the quartz arenite lithofacies consist of two grain-size populations: fine sand (100 μm average) and medium sand (480 μm average) quartz grains. The finer grains are subangular to subrounded and moderately sorted whereas the coarser ones are well rounded to subrounded, and well sorted. Outsized quartz grains and rare feldspathic grains are also present. The lithofacies seldom contains fossils, but intact and broken ostracod carapaces and rare trilobite fragments are seen in thin section. The framework displays linear grain-grain contacts. Authigenic quartz crystals are present and replace some fossils.

X-ray diffraction analysis of this stratum shows the presence of gypsum. Mudcracks, vertical burrows (*Skolithos* sp.), gypsum pseudomorphs, and normal grading are present. The burrows and the mudcracks show certain grade of deformation probably due to pre-lithification compaction.

Stratigraphic distribution

The quartz arenite lithofacies occurs only in the lower part of Unit III (the basal siliciclastics of the Upper Member of the Pamelia Formation), but only in the Ottawa area at Locality 16. It appears that the lithofacies is local to this locality and is not represented in other localities (Locs. 34, 41, 44, & 47) that show Unit III (see Fig. 3.14). All these localities

occur east to southeast of Ottawa.

Interpretation

The presence of mudcracks, vertical burrows, gypsum, and gypsum molds in the lithofacies suggests an upper intertidal environment. The bimodal and frosted quartz grains in both the orange sandstone sublithofacies, as well as the rest of the quartz arenite lithofacies, are interpreted to be of possible eolian origin transported into a shallow marine (intertidal) environment (Folk 1968). Absence of the quartz arenite lithofacies in localities east and southeast of Ottawa suggests two possibilities: (1) the lithofacies was localized in the Ottawa area and never deposited in eastern localities due to change from intertidal facies in the Ottawa area to more open marine shallow subtidal setting to the east; or (2) the quartz arenite lithofacies was deposited in the eastern localities but was eroded later during an erosional event that marks the contact between the Lower and Upper members of the Pamelia Formation (see Fig. 3.14). This erosional event appears to have been more intense in eastern localities than in the Ottawa area. This is suggested not only by the absence of the quartz arenite lithofacies, and well marked erosional pattern which is developed better in the eastern localities (e.g., Locs. 42, 44, & 47), but also several metres of the uppermost strata of Unit II of the Pamelia Formation are missing from Locality 47 near Cornwall. At this latter locality, a possible subaerial exposure is suggested by vadose pendant and meniscus cements which are observed in bioclastic, oolitic grainstone lying below the erosional contact (see also Chapter 6). Considering all these observations, it appears that the second possibility is a better explanation for the absence of the quartz arenite lithofacies from eastern sections.

Shale lithofacies (TLF3)

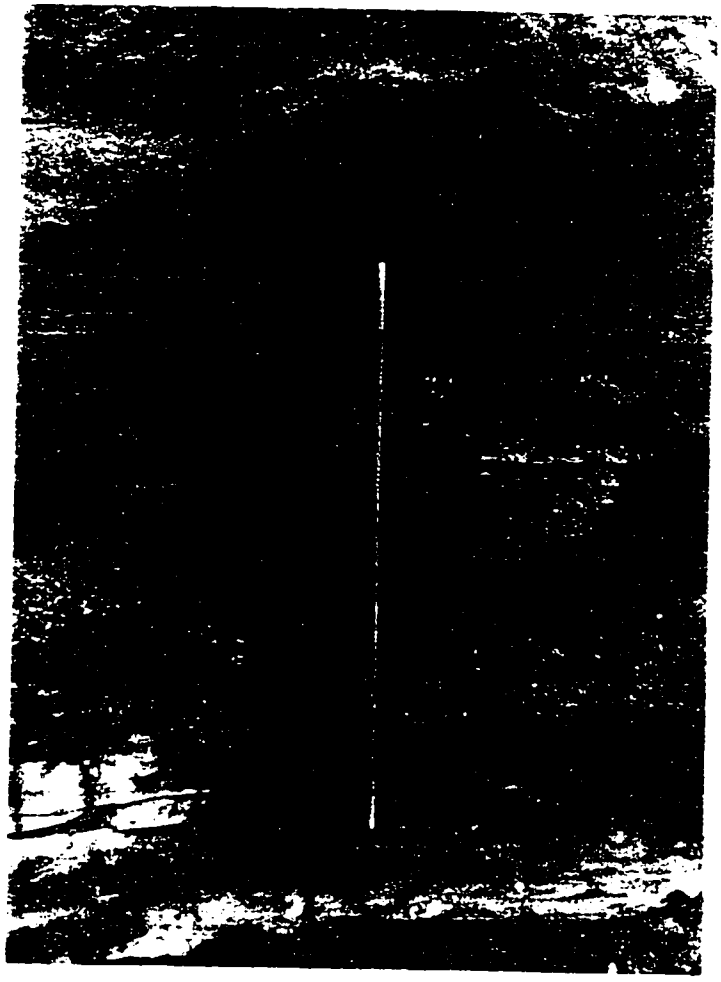
Description

This lithofacies is made up of thinly bedded to laminated, black to dark (greenish) grey shale. Grain size varies from clay to silt. Horizontal burrows (*Planolites* sp.) and mudcracks are locally present but not common. Although the lithofacies is thinly bedded to laminated, stacking of beds and-or laminae forms, locally, a succession of up to 1.2 metres thick (Fig 4.4). Where such thick stacking occurs (e.g., Loc. 20), the shale locally grades (e.g., in the lower part of the Lower Member of the Pamelia Formation) into the quartzwacke lithofacies (TLF1). The shale is also interbedded with various carbonate lithofacies. The shale contains mudcracks and a high sand-size quartz (up to 40 %) component when associated with the dolostone lithofacies (see below). Burrows are often present in the shale whether they are interbedded with the quartzwacke lithofacies or in limestone lithofacies. Fossil content in the shale lithofacies is usually low. When found interbedded with limestone, the shale is moderately fossiliferous with ostracod, orthocone, bryozoan, and brachiopod skeletal fragments and whole shells.

Stratigraphic distribution

The shale lithofacies (TLF3) occurs throughout the Blackriveran formations. Thickly stacked, horizontally burrowed shale that grades up into quartzwacke lithofacies is present only in Unit I of the Pamelia Formation. In the basal siliciclastics of the Lower Member of the Pamelia Formation, the shale is second in abundance after the quartzwacke lithofacies. Both ostracod and orthocone skeletal material is present in these strata. Thin shale beds and

Fig. 4.4 Thinly bedded to laminated shale (S) unit (TLF3) overlain by the quartzwacke lithofacies (W). Uint I of the Pamelia Fm. at Loc. 36, St. Joseph Blvd, Gloucester. The measuring stick is 1.2 m.



laminae are interbedded throughout the rest of the Pamelia and Lowville formations. Mudcracked sandy shale is usually associated with the thick-bedded dolostone of the Pamelia Formation. Thin-bedded black shale (with and without bryozoans, and horizontal burrows) is present throughout the Lowville Formation. Two types of shales are present in the Chaumont Formation: (1) thin (<10 cm), calcareous shale beds which contain abundant brachiopods (*Doleroids* sp. and *Rafinesquina* sp.), and, (2) irregular, non-continuous laminated (millimetre size) shale which produces irregular partings, forming (with the burrows in the formation) a somewhat nodular structure overall. The shaly parting fabric is also present in the Pamelia and Lowville Formations, but less pronounced than in the Chaumont Formation.

Interpretation

There are various depositional environments interpreted for the shale lithofacies. The thickly-stacked shale beds in the lower part of the Pamelia Formation were deposited in a calm subtidal open marine environment, alternating with higher energy facies of the subtidal-intertidal quartzwacke lithofacies. This interpretation is supported by the gradational pattern of the shale up into the quartzwacke lithofacies; the presence of horizontal burrows (Pemberton et al. 1992); and, occurrence of orthocones (Burrett et al. 1984). Mudcracked, sandy shale that is associated with dolostone is interpreted to have accumulated in a supratidal to, probably, high intertidal environment. Other shale facies that contain bryozoa and brachiopod skeletons accumulated under calm subtidal normal marine conditions.

Dolostone lithofacies (CLF1)

Description

This lithofacies consists of medium to thickly bedded (20 to 95 cm), greenish grey dolostone (Fig 4.5a). Petrographically, the dolostone consists of fine-crystalline (usually < 70 μm) dolomite minerals forming unimodal mosaics of euhedral to subhedral fabric (Fig. 4.5b). Minor domain of coarser crystalline dolomite is also present. Petrographic and geochemical details of dolomite are presented in Chapter 6. The lithofacies weathers to a buff green colour. Bedding is poorly to well defined. Two sublithofacies, based on quartz abundance, are recognized. A sandy dolostone sublithofacies (CLF1a) is denoted for dolostone that contains over 10% (and <50%) quartz whereas pure dolostone sublithofacies (CLF1b) is designated for dolostone that is over 90% dolomite (Mount 1985). Where the quartz content locally exceeds 50%, the rock is referred to as dolomitic sandstone. Other framework grains include phosphatic detritus [probably *Lingula* (brachiopod) fragments as well as chemically precipitated, but later reworked, clasts], rare disarticulated ostracod shells, and dolomitized intraclasts. Presence of minor feldspar, gypsum, and mica is confirmed by X-ray diffraction analysis. Pyrite crystals are dispersed throughout the lithofacies. Coarse quartz grains are locally concentrated in the upper part of the dolostone beds, producing a sanding-upward trend. Quartz grains in the lithofacies vary from subangular fine-grained silt (~ 20 μm) to well rounded fine-grained (~ 100 μm) sand. The quartz grains are concentrated in burrows, bores and mudcracks, also randomly dispersed within the host dolomite. The lithofacies is comparable with dolomitized equivalents of SMF 23 and SMF 19 of Flügel (1982).

Fig.4.5a Thick dolostone beds at the upper part of Unit IV (vertical arrows indicate top of the unit). Note calcite nodules (horizontal arrows) preserved in a dolostone bed. Unit IV of the Pamelia Fm. at Loc. 34, (Francon northren quarry). The measuring stick is 1.2 m long.

Fig. 4.5b Thin section micrograph showing thinly laminated, very fine-crystalline dolomite with disseminated fine-grained quartz grains. Unit IV of the Pamelia Fm. at Loc. 34, (Francon northren quarry). Scale bar is 1000 μm.

a
b

The dolostone lithofacies preserves sedimentary structures which include thin microbial laminae, mudcracks with evaporite molds (Fig 4.6a), hardground surfaces (Fig. 4.6b), vertical to sub-vertical burrows (possibly *Psilinichnus* ichnofacies, Fig. 4.6c), calcite-filled fenestral fabric, and relatively big (~ 1 - 8 cm wide) void spaces filled by blocky, white to pinkish calcite and-or celestite nodules. Collapse-breccia, or fragments of host dolostone rocks, are associated with larger (up to 8 cm) nodules (Fig. 4.7). Celestite is locally abundant within the calcite nodules.

Stratigraphic distribution

This lithofacies occurs only in the Pamelia Formation. It forms five of the six stratigraphic intervals (T-1, T-2, T-4, T-5, & T-6) in the formation (see Chap. 3). However, T-1 grades laterally to dolomitic quartzwacke lithofacies (TLF1) from Locality 41 (Russell well) into the Ottawa area (e.g., Locs. 20 & 24). The dolostone lithofacies is locally present in the lower part of Unit V but has limited lateral extension and is not recognized to occur west of Locality 34. Where the lithofacies is preserved in the lower part of Unit V, it is denoted as T-5' (Fig. 3.13). The sandy dolostone sublithofacies is well developed in the Ottawa area and to the west, but the terrigenous component decreases to the southeast (e.g., Loc. 44) giving way to relatively pure dolostone sublithofacies.

Interpretation

This lithofacies is interpreted to represent syn-sedimentary dolomitization within supratidal to high intertidal sites of a sabkha. This interpretation is supported by the predominance of the dense, unimodal mosaics of fine crystalline dolomite (Frisia 1994;

Fig. 4.6a Bedding surface of a dolostone showing mudcracks and refilled evaporite molds (arrows). Unit V (T-5) of the Pamelia Fm. at Loc. 45; Cornwall (Permanent Concrete) quarry. The pencil is 15 cm long.

Fig. 4.6b This photo shows an irregular hardground surface developing in the dolostone lithofacies. Unit I (T-1) of the Pamelia Fm at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. The coin is 2.3 cm in diameter.

Fig. 4.6c Vertical to subvertical burrows (arrow) are locally abundant in the dolostone lithofacies. Note also the hardground surface (at the tip of the pencil) which developed in the lithofacies. Unit IV of the Pamelia Fm. at Loc. 47, Macleod quarry, Cornwall. The pencil is 15 cm long.

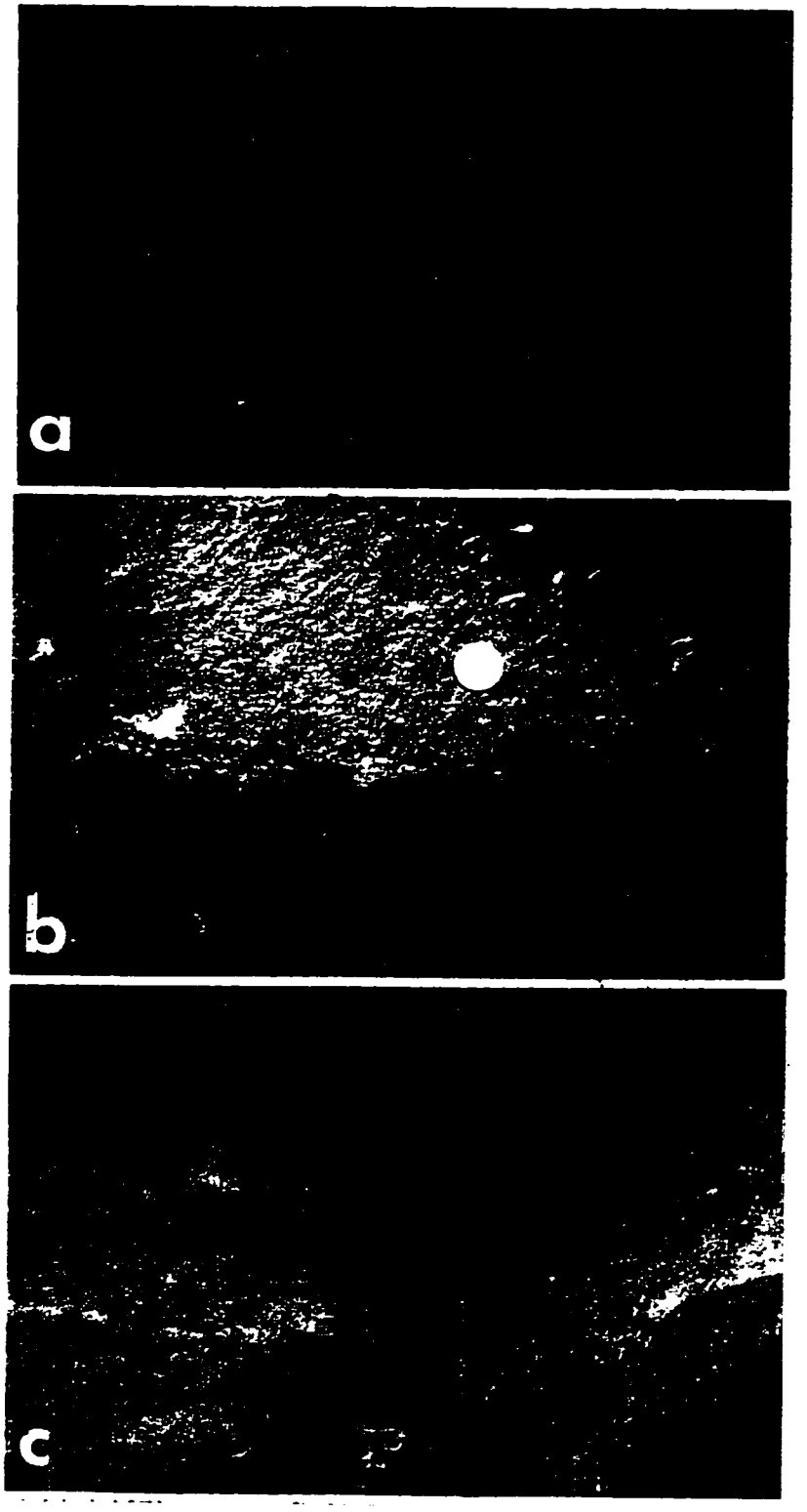

a
b
c

Fig. 4.7 Calcite nodules and lenses are locally abundant in the dolostone lithofacies. Note collapse breccia incorporated with the calcite nodules. Unit II (T-2) of the Pamelia Fm at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. The pencil is 14 cm long.

Nicolaides 1995), fenestral birdseye texture, calcite nodules (filling evaporitic sulphate molds, Veizer et al. 1978), mudcracks and thin laminations. The latter may be of microbial origin. Formation of anhydrite and gypsum nodules and *Leperditiid* ostracod in coastal supratidal flats (e.g., Trucial coast of the Persian Gulf) are well documented (Kinsman 1966). Calcite of present-day nodules in the Ottawa region precipitated in cavities, created by sulphate mineral dissolution. Fragmented host rock around the margins of these cavities suggest disruption of semi-consolidated carbonate sediments during crystallization or dissolution of the sulphate minerals. Intraclasts of dolomite lithology occurring in other lithofacies (e.g., CLF7, see below) within the Pamelia Formation suggest that the dolostone lithofacies is of primary origin. Petrographically and stratigraphically similar dolostone from the Blackriveran succession in eastern and southeastern Ontario and New York have also been interpreted as syngenetic supratidal origin (Cameron 1968; Mukherji 1969; Peterson 1969; Sawford 1972; Walker 1972; 1973; Walker and La Porte 1970; Cameron and Mangion 1977; Steele-Petrovich 1984; Noor 1989; Williams 1991; McFarlane 1992).

Microbialite lithofacies (CLF2)

Description

This lithofacies consists of two sublithofacies: (1) laminated to thinly bedded (<1 - 5 cm), medium grey, flat to wavy laminite (CLF2a); and (2) dark to medium grey stromatolitic mudstone to packstone (CLF2b). Rocks of both lithofacies weather light grey.

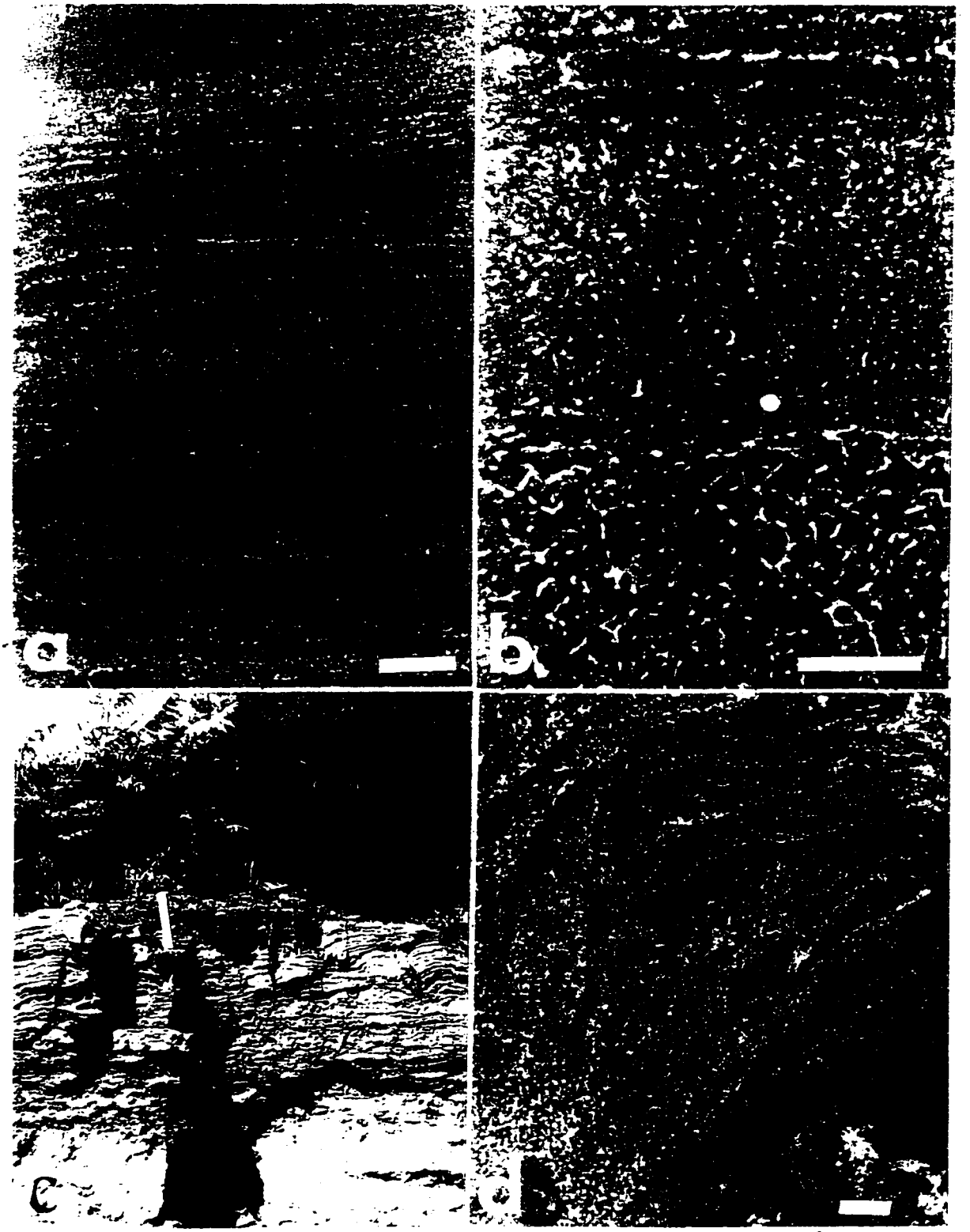
The laminite sublithofacies consists of thin microbial laminations of peloidal mudstone (Fig. 4.8a). The mudstone is characterized by dense micrite and-or clotted micrite with a mesh of fine calcite spar (minute ? fenestral fabric, Fig. 4.8b). The calcite mesh probably developed from calcite precipitation in cyanobacterial filament mold. The sublithofacies locally contains intraclasts forming flat-pebble breccia. Poorly developed mudcracks are present in this

Fig. 4.8a Microbially-laminated peloidal mudstone that forms the laminite sublithofacies of the microbialite lithofacies (CLF2). Most of the tiny white dots scattered throughout the upper 2/3rd of the photo are interpreted to be cyanobacterial molds now filled by calcite. Base of Unit IV of the Pamelia Fm. at Loc. 47, Macleod quarry, Cornwall. Scale bar is 1000 μm.

Fig. 4.8b Dense micrite "clots" with calcite cement filling irregular mesh-like porosity originated as cyanobacterial filament molds. Unit II of the Pamelia Fm. at Loc. 24, Scott St. Transitway, Ottawa. Scale bar is 1000 μm.

Fig. 4.8c LLH-type stromatolites in the field. Unit II of the Pamelia Fm. at Loc. 24, Soctt St. Transitway, Ottawa. The hammer is 25 cm long.

Fig. 4.8d Thin section micrograph of a stromatolitic mudstone sublithofacies. Note the development of calcite-filled, irregular, mesh-like porosity where cyanobacterial filaments were removed.Unit II of the Pamelia Fm. at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. Scale bar is 1000 μm.


a
b
c

sublithofacies. The microbialite lithofacies is similar to SMF-19 of Flügel (1982).

The stromatolite sublithofacies is characterized by laterally linked and stacked hemispheroids (LLH and SH, respectively, Logan et al. 1964). Rare isolated hemispheroids are locally incorporated in the laminated mudstone sublithofacies. LLH-type (Fig. 4.8c) forms represent the dominant lithotype, and consist of poorly fossiliferous mudstone (Fig. 4.8d). The mudstone shows fine irregularly interlacing mesh similar to that described in the laminite sublithofacies (CLF2a). The stromatolite sublithofacies (CLF2b) is lithologically comparable with SMF-20 of Flügel (1982)

The SH-type stromatolites are formed by intraclastic, peloidal, bioclastic, oolitic packstone. Intermound sediments are thinly bedded packstone with a lithology similar to the stromatolites. Particles of the stromatolite-forming packstone are trapped by cyanobacteria, and probably agglutinated together by sticky mucilaginous sheaths. Intraclasts in both the SH-type stromatolites and intermound sediments consist of mudstone with a mesh of fine-crystalline calcite, owing its origin to the LLH stromatolites and-or the laminite mudstone. The intraclasts range in grain size from fine sand to pebbles (80 μm - 3 mm). The fossil content is fairly high, and biociasts include ostracod, bivalves, gastropods, serpulids, calcareous algae and crinoids. Thin laminae of calcareous siltstone drape over certain layers.

Stratigraphic distribution

The microbial laminite sublithofacies (CLF2a) occurs in different intervals throughout the Pamelia Formation (e.g., units I, II, and V, see sections displaying these units in Appendix 1). Stromatolitic mudstone and packstone sublithofacies (CLF2b) are well developed in Unit II of the Pamelia Formation. At least three stromatolitic intervals are recognized in this unit. A thick LLH-type stromatolitic mudstone, which locally (e.g., Loc. 24) forms SH-type

stromatolites, occurs at the base of Unit II of the Lower Member of the formation. The other two intervals are also LLH-type stromatolitic mudstone and occur higher in the section within the unit. The three stromatolitic intervals are well developed in the Ottawa area, and can be traced to Torbolton Township (~ 40 km west of Ottawa) as mapped by Wilson (1924) (see Fig. 3.28). The concentric structure of the stromatolites becomes flatter southeastward from Ottawa, and horizontally laminated to thinly bedded microbialite mudstone become prominent towards this trend (see section at Loc. 44, Appendix 1). A thin (10 -15 cm), but areally extensive, LLH-type stromatolitic layer occurs at the base of Unit IV of the Upper Member of the Pamelia Formation (Fig. 3.14).

Interpretation

The mechanism of formation of microbial structures is well documented in the literature (Demicco and Hardie 1994; Tucker and Wright 1990; Wright 1984; Hardie and Ginsburg 1977; Logan at al. 1964). Demicco and Hardie (1994) define four categories under which modern stromatolites and cryptomicrobial laminites can be formed. These categories include: "(1) mechanical sedimentation not influenced by microbes, (2) microbially-influenced sedimentation, (3) chemical precipitation of carbonate, and (4) episodic growth of a microbial mat with little or no sedimentation or precipitation" (p. 88). Stromatolite and laminite morphologies are not entirely or exclusively the product of environmental factors (Flügel 1982). Therefore, they do not indicate any specific environment of deposition.

The microbialites in the studied area are interpreted to belong to category 2 of Demicco and Hardie's (1994) classification (see above). Agglutination of mud and silt-sized particles by microbial mats was predominant in the laminated mudstone and LLH-type stromatolite sublithofacies, whereas the microbials acted as baffles that trapped coarse

sediments (e.g., ooids, bioclasts and intraclasts) in order to form the SH-type stromatolites (Demicco and Hardie 1994). The microbial laminite mudstone (CLF2a) and the LLH-type stromatolitic mudstone were formed in a (higher) intertidal flat environment (Tucker and Wright 1990; Flügel 1982; Shinn 1986). This is suggested by the presence of desiccation cracks and their association with the dolostone and flat-breccia-rich lithofacies (CLF1 and CLF3, respectively). The tidal flat was dissected by tidal channels and the LLH-type stromatolitic mudstone formed as tidal channel levees. A similar sedimentary setting is documented from the modern carbonate tidal flats of northwest Andros Island, Bahamas (Demicco and Hardie 1994; Shinn 1986).

The framework composition of the SH-type stromatolitic packstone allows two interpretations for the depositional environment: tidal channel (Shinn 1986) or high energy subtidal (Boardman and Carney 1991) sediments. The fact that the SH-type stromatolites are localized (they are seen only at Loc. 24) and are laterally equivalent with LLH-type tidal flat stromatolitic mudstone (compare Loc. 20 with Loc. 24) suggests that they were most likely deposited in a tidal channel. In this channel, single-celled prokaryotes were capable of trapping and agglutinating the sedimentary particles onto their sticky sheaths. Such prokaryotes were capable of growing through a sediment layer immediately after being buried by the trapped or physically deposited sediments (Ginsburg 1996, pers. comm.; Demicco and Hardie 1994). The process of trapping and agglutinating continued until the thick stromatolitic unit (1.2 m at Loc. 24) was built. Presence of mudstone intraclasts among the framework grains of the stromatolitic packstone likely represent eroded margins of channel levee (Shinn 1986).

Intraclastic (flat-pebble breccia) packstone to rudstone (CLF3)

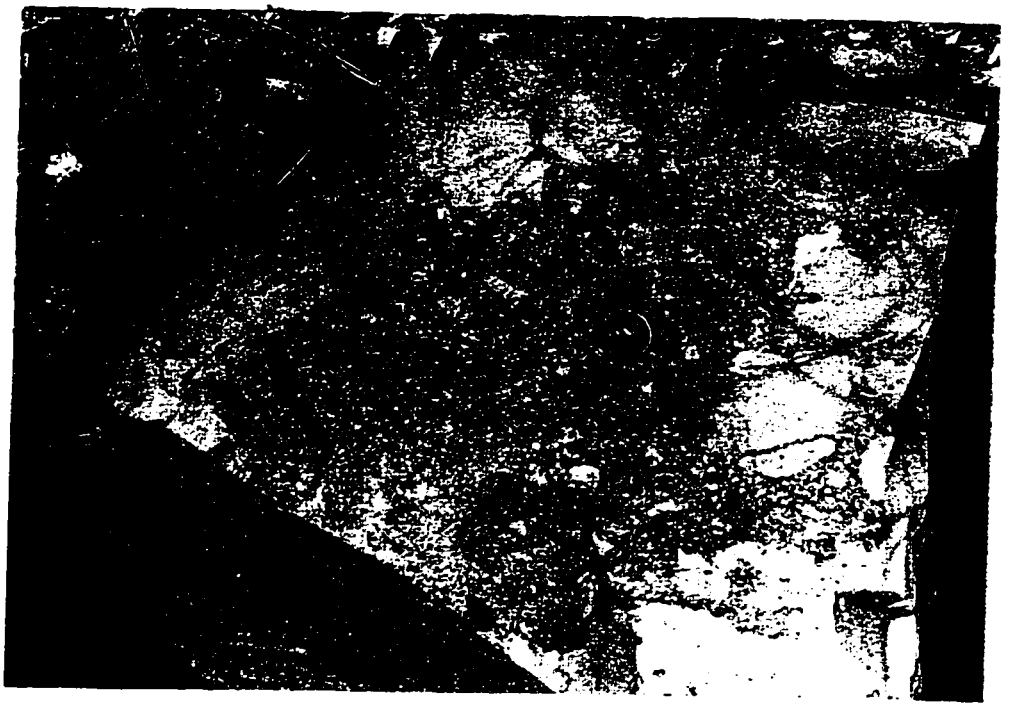
Description

This lithofacies consists of thin to medium bedded (4 to 20 cm) peloidal, intraclastic packstone to rudstone. The rock has a medium brownish grey colour on its fresh surface and weathers light (dove) grey. The intraclasts are angular, poorly sorted (fine sand to pebble size, Figs. 3.17, 4.9), thin plates (mud chips) showing no obvious imbrication. The intraclasts consist of homogeneous or internally laminated mudstone. Intraclasts often contain calcite mesh similar to that described in the microbialite lithofacies (CLF2). Mudcracks sometimes define the borders of the intraclasts (Fig. 4.9). Vertical to subvertical burrows (possibly *Psilonichnus* ichnofacies), stylolites, and fenestral (birdseye) texture are also common sedimentary structures in the CLF3 lithofacies. Fossils are generally absent; however, a few disarticulated ostracod tests have been recognized in thin section. The lithofacies is generally interbedded or interlaminated with the microbially laminated mudstone sublithofacies (CLF2a). Bioclastic packstone beds with erosional basal contacts are also locally associated with the CLF3 lithofacies. The latter can be compared with a brecciated version of SMF-19 of Flügel (1982)

Stratigraphic distribution

This lithofacies is present in Unit V of the Upper Member of the Pamelia Formation. It also forms local, discontinuous, relatively thin intervals within Unit II (e.g., Loc. 44) of the Lower Member of the Pamelia Formation. The lithofacies is not recognized in the Lowville and Chaumont formations.

Fig. 4.9 The intraclastic packstone to rudstone lithofacies is characterized by flat-pebble breccia. The intraclasts consist of thin mudchips with little current or wave reworking. They were likely formed from desiccated mudstone lithofacies with which the intraclasts are associated. Mudcracks (arrow) sometimes define the borders of the intraclasts indicating preservation of *in situ* mudchips. Unit V of the Pamelia Fm. at loc. 24, Scott St. Transitway, Ottawa. The coin is 20 cm in diameter.



Interpretation

The mud-size composition of the intraclasts, combined with scarce and low diversity fauna, desiccation cracks, and fenestral birdseye texture which are common in the CLF3 lithofacies suggest that the intraclasts were derived from a low energy, hypersaline, tidal - supratidal flat. The formation of the intraclastic breccia is attributed to poorly-reworked mudchips created from cracked (due to desiccation) mud laminite (e.g., CLF2). This kind of sedimentation is ubiquitous in low energy, high intertidal flats to supratidal environments (Demicco and Hardie 1994; Pratt et al. 1992; Flügel 1982). This interpretation is also supported by the fact the CLF3 is associated with high intertidal flat lime mudstone laminites (CLF2). Accumulation of bioclastic packstone associated with this lithofacies can be interpreted as shallow, poorly developed incipient intertidal channels or storm sediment.

Bioclastic mudstone and wackestone (CLF4)

Description

This lithofacies is made up of laminated to medium bedded (<1 - 20 cm), light (dove) grey to medium brownish grey (intraclastic) peloidal bioclastic mudstone to wackestone (Fig. 4.10). The dove grey beds weather to whitish grey whereas the medium brownish grey beds weather light brownish grey. Thin (< 1 cm) horizontal to irregular shaly partings are common in the lithofacies. Where these shaly partings are abundant, the rock produces a rubbly texture. Other sedimentary structures include fenestral fabric, horizontal burrows, stylolites, mudcracks and thin laminations. The latter two structures are not very common.

The lithofacies is associated with the *Tetradium*-rich floatstone - bafflestone (CLF5, see below). Thin lenses and laminae of bioclastic and peloidal packstone, as well as dolostone beds are locally associated with this lithofacies. Vertical burrows are observed where

Fig. 4.10 Thin section micrograph of bioclastic wackestone with various fossil fragments. The most abundant bioclasts in this lithofacies are *Tetradium* (t) corals and ostracods. A Solenopora algae (s) and mollusk fragments are also present. Unit IV of the Pamelia Fm. at Loc. 47, Macleod quarry, Cornwall. Scale bar is 1200 μm.

packstone is interlaminated with the lithofacies. The latter may be lithologically comparable with SMF-19 and SMF-22 of Flügel (1982), but lacks oncoids.

The lithofacies is poorly to moderately fossiliferous. Bioclasts include: ostracods, *Tetradium* corals, gastropods, bivalves, crinoids, bryozoans, trilobites, *Solenopora*, oncolites and orthocones. Other uncommon framework grains in this sublithofacies include intraclasts (flat-pebble breccia and conglomerate), ooids, and quartz grains that may locally make up to about 20% of the rock.

Stratigraphic distribution

This lithofacies occurs in the Pamelia and Lowville formations. In Unit I of the Pamelia Formation it develops as thin beds of ostracodal and rarely bryozoan mudstone to wackestone interbedded with thin-bedded shale of TLF3. The lithofacies is also present in units II and V, and poorly represented in Unit VI of the Pamelia Formation. In Unit II, it is predominant in the upper part, whereas in Unit V, it occurs rhythmically throughout the unit. In Unit VI, minor interbeds of the lithofacies occur in the upper part (but below the highest dolostone). In the Lowville Formation, the mudstone-wackestone lithofacies is more common in the upper part where it is strictly associated with the *Tetradium*-rich lithofacies (CLF5).

Interpretation

This lithofacies reflects deposition in a low-energy, peritidal environment. Bioclastic and-or oolitic mudstone and wackestone interbedded with subtidal *Tetradium*-rich bafflestone and floatstone are interpreted to have formed in a subtidal lagoonal environment. However, a restricted (hypersaline) tidal flat to supratidal pond is suggested where the mudstone and wackestone display mudcracks, flat-pebble breccia and conglomerate, fenestral fabric, high

amount of terrigenous grains, limited fauna content (particularly ostracods); or, as also found in the Pamelia Formation, interbedded with dolostone lithofacies (Flügel 1982).

Bioclastic floatstone to bafflestone (CLF5)

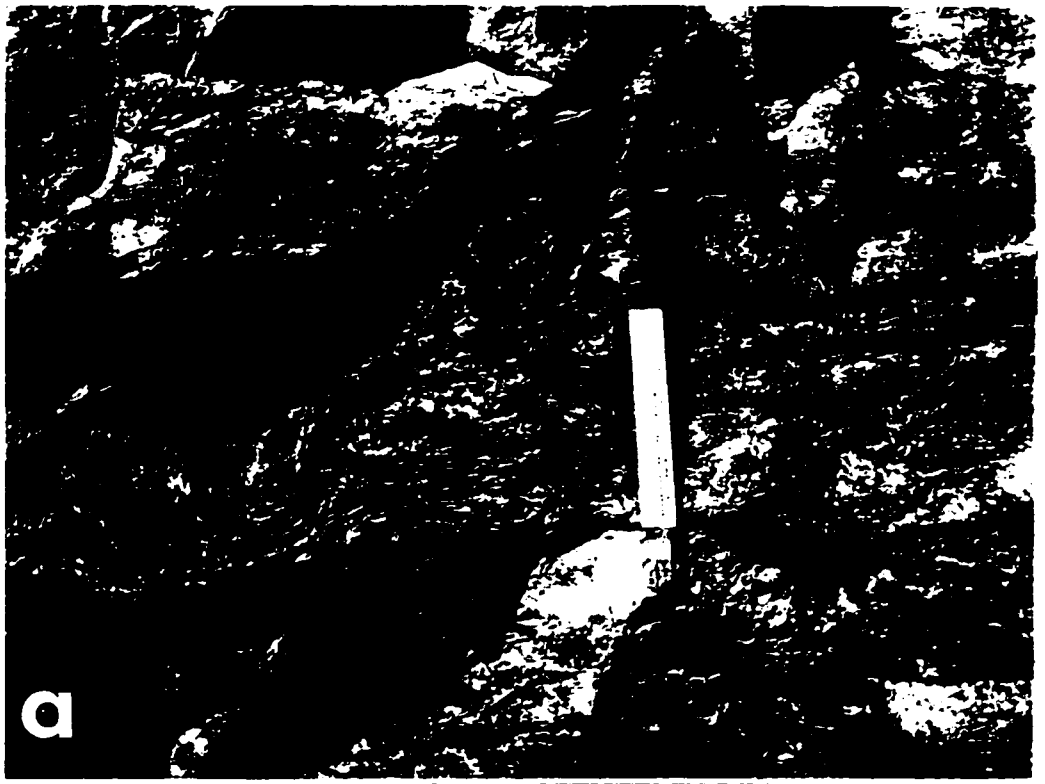
Description

This lithofacies consists of medium to dark grey peloidal, bioclastic floatstone to bafflestone. It weathers to a light (ashen) grey colour. Beds are generally thin to medium (3 - 15 cm) thick but locally reach thickness of up to 35 cm. The dominant bioclasts in this lithofacies are *Tetradium* corals (Fig. 4.11a). Branching bryozoans may locally be the most abundant baffle organisms (Fig. 4.11b). *Tetradium cellulosum* and *T. fibratum* were recognized during mapping, and *T. syringoporoides*, *T. clarki* and *T. halysitoides* have been reported by other workers (Wilson 1946; Sawford 1972; Steele-Petrovich 1984). *Tetradium* corals form vertical to subvertical digitate colonies surrounded by micrite matrix. However, fragmented corals (> 2 mm) are also common in the lithofacies. Locally abundant, fallen colonies and branches form rudstone layers. The corallites, whether in growth position or broken, are leached and filled by blocky calcite spar. This produces the white calcite strips that Wilson (1946; 1932) referred to as "typical birdseye effect of the Lowville Formation" or *Phytopsis tubulosum* (Young 1943a; Wilson 1932; Raymond 1931). However, micrite and-or peloid matrix, instead of calcite, sometimes fill the corallites (space originally filled by organic matter) and preserve the general corallite morphology. Other bioclasts in the lithofacies include ostracods, bivalves, gastropods, trilobites, orthocones, and *Solenopora* (algae). Regular to irregular thin dark shale is common in the lithofacies. Where shale content is high, the rock shows a rubbly appearance. Horizontal burrows are present but not common.

The lithofacies is associated with the bioclastic and oolitic packstone - grainstone

Fig. 4.11a *Tetradium* corals are the most abundant organisms that form the floatstone - bafflestone lithofacies. Note vertical to subhorizontal branching of the *Tetradium* colony. These branches were capable of baffling waves and currents, promoting accumulation of relatively fine-grained peloidal and bioclastic particles as well as micrite. Lowville Fm. at Loc. 34, Francon norhtern quarry, Blackburn Hamlet, Gloucester. The ruler is 6 inches (19.6 cm) long.

Fig. 4.11b Branching bryozoans locally form the dominant baffle organisms. The photo shows interbedded floatstone and bafflestone. Although bryozoan branches are mostly broken, some vertical to subvertical branches (arrows) are preserved. Unit V of the Pamelia Fm. at Loc. 34, Francon norhtern quarry, Blackburn Hamlet, Gloucester. The coin (loony) is 2.5 cm in diameter.


a

lithofacies (CLF6 & CLF7, respectively, see below). The upper boundary of the floatstone-bafflestone lithofacies is generally erosional or sharp when succeeded by grainy lithofacies, CLF6 and-or CLF7 (see below). However, its lower boundary is usually abrupt (or locally interbedded) with the bioclastic and-or oolitic packstone to grainstone (CLF6 & CLF7) lithofacies. Thin interbeds of locally mudcracked bioclastic mudstone and wackestone (CLF4) are also present within the floatstone - bafflestone lithofacies.

Stratigraphic distribution

This lithofacies is well developed throughout the Lowville Formation, becoming abundant in the uppermost part (about the upper 3 metres, see sections at Appendix 1). The lithofacies is poorly developed in the lower part of Unit IV and the upper part of Unit V of the Pamelia Formation in the Ottawa area. In the former unit, limestone beds with *in situ* isolated colony of *Tetradium* (~ 20 cm wide, Loc. 24) are interbedded with the dolostone lithofacies (CLF1). In localities 24 and 34, bryozoan bafflestone occurs at the upper part of Unit V (Fig 4. 11b).

Interpretation

The interbedded character of this lithofacies with bioclastic and oolitic packstone to grainstone lithofacies (CLF6 and CLF7, respectively, see below) in the Lowville formation suggests that it likely developed in an open, subtidal lagoon protected by the bioclastic and oolitic shoals (see also Noor 1989; Read 1980; Walker 1973; 1972). Occasional intertidal environment is suggested by the mudcracked mudstone and wackestone lithofacies. Beds containing *in situ* colonies of *Tetradium*, and interbedded with supratidal dolostone of the Pamelia Formation (see above), may also indicate that *Tetradium* corals developed adjacent

to intertidal - supratidal environments. The *Tetradium* corals were capable of baffling waves. Such effectiveness is demonstrated by upright branches of the organisms which lie imbedded in the fine-grained carbonate matrix (Walker and La Porte 1970; Walker 1973; 1972; Cameron and Mangion 1977; McFarlane 1992). Interbeds of *Tetradium*-rich rudstone also suggest that episodic elevated levels of wave or current energy which broke branches of the corals. The interpreted environment may be equivalent to Walker's (1973) wave baffle margin where lithology is dominated by "biopelsparite containing fallen *T. cellulosum* coralla and coarse silt to fine sand size pellets with sparry calcite cement. ..... This lithology is composed of debris derived from the wave-baffle" (pp. 29-30).

Bioclastic packstone to grainstone (CLF6)

Description

This lithofacies consists of thinly to thickly (2 - 40 cm) bedded, medium to dark brownish grey packstone to grainstone. Framework grains are dominated by bioclasts (Fig. 4.12); however, peloids, ooids and intraclasts are also present and locally abundant. The intraclasts consist of either lime mud or fine-crystalline dolo-mudstone. The lithofacies weathers to a medium brownish grey. Planar and cross bedding, current and wave ripple marks, scoured surfaces, vertical and horizontal burrows, horizontal to irregular shaly partings, and birdseye texture due to calcite fill in once-present shelter porosity are common sedimentary features in the lithofacies. Graded and laminated geopetal fill in intra-skeletal porosity is also present.

Bioclasts form over 50% of the framework. They are generally of sand-size (80 μm - 2 mm) but pebble-size grains (up to 3.4 mm) are also present. Fossils include bivalves (Fig. 4.12a), ostracod, trilobites, *Tetradium* corals, bryozoans, serpulid worms, gastropods,

Fig. 4.12a The bioclastic packstone to grainstone lithofacies is generally dominated by bivalve shells. Bivalves are leached out and their outlines are usually preserved by micrite envelope. Molds are filled by various cement generations. Lowville Fm. at Loc. 19, McCarthy Road at Walkley Road, Ottawa. Scale bar is 500 μm.

Fig. 4.12b Other bioclasts which are locally dominent in the bioclastic packstone - grainstone lithofacies include possible phylloid algae. Note also the stylolitic nature along surfaces of the ? algal fragments. Unit II of the Pamelia Fm. at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. Scale bar is 500 μm.

brachiopods, calcareous (? phylloid) algae (Fig. 4. 12b), *Solenopora*, crinoids and orthocones. *Tetradium* corals are generally fragmented and redeposited, but are locally in growth position. Overturned colonies of *Tetradium fibratum* are also present. Bioclasts (particularly bivalves, gastropods, calcareous algae and *Tetradium* corals) have been leached, and filled by blocky calcite. Their outlines are usually preserved by micrite envelopes. The lithofacies is comparable with SMF-11 of Flügel (1982).

The lithofacies is usually interbedded with oolitic packstone and grainstone of lithofacies CLF7 (see below). It also forms local thin to medium interbeds in the bioclastic mudstone and wackestone, and *Tetradium*-rich bafflestone of CLF4 and CLF5, respectively. Ooid grains in the bioclastic packstone and grainstone may represent as much as 25 % of the rock. Ooid grains range from 80 μm to 360 μm in size. Contacts between this lithofacies (CLF6) and ooid-dominated lithofacies of CLF7 (see below) is generally gradational or sharp. Bioclastic packstone and grainstone lithofacies (CLF6) has an erosional lower contact where it overlies muddy lithofacies (e.g., CLF4 or CLF5), but the former shows a gradational or sharp contact where overlain by the muddy facies.

Stratigraphic distribution

This lithofacies occurs in units II and VI of the Pamelia Formation, and throughout the Lowville Formation. Rare thin beds of coarse-grained bioclastic grainstone locally occur in the Chaumont Formation. Thin bioclastic packstone beds, with *in situ* growth of serpulid worm (*Cornulites*) colonies, occur in Unit II of the Pamelia Formation in the Ottawa area (Locs. 16 & 24). The same unit contains a grainstone with elongated plates of calcareous (possibly phylloid) algae (Fig. 4.12) in Locality 44. Other bioclastic packstone and grainstone

beds in the studied area are commonly dominated by ostracods and-or bivalves (Pamelia & Lowville Fms) or crinoids and brachiopods (Chaumont Fm).

Interpretation

High faunal diversity, relatively coarse framework grains, and sedimentary structures preserved in this lithofacies indicate a normal-marine, high-energy depositional setting. This lithofacies is interpreted to represent hydrodynamic shallow subtidal to intertidal sand bars subject to constant wave agitation. Lateral migration of these bars developed lower scoured contacts as well as erosional surfaces within the lithofacies.

Oolitic packstone and grainstone (CLF7)

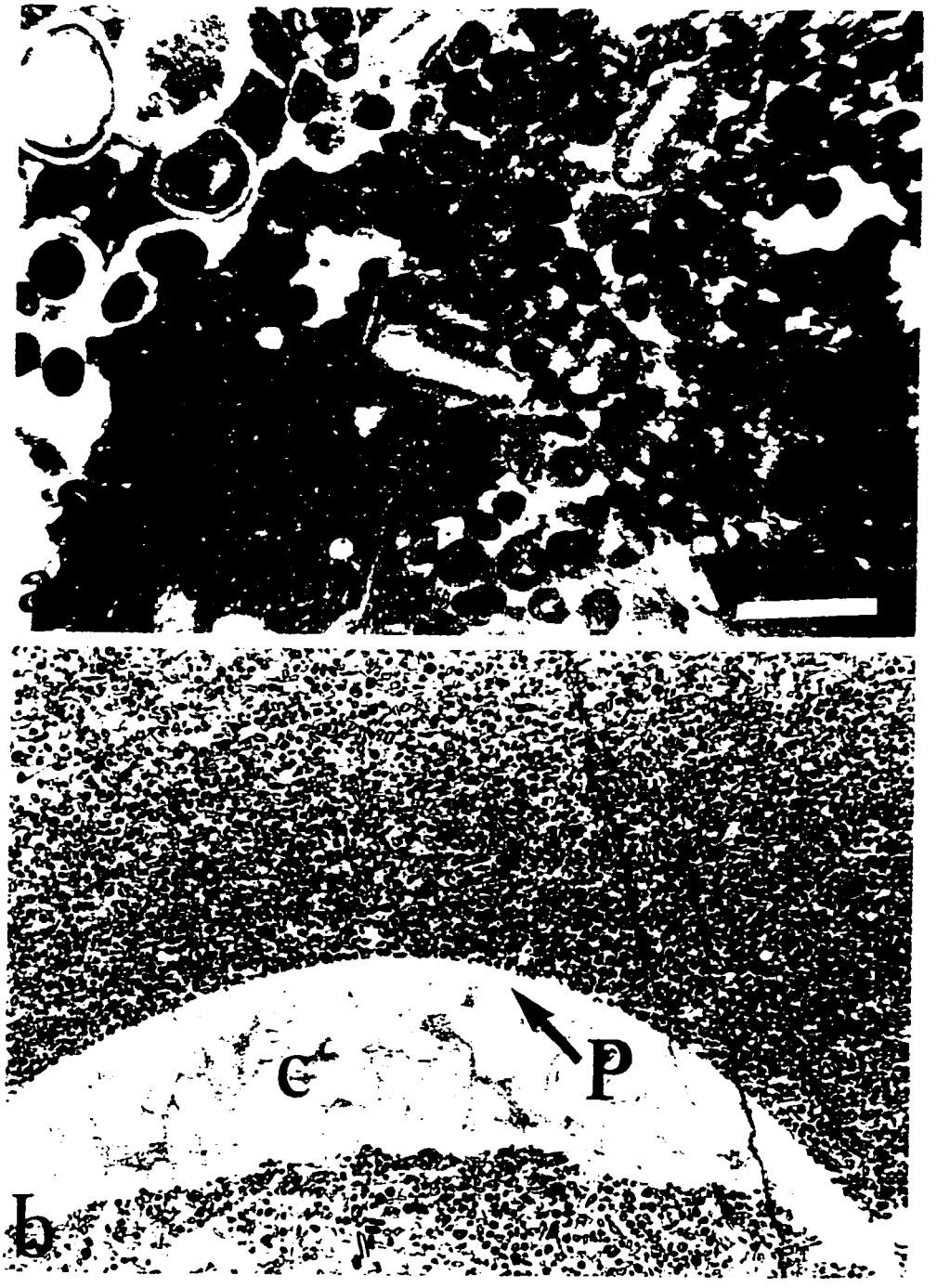
Description

This lithofacies consists of thinly to thickly (5 - 40 cm) bedded, dark brownish grey intraclastic, bioclastic, oolitic packstone to grainstone (Fig. 4.13a, b). It weathers to medium (brownish) grey. Quartz grains are usually present and may locally reach up to 5%, but generally represent less that 1% of the rock. Sedimentary structures in the lithofacies include planar bedding and tabular (rarely trough) cross-bedding (Fig. 3.12), current and interfacing wave ripple marks, scoured surfaces, imbrication of intraclasts and elongated ooids and bioclasts and normal grading. Calcite-filled fenestral (birdseye) fabric is locally present. Intraclast grains consist of both dolomite and lime mudstone.

Ooids form the dominant framework component in this lithofacies. They are spherical to elongated. Although the grain size of the ooids generally varies from 50 μm to 1 mm in studied thin sections, a given rock specimen shows good to moderate sorting. Ooid cores are

Fig. 4.13a Photomicrograph showing bioclastic, oolitic packstone lithofacies. Unit II of the Pamelia Fm. at Loc. 24, Scott St. Transitway, Ottawa. Scale bar is 600 μm.

Fig. 4.13b Photomicrograph of bioclastic, oolitic grainstone. Large, concave-downward, bivalve shells (mostly *Cyrtodonta* sp.) are common in this lithofacies. These shells create shelter porosity which is later filled by various generations of calcite cement including prismatic (p), and blocky calcite (c). Unit II of the Pamelia Fm. at Loc. 24, Scott St. Transitway, Ottawa. Scale bar is 600 μm.


c
p
b

mostly bioclasts, now displaying leached bivalves, but quartz, ooid fragments, and pelletoids are other ooid nucleii. The ooids consist of concentric thin laminae with radially arranged calcite crystals.

Bioclasts are second in abundance in this lithofacies. They are generally coarser-grained than the ooids, ranging from fine sand to pebble size. Bioclasts include bivalves (*Cyrtodonta sp.*), ostracod, trilobites, *Tetradium* corals, bryozoans, serpulid worm tubes, gastropods, crinoids and orthocones. This fauna is dominated by *Cyrtodonta sp.* The shells are generally found concave-downward, and create sheltered spaces now filled by blocky calcite spar (Fig. 4.13b). Intraclasts are sand to pebble in size, and consist of lime and dolomitic mudstone. Intraclasts of bioclastic and oolitic packstone are also present. Framboidal pyrite and authigenic quartz are present in this lithofacies.

The oolitic packstone to grainstone lithofacies is comparable with SMF-15 of Flügel (1982). It is generally interbedded with CLF6 (see above) with gradational to sharp contacts. It is also locally present as thin beds within CLF4 and CLF5.

Stratigraphic distribution

Oolitic packstone and grainstone lithofacies occur in both Pamelia and Lowville formations, and have not been found in the Chaumont Formation. It occurs in Unit II and Unit VI of the Pamelia Formation. The lithofacies is present in various intervals throughout the Lowville Formation, and is pronounced in the lower two-thirds of the formation.

Interpretation

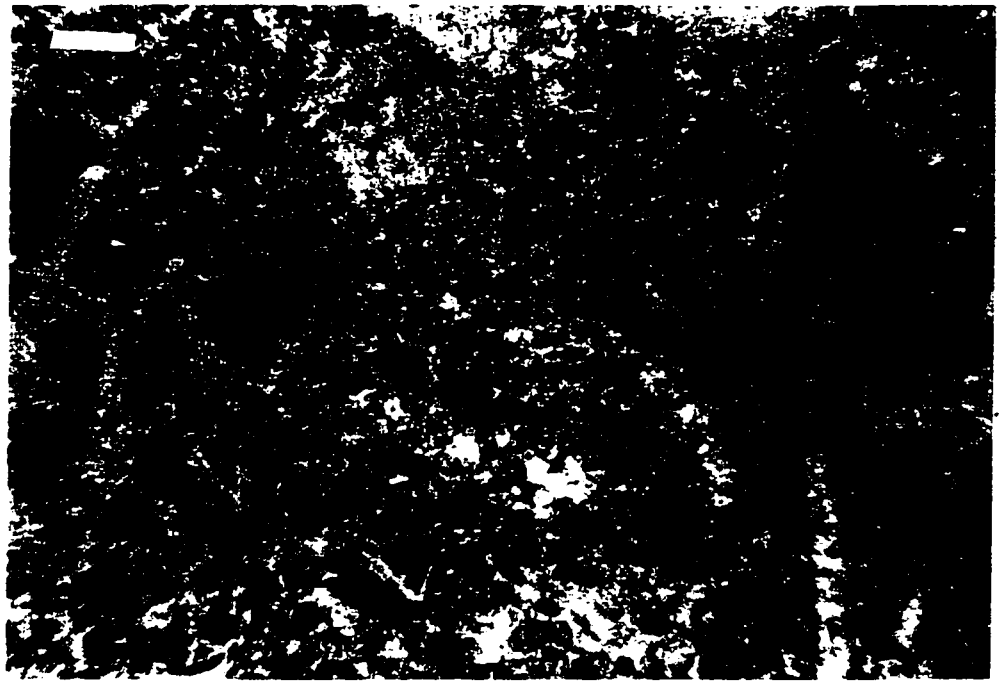
Marine ooids form mostly in very shallow (generally less than 2 m deep) tropical marine settings (e.g., oolite shoals of the Bahama Bank and Arabian Gulf, Flügel 1982; Tucker and Wright 1990). The grain size of the ooids is directly proportional to the ambient energy (Flügel 1982). The predominantly grainstone and packstone texture, moderate to good sorting, abraded bioclasts, and planar to cross-stratified character of this lithofacies suggests a high-energy depositional setting in which currents and-or waves actively reworked and transported carbonate sand. The lithofacies is interpreted to have been formed in a shallow, fairly high-energy subtidal environment. It developed oolitic sandflats and-or shoals. Isolated beds of oolitic packstone or grainstone within intertidal or lagoonal mudstone facies may represent local spill-overs behind or in front of this environment. Alternatively, these oolitic packstone and grainstone beds may represent short-lived subtidal sand shoals.

Burrowed, bioclastic peloidal wackestone to packstone (CLF8)

Description

This lithofacies is made up of medium to very thick beds (~ 20 - >100 cm, Fig. 3.24) of medium to dark grey bioclastic peloidal wackestone and packstone (Fig. 4.14). It weathers to a medium grey. The lithofacies is intensely horizontally burrowed (*Planolites* ichnofacies). The burrows are quite large (may reach up to 2 cm in diameter) and inter-connected. Burrow-filled sediment is usually dolomitized and weathers to a lighter colour than the rest of the rock. Such differential weathering gives the rock a mottled appearance (Fig. 3.25). Although the burrows are abundant in the lithofacies, they decrease in abundance upsection as well to the west of Ottawa.

Fig. 4.14 A thin section photomicrograph showing bioclastic, peloidal packstone lithofacies (CLF8). Chaumont Fm. at Loc. 34, Francon norhtern quarry, Blackburn Hamlet, Gloucestter. Scale bar is 300 μm.



Framework grains in this lithofacies are predominantly peloids or bioclasts. The peloids are silt- to fine-sand size, and may locally reach up to 35 % of the rock. The overall percentage decreases up-section. Bioclasts are generally fine to medium sand size. Contrary to the distribution of the burrows, the bioclasts become coarser and more volumetrically significant upsection and to the west within the Ottawa Embayment. Oversized bioclasts, including domal tabulate corals (in life position) and solitary corals (*Foerstephyllum halli* and Rugosa, respectively), brachiopods, orthocones and crinoid stems are the most common fossils in this lithofacies. Other fossils include bivalves, bryozoans, ostracods, gastropods, and trilobites. Rare black chert nodules are also present. The lithofacies is comparable with SMF-9 of Flügel (1982).

Thin (millimetre-thick) irregular and laterally discontinuous laminae of shale are common throughout the lithofacies, and create an irregular, anastomosing parting fabric. Coexistence of these shaly partings and intense burrow fabric renders a poorly-developed nodular appearance to the lithofacies. Other sedimentary structures include planar and stylolitic bed contacts and hardground surfaces.

Stratigraphic distribution

This lithofacies is the major constituent of the Chaumont Formation. It seldom occurs in the overlying Bobcaygeon Formation. The lithofacies is not apparently incorporated with any depositional cycles comparable with the higher order ones interpreted to occur in the Pamelia and Lowville formations (see below).

Interpretation

Predominance of fine- to medium-grained framework grains, diversified open marine fauna and extensive occurrence of *Planolites* ichnofacies indicates subtidal, low to medium energy depositional environment overwhelmed by deposit feeders (Pemberton et al. 1992). The depositional site was below wave-base level as suggested by absence of wave and current bedforms and presence of "level-bottom marine community" (e.g., orthocones, *Foerstephyllum* corals, and brachiopods, see Walker, 1972). Bioclastic peloidal wackestone and packstone lithofacies with dolomitized worm burrows and diverse biota (e.g., corals, crinoids, brachiopods, bryozoans, nautiloids, etc) are recognized in Blackriveran strata in Kingston (McFarlane, 1992) and New York (Walker, 1972, 1973, Textoris, 1968) regions, and are interpreted to have formed in subtidal, below wave-base setting. There are similar facies, interpreted as subtidal deposition, documented in Ordovician rocks at Ida and Surprise bays in southern Tasmania, Australia (Burrett et al. 1984).

Vertical facies association of the Blackriveran strata in the Ottawa Embayment

Introduction

Vertical lithofacies associations of the Pamelia and Lowville formations are characterized by shallowing-upward successions, and produce vertically-stacked rhythmic units. This rhythmic sedimentation is not recognized in the Chaumont Formation; however, the latter appears to shallow upwards. Previous work interpreted the Blackriveran succession in the Ottawa Valley, in general terms, as shallow marine deposits (Sawford 1972; Steele-Petrovich 1984) but did not report any rhythmic sedimentation. The purpose of this section is to present evidence for the repetitive, vertically-stacking patterns within the Pamelia and Lowville formations to enable reconstruction of reliable depositional models (see Chap. 5)

and intrabasinal sea level changes through time (see Chap. 8).

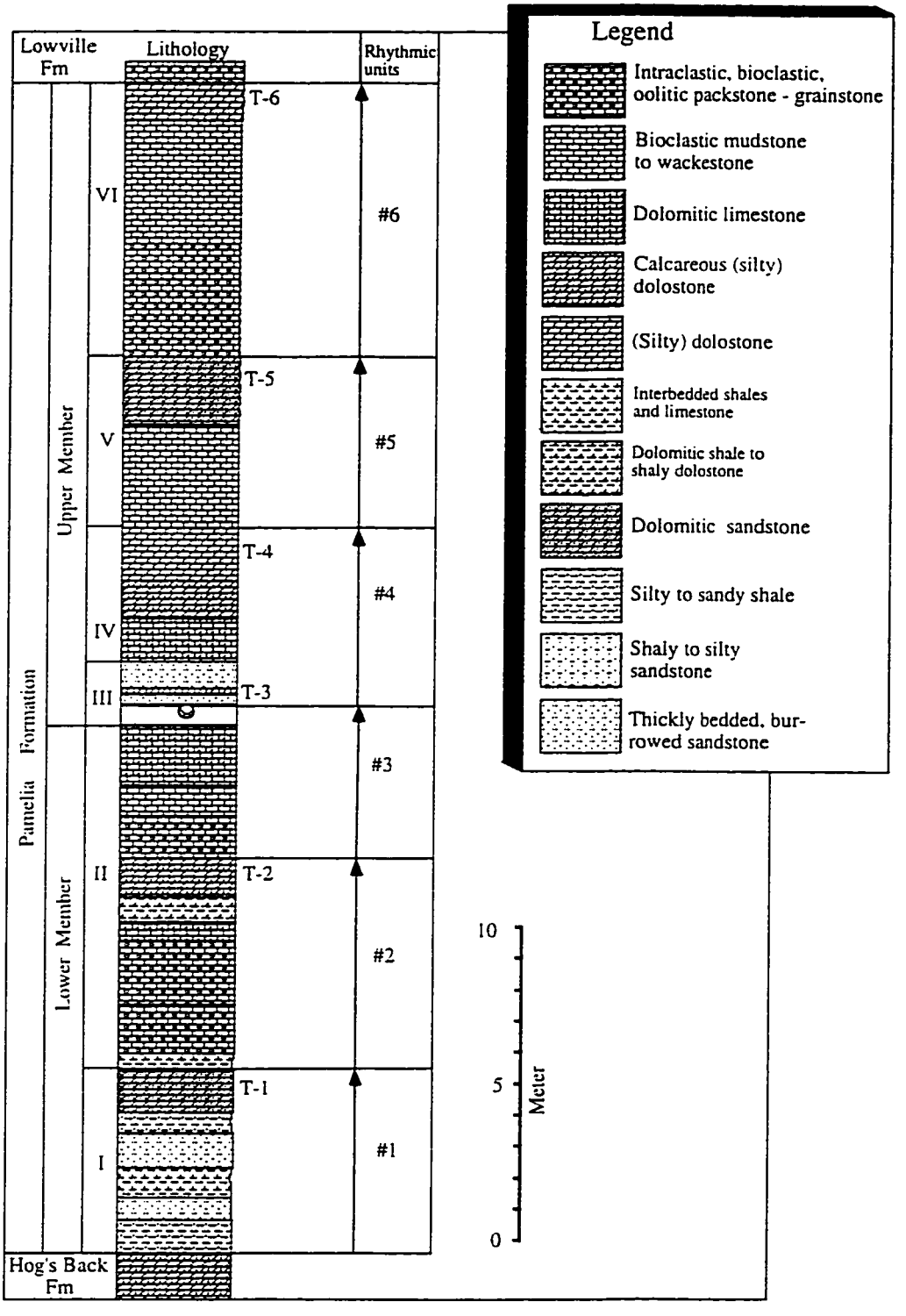
Determination of rhythmic sedimentation in the Pamelia and Lowville formations is based on sedimentologic features that include vertical facies association defined by types of framework grains, grain size, textural differences, sedimentary structures, and composition. The Pamelia Formation consists of six, about 5 to 9 m thick, shallowing-upward successions (Fig. 4.15). Vertical facies associations of these successions can be grouped under two stacking patterns; Stacking Pattern-A referred to as SP-A and Stacking Pattern-B referred to as SP-B. There are higher order rhythmic units within each shallowing-upward succession (Salad Hersi and Dix 1997b, see also below). The Lowville Formation consists of four rhythmic units, each displaying a common stacking pattern (Stacking Pattern-C). Like the rhythmites of the Pamelia Formation, the Lowville Formation may locally display higher order, minor stacking patterns that are superimposed on the dominant succession. Reconstruction of sea level curves from the facies association within the rhythmites is based on the assumption that, where continuity of depositional environments, as interpreted from the preserved facies association (e.g., subtidal through intertidal to supratidal), is recognized, the relative sea level change was gradual. If there is no continuity of the depositional environments (e.g., subtidal to supratidal with no intertidal sediments preserved), the sea level change was relatively rapid. In this case, sea level curve is shown with sharp change, rather than gradual change.

Rhythmites in the Pamelia Formation

Stacking Pattern - A

SP-A is well represented in the siliciclastic-dominated Unit I of the Pamelia

Fig. 4.15 The Pamelia Formation consists of six rhythmic units (#1 to #6). The tops of these units are defined by (dolomitic) sandstone to (sandy) dolostone layers (T-1 to T-6). Rhythmite #3 a dolomitic lime mudstone followed by quartz arenite beds (lower part of Unit III) in its upper part. The quartz arenite has gypsum (shown by XRD) and gypsum molds, and is interpreted as intertidal sediment. It forms the top of this rhythmic unit. The upper part of Unit III is interpreted as subtidal to intertidal sandstone and forms the basal part of rhythmite #4.


Lowville Fm
Lithology
Rhythmic units
Pamelia Formation
Upper Member
Lower Member
VI
V
IV
III
II
I
T-6
T-5
T-4
T-3
T-2
T-1
#6
#5
#4
#3
#2
#1
Hog's Back Fm
10
5
0
Meter
Legend
Intraclastic, bioclastic, oolitic packstone - grainstone
Bioclastic mudstone to wackestone
Dolomitic limestone
Calcareous (silty) dolostone
(Silty) dolostone
Interbedded shales and limestone
Dolomitic shale to shaly dolostone
Dolomitic sandstone
Silty to sandy shale
Shaly to silty sandstone
Thickly bedded, burrowed sandstone

Formation, and forms the lowest of the six rhythmic units in the formation. Rocks which build this pattern consist of basal transgressive shale (TLF3), followed by interbeds of the quartzwacke (TLF1), shale (TLF3) and minor bioclastic wackestone (CLF4) lithofacies (Fig. 4.16), and then followed by supratidal dolomitic sandstone (Ottawa area) or pure to sandy dolostone (eastern localities, e.g., Loc. 44, Fig. 4.17). The interbedded units are arranged in such a manner so as to produce thinner rhythmite sets within SP-A. The thinner rhythmites usually have shaly bases that grade up to quartzwacke (SP-A1) or shale and limestone interbeds followed by the quartzwacke facies (SP-A2) or shale followed by dolomitic sandstone to pure to sandy dolostone facies (SP-A3, Fig. 4.17).

Stacking Pattern - B

This type of stacking pattern characterizes the carbonate-dominated strata in both lower and upper members of the Pamelia Formation (Units II, IV, V, and VI). Stacking Pattern B defines the upper five rhythmites in the formation. The lower part of SP-B is usually dominated by subtidal coarse grained lithofacies (e.g., CLF6 & CLF7) with (locally) transgressive subtidal shale (TLF3). This is followed by intertidal, fine-grained bioclastic and-or intraclastic (flat pebble breccia) wackestone (locally rudstone), mudstone, and-or microbially laminated mudstone (CLF2, CLF3, and CLF4). The upper part of SP-B consists of supratidal sandy to pure dolostone lithofacies (CLF1) (Fig 4.18). Erosional surfaces, due to the transgressive nature of the basal grainy lithofacies (CLF6 & CLF7), often occur at both boundaries of the rhythm. The subtidal-intertidal lithofacies of the rhythmites defined by SP-B show higher order rhythmics pattern which are superimposed on the gross SP-B pattern. These sub-rhythmites include four types, SP-B1, SP-B2, SP-B3, and SP-B4, and define

Fig. 4.16 Field view of Stacking Pattern A. Shale interbedded with mudstone lithofacies are overlain by thick quartzwacke lithofacies. The lower part of the photo (below the hammer) is a sandstone bed which defines uppermost unit of one rhythmic unit, and the remaining part of the photo represents a second rhythmic unit. Unit I of the Pamelia Fm. at Loc. 20, Prince of Wales Falls, Ottawa. The hammer is 25 cm long.

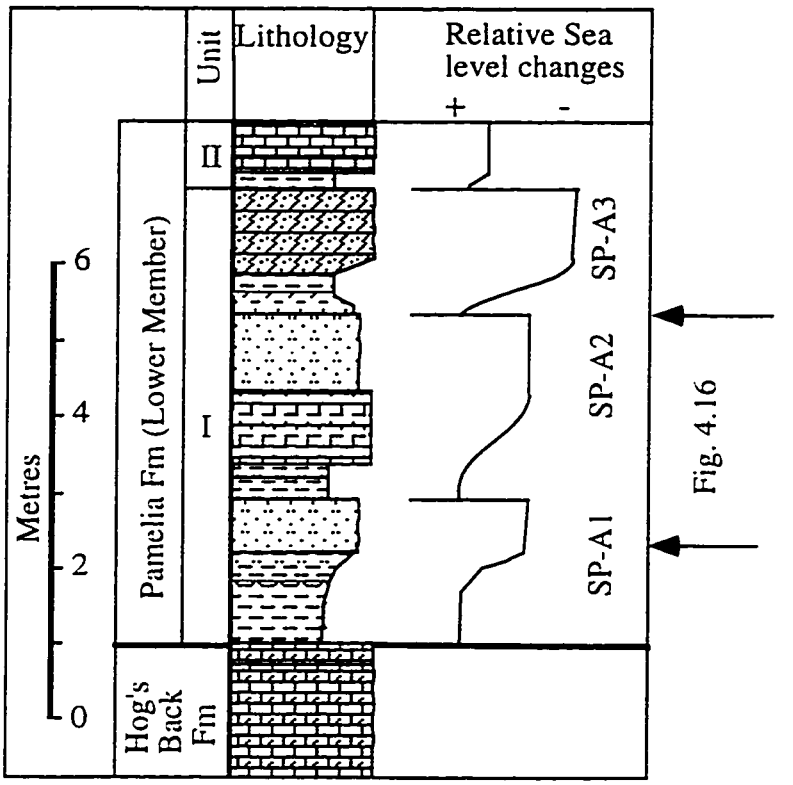


Fig. 4.17 Stacking pattern A (SP-A) is characterized by repetitive units of mostly siliciclastic lithofacies which define an overall shallowing-upward (falling sea level) succession. Higher order rhythmic units (SP-A1, SP-A2, and SP-A3) are superimposed on the general shallowing upward trend. The section is taken from the basal siliciclastic beds of the Lower Member of the Pamelia Formation at Loc. 20

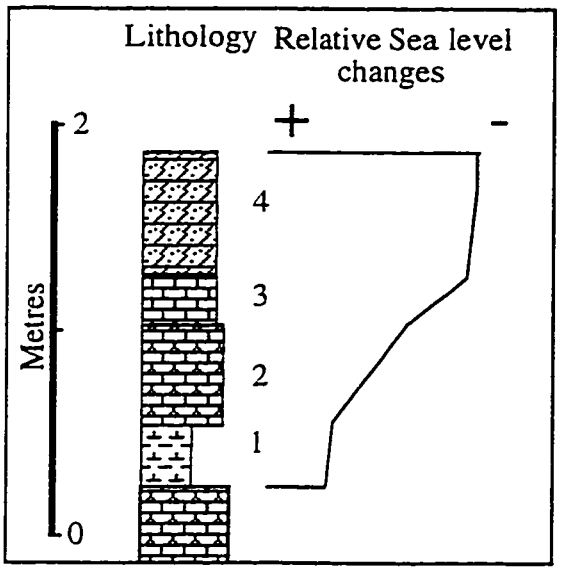


Fig 4.18 Stacking pattern B1 (SP-B1) is characterized by subtidal calcareous shale (1) and bioclastic packstone (2), intertidal mudstone (3), and supratidal dolomitic sandstone to sandy dolostone (4). This describes a gradual sea level drop.

higher frequency, shallowing-upward successions.

SP-B1 consists of recurring units (within 1 to 1.5 m) of thin- to medium-bedded, basal transgressive (calcareous) shale (TLF3) followed by subtidal bioclastic packstone (CLF6) and-or intraclastic, bioclastic, oolitic packstone - grainstone (CLF7). The basal shale facies may be locally missing. In the upper part of SP-B that is characterized by SP-B1 repetitive units, the subtidal shales and packstone - grainstone lithofacies pass into intertidal mudstone (CLF4), which is then succeeded by the dolostone lithofacies that caps the SP-B-type rhythmite (Fig. 4.18). SP-B1 usually occurs in the upper parts of units II, V, and throughout Unit VI of the Pamelia Formation.

SP-B2 rhythmites are characterized by a lower, subtidal bioclastic packstone (CLF6) or (rarely) intraclastic, bioclastic, oolitic packstone - grainstone lithofacies (CLF7) succeeded by dolostone of CLF1 (Figs. 4.19, 4.20). This type of rhythmic pattern occurs in the lower part of Unit IV. A rare succession contains oolitic packstone - grainstone lithofacies at the base, and occurs only in the upper part of Unit V at Locality 44.

SP-B3 consists of intraclastic, bioclastic, oolitic grainstone interbedded with or overlain by bioclastic packstone, then followed by laterally linked hemispheroids (LLH, Logan et al. 1964) of stromatolitic mudstone (Figs. 4.21, 4.22). The latter are covered by supratidal (sandy) dolostone (CLF1). SP-B3 occurs in lower part of Unit II of the Pamelia Formation. It is best developed west of Locality 43 (Russell well). In Locality 44, stromatolites are poorly developed and correlate with flat, microbially laminated to thinly bedded mudstone which contain small isolated stromatolitic, lime-mudstone mounds (see Chapters 3 & 4 for more details). However, the stacking pattern of SP-B3 is still preserved at this locality.

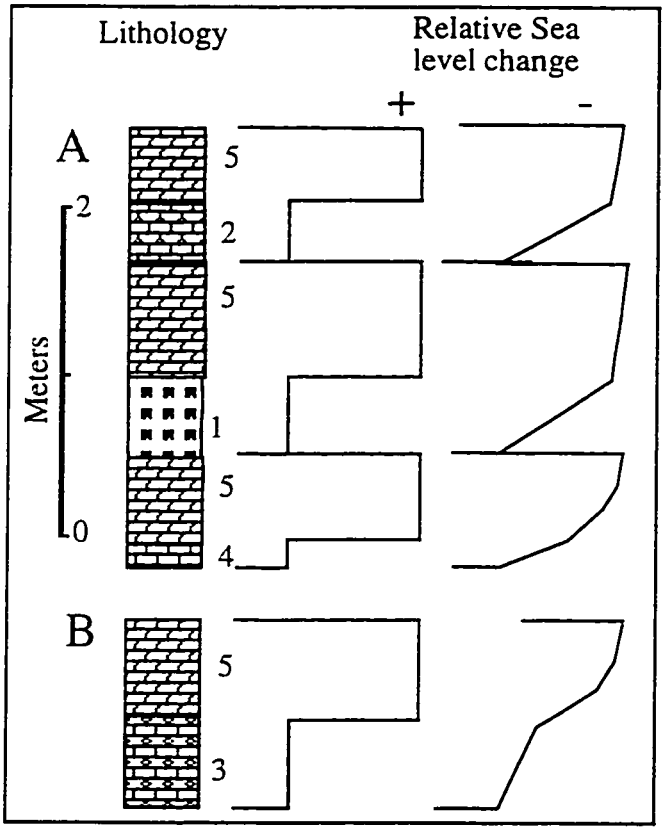


Fig. 4.19 Stacking pattern B2 (SP-B2) is characterized by subtidal lithofacies, including bioclastic wackestone (1), bioclastic packstone (2), bioclastic, oolitic grainstone and packstone (3) and bioclastic mudstone (4) followed by supratidal (sandy) dolostone (5). The figure shows two possible interpretations of (i) rapid sea level changes (curves to the left) or (ii) gradual sea level drop (curves to the right).

Fig. 4.20 Relatively high frequency dolomite (light-coloured layers) and limestone (dark layers) interbeds define Stacking Pattern B2 (SP-B2, Loc. 47, Macleod quarry, Cornwall). Middle white-coloured layer (s) is the sandstone lithofacies of Unit III (basal sandstone of the Upper Member of the Pamelia Formation). The nearst cliffe (i.e left) of the quarry wall is about 11 m high.

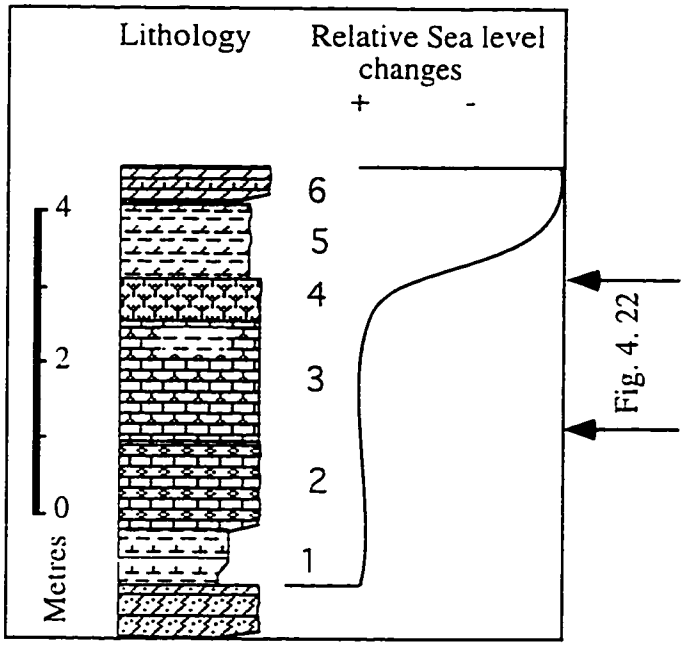
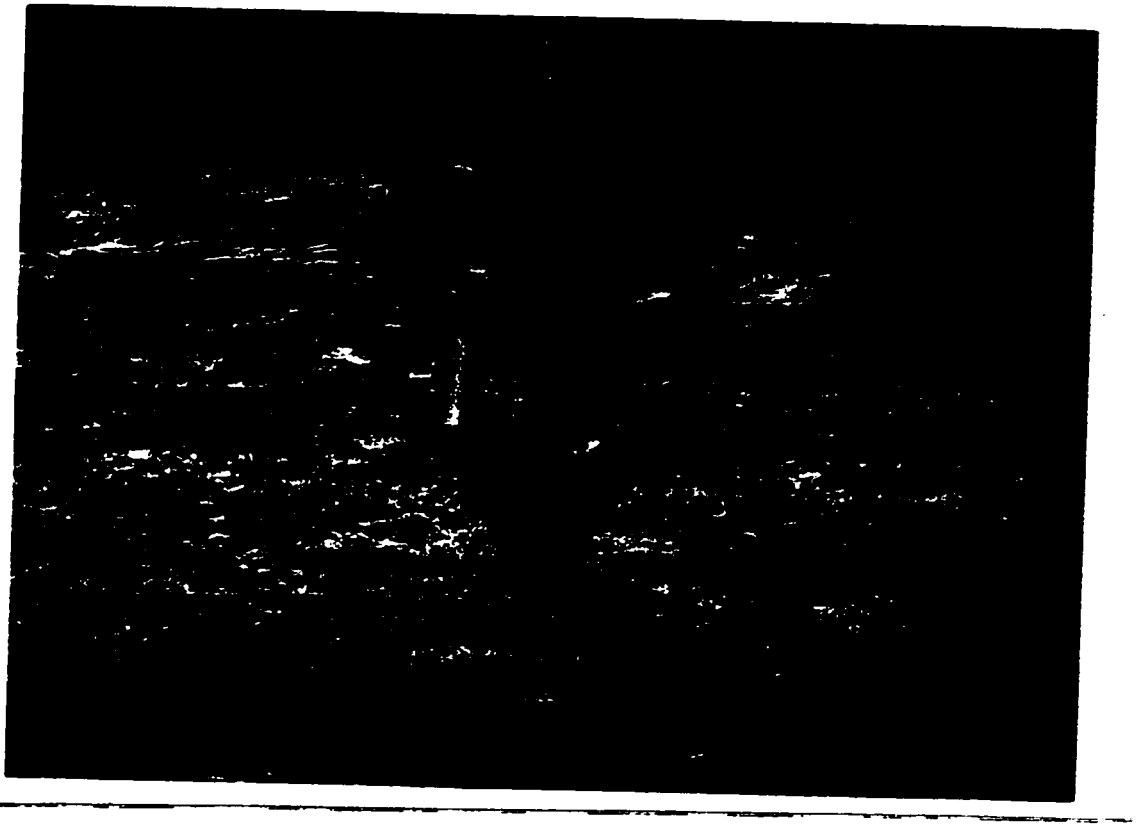


Fig. 4.21 Stacking pattern B3 (SP-B3) is characterized by subtidal calcareous shale (1), bioclastic, oolitic packstone and grainstone (2), oolitic, bioclastic packstone and grainstone (3), followed by intertidal (stromatolitic) mudstone to bioclastic wackstone (4), (local) shallow intertidal to supratidal shaly sandy dolostone (5), and supratidal calcareaus to sandy dolostone (6). The succession suggests gradual sea-level drop.

Fig. 4.22 Bioclastic packstone lithofacies (p) is succeeded by stromatolitic (s) mudstone (Loc. 24). The succession is part of the Stacking Pattern B3 (SP-B3, see Fig 4.21 for the stratigraphic range of this picture). Vertical facies association of SP-B3 shows a change from subtidal bioclastic and oolitic packstone and grainstone facies through intertidal (mudflat) stromatolitic mudstone to supratidal sandy dolostone (not present in this figure). The hammer is 25 cm long.



SP-B4 is characterized by basal bioclastic packstone (CLF6) that is succeeded by microbially laminated to thinly bedded mudstone to intraclastic wackestone (CLF2), with local intraclastic rudstone interbeds (CLF3) (Figs. 4.23, 4.24). The packstone has an erosional base, and sharp to gradational upper contacts with the overlying mudstone. SP-B4 occurs preferentially in the lower part (~ 2/3) of Unit IV of the Pamelia Formation.

Rhythmites in the Lowville Formation

One type of stacking pattern (SP-C) is recognized for rhythmic bedding in the Lowville Formation. It is predominantly formed by two distinctive and alternating lithofacies: (1) intraclastic, oolitic and/or bioclastic grainstone and packstone lithofacies (CLF6 and CLF7); and (2) *Tetradium*-rich bafflestone and floatstone (CLF5) interbedded with wackestone and mudstone lithofacies (CLF4) (Figs. 4.25, 4.26). Thin-bedded shale (TLF3) is often present throughout the rhythmites, and their role in defining rhythmicity (i.e., whether they define transgressive bases for more subtle rhythmites or not) is not clear. The lower contacts of the grainstone and packstone are usually erosional, and they show gradational to alternating contacts with overlying CLF4 or CLF5 lithofacies.

Lateral continuity of rhythmites

The six rhythmic units comprising SP-A and SP-B in the Pamelia Formation are laterally extensive and traceable across the Ottawa Embayment. Recognition of the higher-frequency rhythmic patterns (i.e., SP-A1, SP-A2, SP-A3, SP-B1, SP-B2, SP-B3, & SP-B4) is generally poor (not beyond a few kilometres) due to lateral lithofacies changes. However, the overall lithology within each rhythmite remains satisfactorily identifiable within the

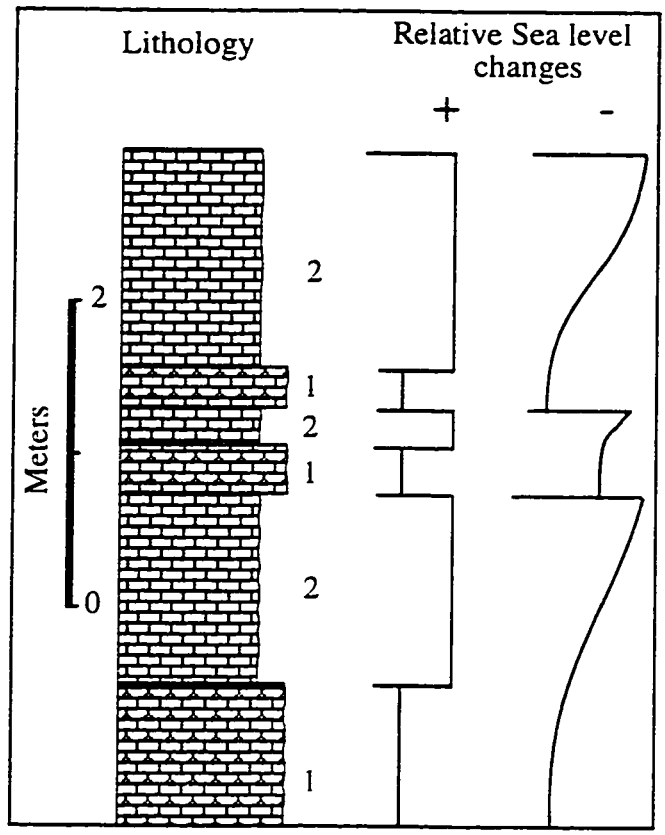
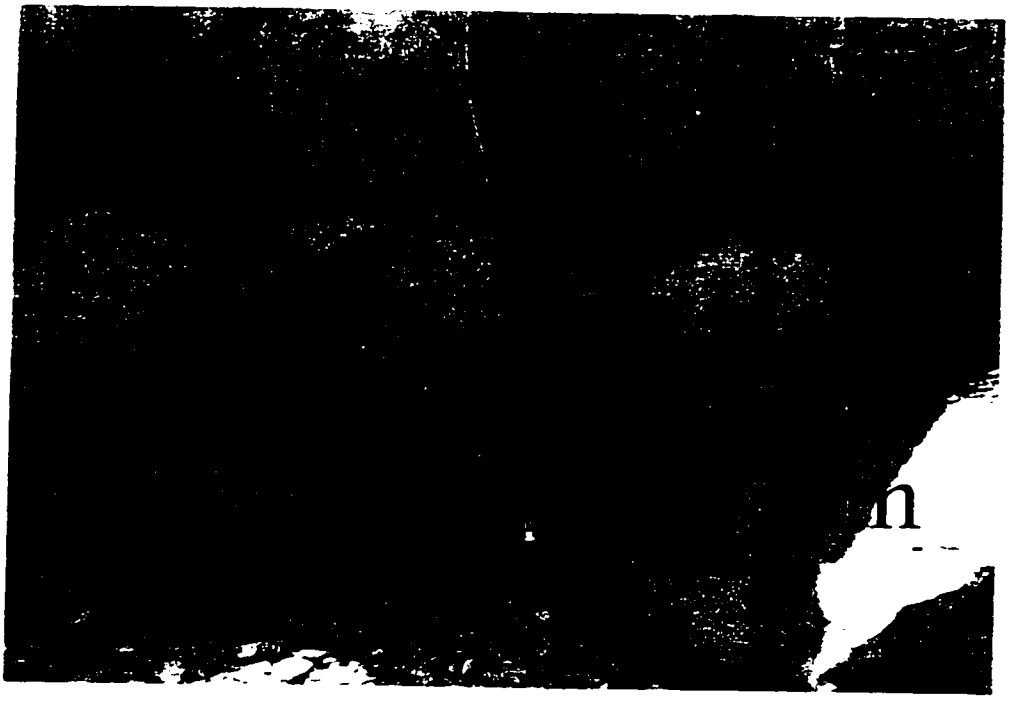


Fig. 4.23 Stacking pattern B4 (SP-B4) is characterized by repetitive bioclastic packstone (1) and microbially laminated, intraclastic (flat-pebble breccia) mudstone, wackstone and (locally) rudstone (2). The packstone facies often has an erosional lower contact suggesting storm sedimentation in a shallow intertidal to supratidal environment. If this is the case, the relative sea level changes were rapid (curves to the left). The curves to the right suggest an alternative interpretation of gradual sea level changes.

Fig. 4.24 Intraclastic (flat-pebble breccia) rudstone bed (r) sandwiched between thinly laminated (lower) and intraclastic (upper) mudstone lithofacies (m). These lithofacies form the upper part of Stacking Pattern B4 (SP-B4). Unit V of the Pamelia Formation at Loc. 24. Scott St. Transitway, Ottawa. The pencil is 15 cm long.



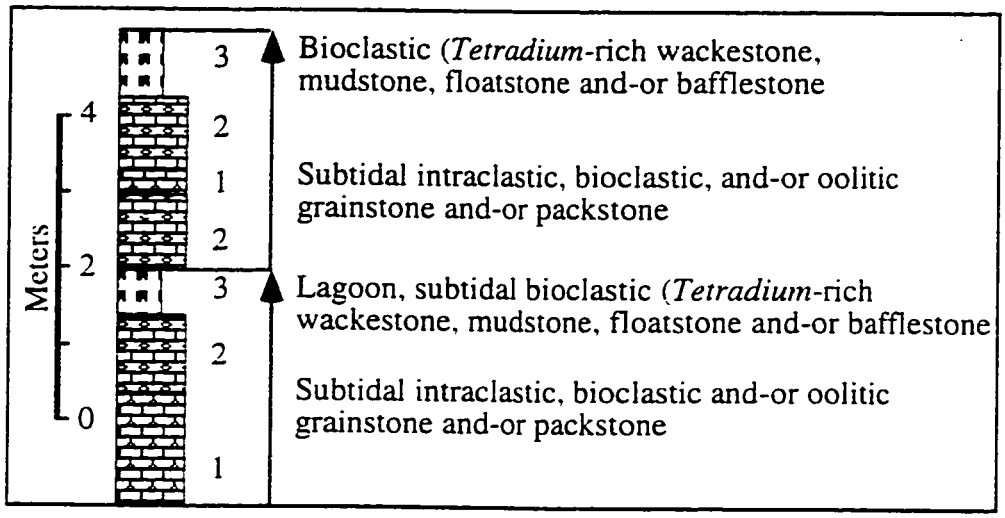


Fig. 4.25 Stacking pattern C (SP-C) characterized by repetitive lithofacies of subtidal oolitic, bioclastic packstone (1) and grainstone and-or bioclastic, oolitic packstone and grainstone (2) followed by bioclastic (mostly *Tetradium* corals) mudstone, wackstone, floatstone and-or bafflestone (3).

Fig. 4.26 Stacking pattern C (SP-C) is confined to the Lowville Formation and characterized by repetitive units of bioclastic and oolitic packstone and grainstone lithofacies (dark beds, a) and *Tetradium*-rich mudstone to rudstone (b). The figure also shows Chaumont (C) - Lowville (L) contact (arrows). Loc. 17 (redeveloped quarry beween Bourbon St. and Owl Dr., Ottawa. The hammer is 25 cm long.

Ottawa Embayment. The sandy dolostone and dolomitic sandstone intervals that cap individual rhythmites are used as marker beds for lithological correlations among mapped sections in the Embayment. In addition, certain prominent units can be laterally traced within a distance of about 40 to 50 km. These units include stromatolites and some oolitic grainstone and packstone intervals.

The extent of lateral continuity of the SP-C rhythms that form the Lowville Formation is not easily defined. Four successions of SP-C are tentatively recognized throughout the Lowville Formation of the Ottawa Embayment (Fig. 4.27). Where lagoonal beds which define the upper part of these rhythmites are missing, erosional surfaces occurring approximately at similar horizons of the missing strata are assumed to form contacts between successive rhythmites. Like the rhythms in the Pamelia Formation, the internal lithofacies units are generally recognizable within the Embayment but recognition of their lateral correlation is poor beyond a distance of about one kilometre.

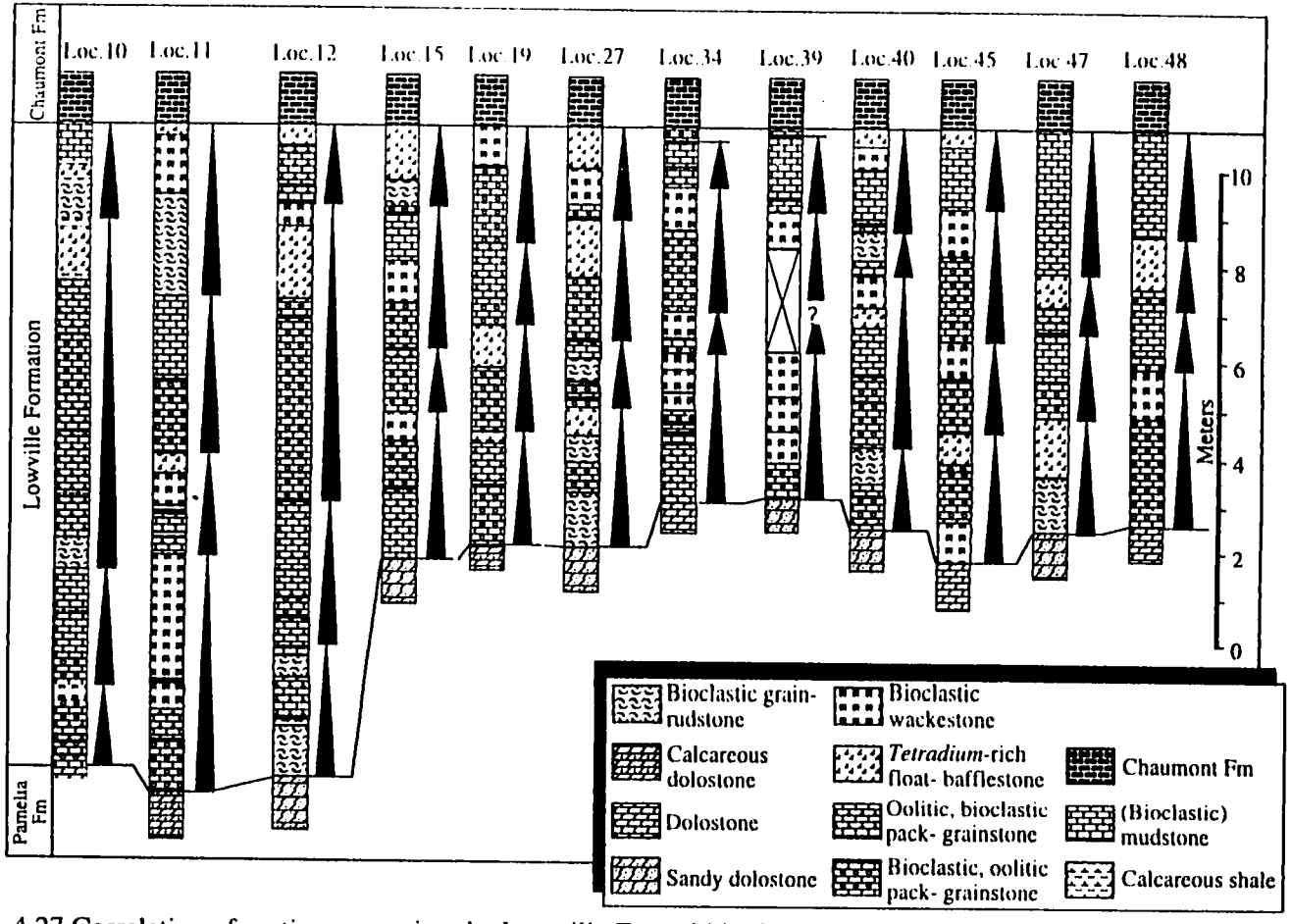


Fig. 4.27 Correlation of sections exposing the Lowville Fm. within the Ottawa Embayment. The formation is characterized by rhythmic units (filled arrow heads) defined by oolitic and bioclastic grainstone - packstone interbedded with bioclastic (mostly *Tetradium* corals) mudstone to bafflestone. Loc. 10 = Moodie Dr. quarry, Nepean, Loc. 11 = Fallowfield quarry, Nepean, Loc. 12 = Houlahan (Fallowfield) quarry, Nepean, Loc. 15 = Frazer Duntile quarry, Carling Ave. at Kirkwood Rd., Ottawa, Loc. 19 = McCarthy Rd. at Walkley Rd., Ottawa, Loc. 27 = Beechwood Rd., Ottawa, Loc. 34 = Francon quarry - north, Gloucester, Loc. 39 = St. Joseph Rd., at ~ 300 m east of Tenth Line, Orleans , Loc. 40 = Rockland quarry, Rockland, Loc. 45 = Cornwll quarry, Cornwall, Loc. 47 = MacLeod quarry, Cornwall, Loc. 48 = Green Valley quarry, Lancaster.

CHAPTER FIVE

PALEOENVIRONMENTAL RECONSTRUCTION OF THE BLACKRIVERAN SUCCESSION

Basin morphology and development

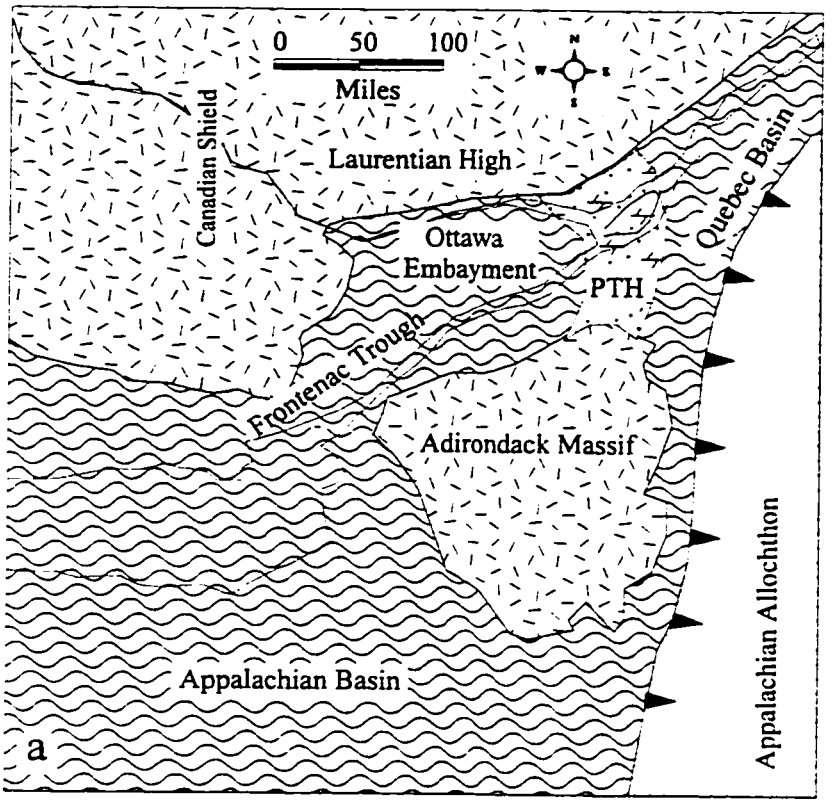
Analysis of available geologic data (this work and published data) indicates that the Ottawa Embayment was a shallow semi-restricted embayment during early Blackriveran time (during deposition of the Pamelia Fm), and evolved to more open marine shelf environments (post-Pamelia deposition). The Ottawa Embayment, at the time of the Pamelia deposition, was bounded to the north and west by the Canadian Shield, to the southeast by the Adirondack Massif, and, to the east, by a relatively low relief plateau in the Beauharnois - Montreal area, which acted as a positive structural corridor between the Laurentian High of the Canadian Shield and the Adirondack Massif (Fig. 5.1a). Existence of paleo-topographic relief in the Beauharnois - Montreal area is suggested by: (1) thinning of the Pamelia Formation in the Montreal area (~ 3 m) relative to thickness in the Ottawa area (~ 42 m) (Okulitch 1936; 1939b; Clark 1972a; this study); (2) evidence of major faulting events from late Pre-Cambrian to Late Ordovician time (St. Julien and Hubert 1975; Globensky 1987; Gérald et al. 1992; Lavoie 1993; 1994), possibly creating differential movement along fault-blocks in the Montreal region; and (3) a pronounced disconformity at the Chazyan - Blackriveran contact in the Montreal area (Okulitch 1936) that becomes an angular unconformity in the area of Trois-Rivières (~ 100 km northeast of Montreal, Roliff 1967).

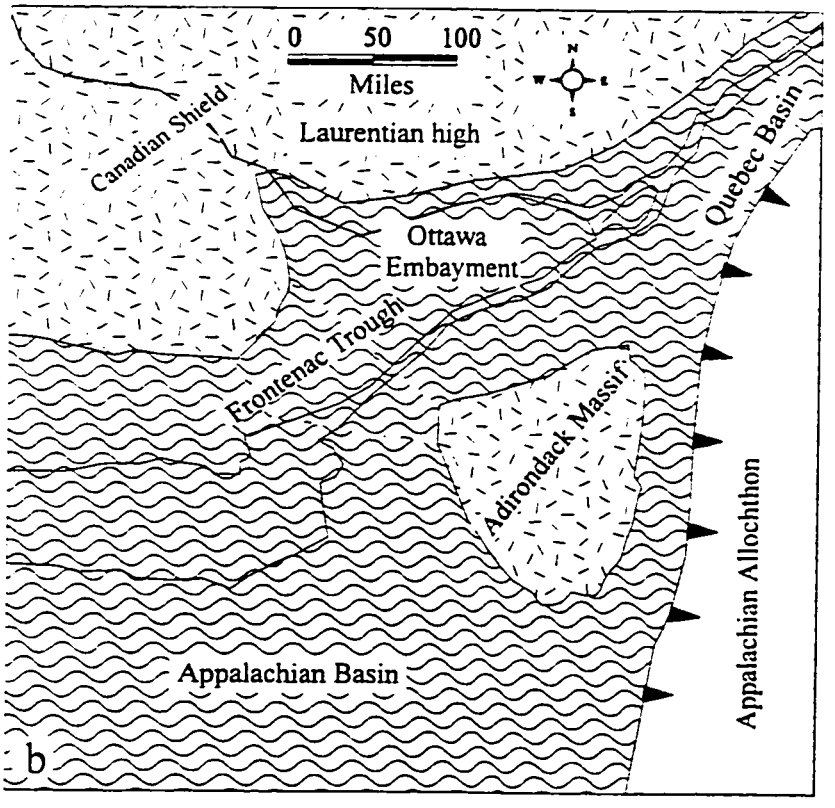
Although the earliest development of the Beauharnois Anticline is usually considered to be Late (or latest) Ordovician in age (see Bernstein 1991), thinning of the Pamelia may identify a much earlier period of relative uplift.

Lithostratigraphic correlation between the Chazyan Hog's Back Formation (Salad

Fig. 5.1a Paleogeographic reconstruction of the Ottawa Embayment and surrounding regions during the early Blackriveran Stage. Note that a paleotopographic high (PTH) existed east of the embayment (Montreal area) which hindered water circulation between the embayment and eastern Quebec basin. Instead, the embayment was connected with the southern Appalachian Basin through the "Frontenac Trough".

Fig. 5.1b Paleogeographic reconstruction of the Ottawa Embayment and surrounding areas during late Blackriveran Stage. During the time of Lowville deposition, the embayment became connected with the Quebec Basin.


0 50 100
Miles
N
W
E
S
Canadian Shield
Laurentian High
Ottawa
Embayment
PTH
Quebec Basin
Frontenac Trough
Adirondack Massif
Appalachian Basin
Appalachian Allochthon
a


0 50 100
Miles
N
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E
S
Canadian Shield
Laurentian high
Ottawa
Embayment
Quebec Basin
Frontenac Trough
Adirondack Massif
Appalachian Basin
Appalachian Allochthon
b

Hersi and Dix 1997a) in the Ottawa Embayment and the upper Laval Formation of Montreal region (see also Chapter 2) suggests that initial uplift of the plateau may even have occurred by late Chazyan - early Blackriveran time. Okulitch (1936) also recognized possible tectonic disturbance at the end of the Chazyan stage in the region of Montreal. This tectonic event was coincident with a southeastward withdrawal of the Chazyan sea (Okulitch 1936). The angular and erosional unconformity at the Chazy - Blackriver contact in the Trois-Rivières area (Roliff 1967) may be related to this tectonic event. The paleo-plateau acted as a structural margin establishing restricted marine water circulation between the Ottawa Embayment and the foreland basin sea lying east of the plateau during the early Blackriveran stage (most of the time of Pamelia deposition, see Fig. 5.1a).

Despite differences in thickness, lithologic similarities between the Lowville and Chaumont formations of the Ottawa and Montreal regions are well recognized (Clark 1972a). This suggests that the Ottawa Embayment became fully connected with the eastern sea by the beginning of Lowville sedimentation (Fig. 5.1b). This interpretation raises an important question: which sea was the Ottawa Embayment connected to during most of "Pamelia time" and how? Available stratigraphic correlations suggest that a marine bypass across the Frontenac Arch may have linked the Ottawa Embayment with the southern Ontario basin (i.e., Appalachian Basin). This bypass is called here the "Frontenac Trough" (Fig. 5.1b). The arch was a positive area that may have separated the Ottawa Embayment to the east from western New York and southern Ontario, to the west, until the end of the Chazyan Stage (Johnson et al. 1992; Dix et al. 1997a). In the early Blackriveran Stage, the southern sea flooded over the arch and advanced northward into the Ottawa - St. Lawrence Lowland. Although the Blackriveran sea advanced gradually in all directions around the Ottawa Embayment, it did not reach the eastern plateau (nor beyond the Montreal region as indicated

by the eastward pinching out of the Pamelia Formation; Clark 1972b; Okulitch 1936) until about the end of Pamelian deposition. This interpretation is supported by: (1) absence of Chazyan strata in the region occurring west of the arch (Dix et al 1997a); (2) good stratigraphic correlation between Blackriveran strata across the arch (i.e., Ottawa area versus Kingston and New York regions, see Chapter 3); (3) a continuous section of a core and a quarry from an outlier within the arch at Westport (Loc. 5) that shows rocks of the lower Pamelia Formation are lithologically similar with those in the Ottawa and Kingston regions. (Fig. 5.2); and (4) gradual thinning and onlapping of the Pamelia Formation onto older rocks towards Montreal.

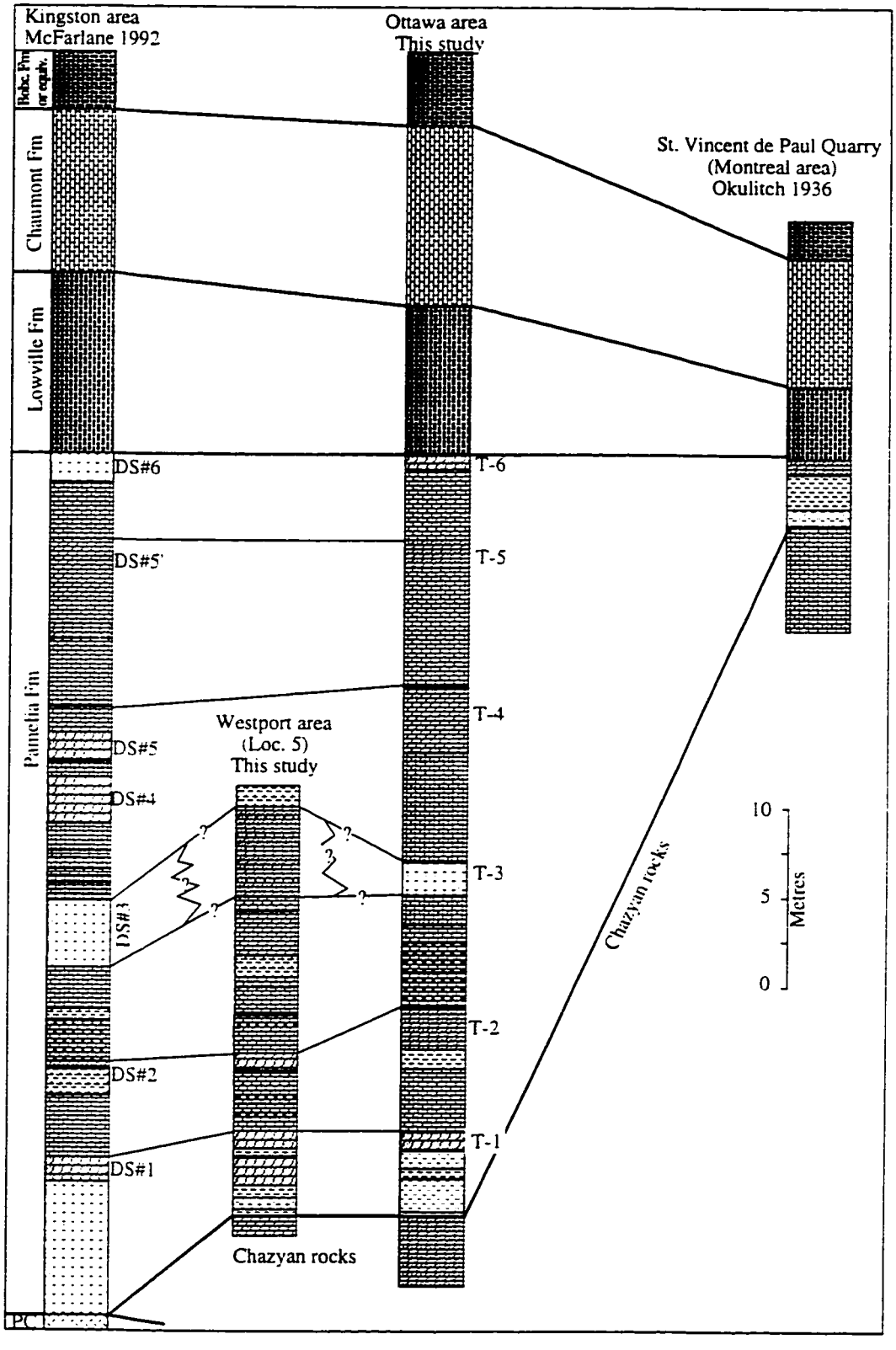
Depositional model

Cyclic sedimentation and boundaries as "time markers"

The interpreted paleogeography of the Ottawa Embayment, and the various lithofacies of the lower Ottawa Group (Chapter 4), allow reconstruction of a depositional model for the Blackriveran formations in the region.

Most of the lithofacies in the studied succession define recurring m-scale shallowing-upward successions. Cyclicity is a common phenomenon of carbonate platformal sediments where individual cycles are laterally continuous, and often cover large areas. Cyclic sedimentary patterns are employed as potential tool for chronostratigraphic correlation (Coogan 1972; Wilson 1975; Goodwin and Anderson 1985) although the roles of tectonism and potential diachroneity of cycles establishes controversy (Goodwin and Anderson 1985; Pratt et al. 1992; Ettensohn 1994; Lehman et al. 1994). Four principles are considered

Fig. 5.2 Correlation of the Blackriveran strata from the Kingston area, through Westport, Ottawa, and into the Montreal region. Note lithologic similarities of the Pamelia Formation among Kingston, Westport and Ottawa sections, whereas the section from Montreal region shows little correlation with the other localities. The sandstone unit (DS#3 of the Kingston section and T-3 of the Ottawa section) is poorly developed, weathered, and with more carbonate interbeds in the Westport area.


Kingston area
McFarlane 1992
Ottawa area
This study
St. Vincent de Paul Quarry
(Montreal area)
Okulitch 1936
Bobc. Fm or equiv.
Chaumont Fm
Lowville Fm
Pamelia Fm
DS#6
DS#5'
DS#5
DS#4
DS#3
DS#2
DS#1
PC
T-6
T-5
T-4
T-3
T-2
T-1
Westport area
(Loc. 5)
This study
Chazyan rocks
Chazyan rocks
10
5
0
Metres

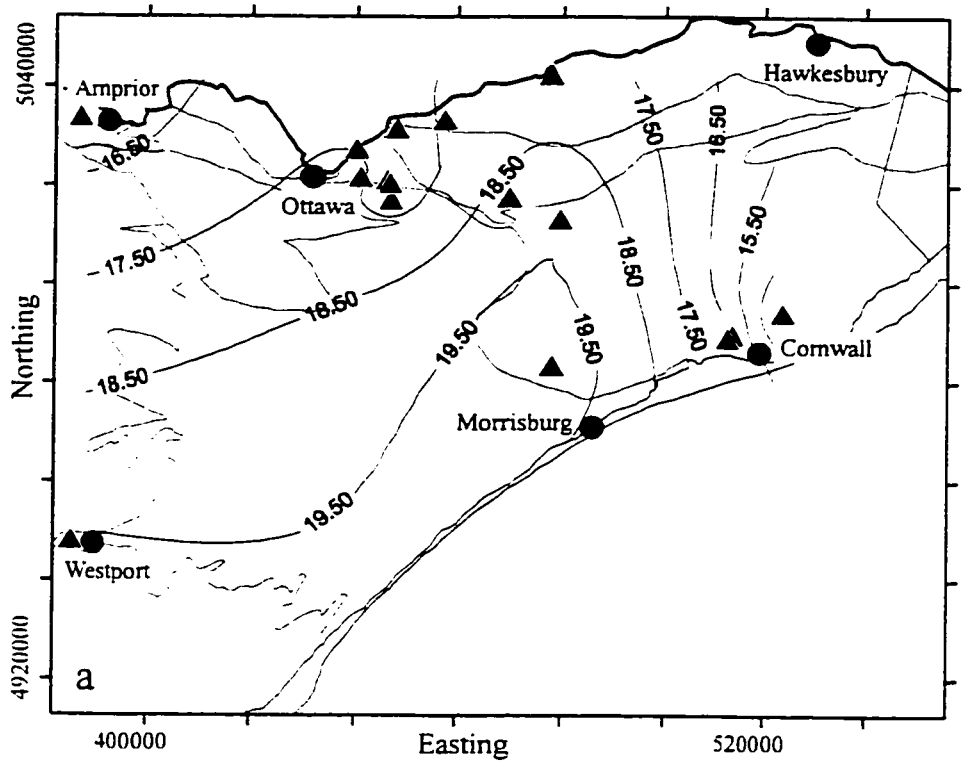
important in order to use carbonate platform cycles as time boundaries (Wilson 1975): (1) transgressive surfaces must have been levelled by the preceding regressive phase; (2) sea-level rise must "rapidly" flood wide areas of such surfaces, especially when they are tectonically subsiding; (3) once carbonate production is established, a shallowing-upward cycle is rapidly developed; and (4) rate of regressive outbuilding is, for any one cycle, generally so rapid that it is beyond the resolution of our biostratigraphic calender (Wilson 1975, p. 54). Wilson (1975) concludes that boundaries between sedimentary cycles "may closely approximate "time markers" and are more useful as such than the diachronous facies within each cycle" (p.54). Similar conclusion was reached by Goodwin and Anderson (1985) for their Punctuated Aggradational Cycles (PACs). They stated that abrupt facies changes at PAC boundaries that can be traced laterally for tens of kilometres, "provide the basis for interpreting PAC boundaries as isochronous surfaces" (p.519). This concept is applied to the sedimentary cycles of the Pamelia and Lowville formations and is further discussed within each formation. Depositional environments of the three Blackriveran formations with possible models are presented in the following sections.

The Pamelia Formation

An isopach map of the lowest siliciclastic-dominated unit (Unit I) of the Pamelia Formation shows a uniform thickness (Fig. 3.9) across the embayment. This suggests that the embayment had an almost flat paleotopographic surface. Uneven subsidence rates or paleotopography within a basin would create different accommodation spaces, and, consequently, differential thickness. Isopach maps of the Lower and Upper members (Figs. 5.3a & 5.3b, respectively) of the formation also reveal comparable thicknesses. The contour

Fig. 5.3a Isopach map showing thickness variation of the Lower Member of the Pamelia Formation within the Ottawa Embayment. Note the NE-SW trend of thickness increases. Contour intervals are in metres. Dashed lines are geologic boundaries (see Fig. 1.1 for details).

Fig. 5.3b Isopach map showing thickness variation of the Upper Member of the Pamelia Formation within the Ottawa Embayment. Note the N-S trend with a small NW-SE branch of thickness increase. Contour intervals are in metres. Dashed lines are geologic boundaries (see Fig. 1.1 for details).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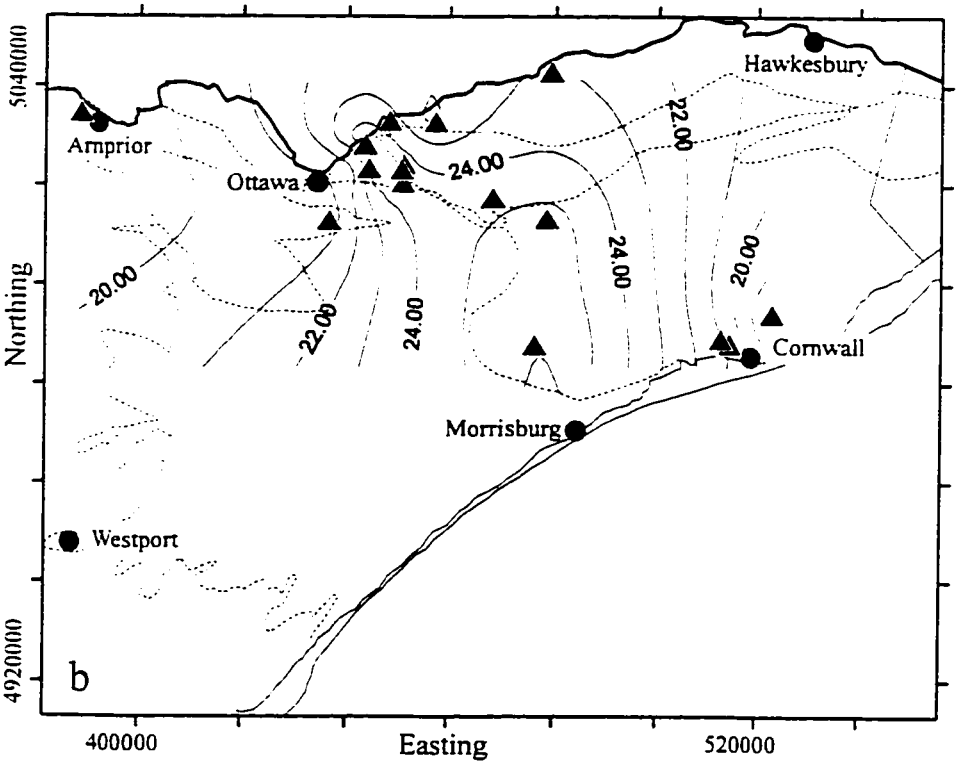
a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b

maps show a slight increase in thickness defining NE-SW and N-S corridors between Ottawa and Cornwall. Considering the small contour interval (1 m interval) used in these figures, thickness differences may indicate either (1) gentle slope or (2) slight difference in subsidence rate allowing greater accumulation of sediments between Ottawa and Cornwall. Geomagnetic and vertical gravity maps of southern Ontario (Gupta 1991; 1992) show NE - SW trending lineaments which may reflect tectonic features (e.g., faults) in the Precambrian bedrock (Blenkinsop, pers. comm. 1997). The geographic position of these features coincide with sites of increased thickness in the Pamelia Formation. Thus, thickness changes may reflect fault-control during deposition of the Pamelia Formation.

Not only is the thickness of the lithic units of the Pamelia Formation relatively uniform but lithofacies associations within these units also appear to be continuous and correlative laterally within the embayment. This suggests that wide facies zones prevailed across the depositional basin. Wide facies belts are known to occur in near-to-flat platform interiors (e.g., slope of 30 cm per km, see Wilson 1975, p. 30). Significant thickness and lithofacies changes of the Pamelia Formation towards Montreal, therefore, identify an anomaly, and as interpreted above, is due to onlap onto the Beauharnois - Montreal plateau.

The Pamelia Formation consists of six well developed cycles with dolomitic sandstone to sandy dolomite (CLF1) capping each cycle (Fig.5.4). Each cycle consists of transgressive-regressive subtidal lithofacies (e.g., TLF1, TLF2, CLF6, CLF7) through regressive intertidal deposits (e.g., CLF2, CLF3, CLF4) to regressive (prograding) supratidal dolomitic sandstone to sandy dolostone (e.g., CLF1). The tops of these cycles are considered to approximate "time lines", and are employed as correlation markers across the embayment.

Although Walker's (1973) interpretation that facies boundaries are roughly time-

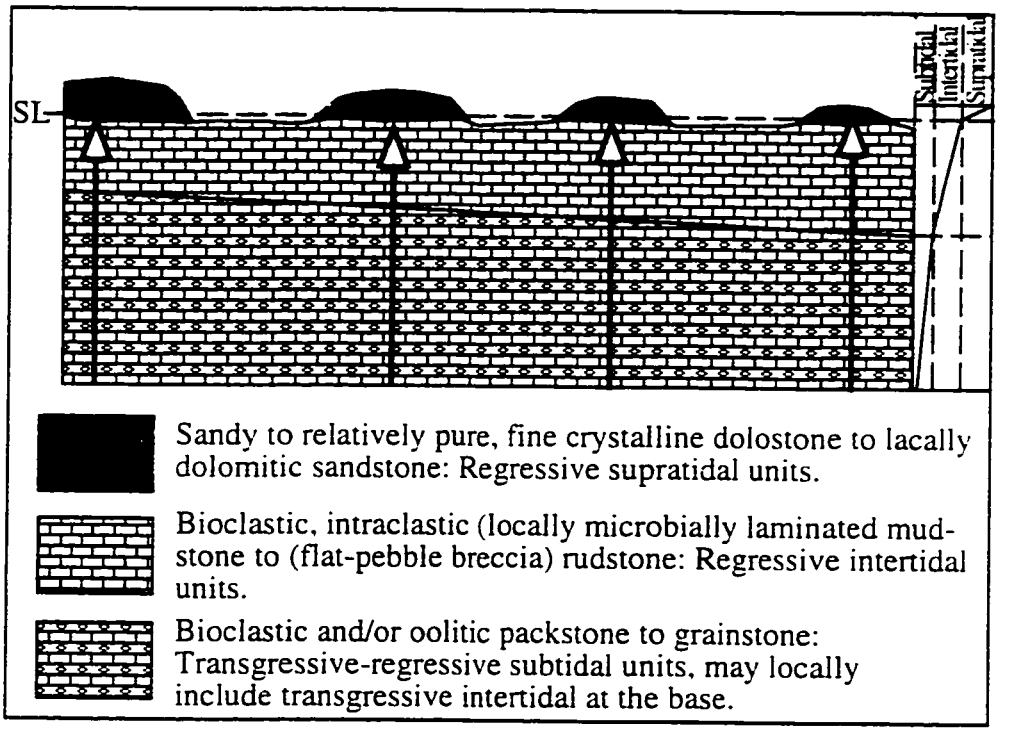


Fig. 5.4 The figure shows shallowing-upward succession which characterizes rhythmic units of the Pamelia Fm. Rhythmic units of the Pamelia Fm are defined by shallowing-upward successions comparable with "simultaneously aggrading sheet" model of Pratt et al. (1992). Newly-created accomodation spaces due to subsidance and-or sea-level rise were followed by relativly high carbonate production which enable catch-up of the sea floor with the sea level.

parallel along the depositional strike, and asynchronous across strike, remains generally valid, this relationship is best developed in "steeply" sloping platforms where facies belts are narrow (Wilson 1975). The time-line will cut across, with a relatively high angle, boundaries of such facies belts. This angle will increase with higher angles of the slope of the platform surface (Wilson 1975, p.37). On the other hand, where the slope of the platform is near horizontal, as interpreted for the Ottawa Embayment during the time of Pamelia Formation, the facies belts become wide (tens of km across the platform) and their boundaries, not only along the depositional strike but also across it, will almost be time-parallel. Moreover, the asynchroneity of such boundaries may become more significant when considered on a regional scale (e.g., across vast, distally deepening platforms and ramps). Given the relative small area of the Ottawa Embayment and its location in a platform interior, time lines will be parallel to lithofacies boundaries during depostion of the Pamelia Formation.

In summary, deposition of the Pamelia Formation was dictated by intermittent transgressions on a roughly flat surface of the Ottawa Embayment. Each transgressive event was followed by *in situ* carbonate production which steadily accreted vertically to sea level. In this setting, the embayment became subtidal which then passed through intertidal to supratidal environments (Fig. 5.4). This depositional setting fits the "simultaneously aggrading sheet" model (Fig. 5. 5) of Pratt et al. (1992) where a high rate of carbonate production allowed "catch-up" of the sea floor with the sea level (Jones and Desrochers 1992). The model further underscores the application of the facies boundaries as synchronous surfaces across the embayment. It also explains better the lateral lithofacies uniformity, as well as comparable thicknesses of individual sedimentary cycles, at various sites within the embayment.

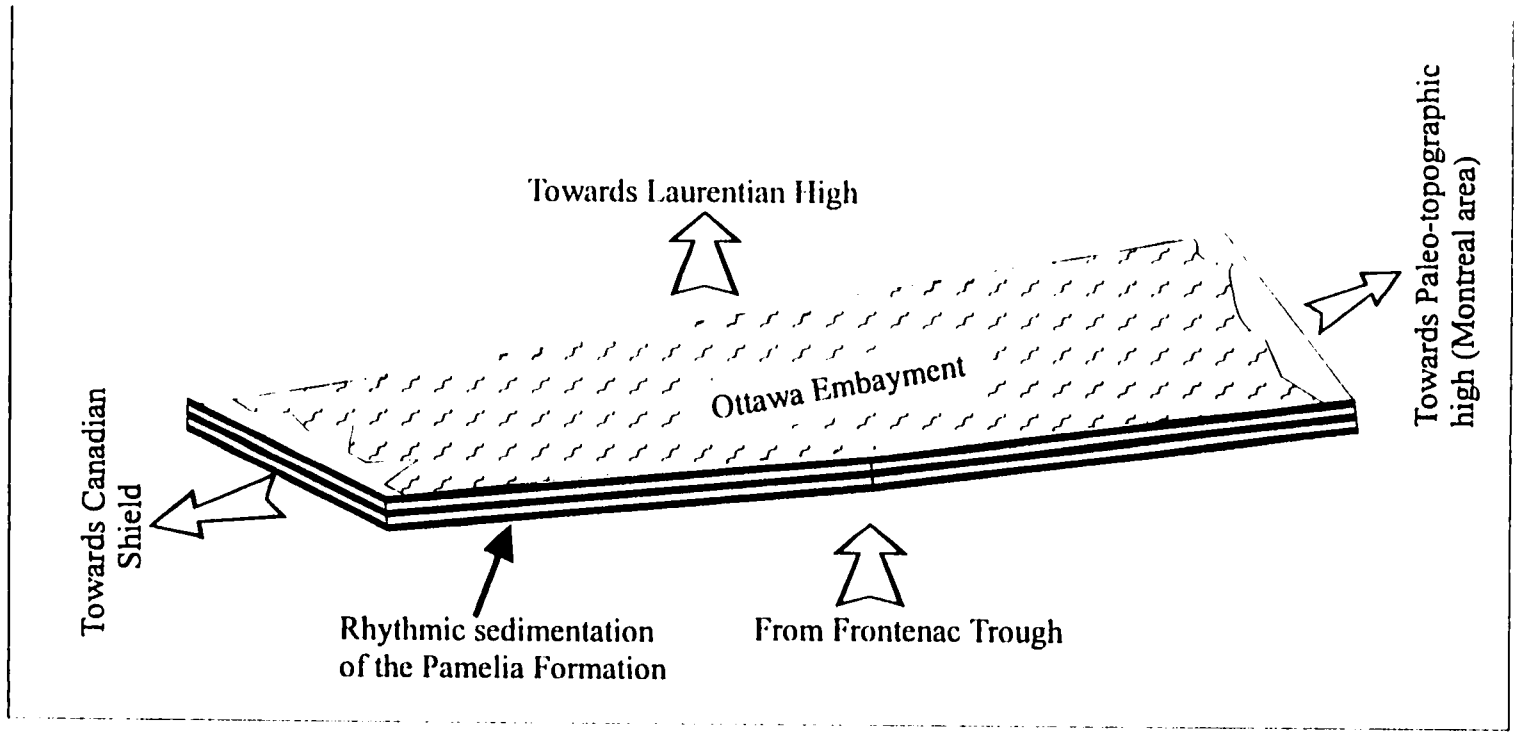


Fig. 5.5 Shallow sea covered the Ottawa Embayment during deposition of the Pamelia Fm. The Embayment was relatively flat and sedimentation was predominated by aggrading peritidal, carbonate sediments. This allowed the "catch-up" of the sea floor with the sea level. Fluctuation of relative sea level accompanied by the aggradational response of the carbonate factory defined metre-scale, repetitive units that characterize the Pamelia Formation.

Lowville Formation

Lithofacies relationships of the Lowville Formation offer a different depositional model from that of the Pamelia Formation. The rocks of the Lowville Formation were mostly deposited in a subtidal environment, and include lithofacies of bioclastic and-or oolitic packstone and grainstone, and *Tetradium*-rich mudstone, wackestone, floatstone and bafflestone. The presence of locally mudcracked mudstone indicates occasional intertidal environments. No supratidal rocks are recognized in the formation.

The lithofacies association of the Lowville Formation indicates a shelf lagoonal environment sheltered by bioclastic and oolitic sand shoals (Fig. 5.6). The lagoon remained fully connected with the open sea as suggested by the proliferation of stenohaline, delicate branched colonial corals (i.e., *Tetradium* sp). These corals were able to baffle already shoal-dampened waves and currents sweeping across the lagoon. However, storm activity occasionally overcame the resistance of the delicate wave-baffling *Tetradium* branches, resulting in deposition of thin bioclastic and-or oolitic packstone and-or grainstone layers interbedded with the lagoonal strata (e.g., CLF4 & CLF5). During storm activity, larger *Tetradium* coral colonies were also broken and overturned, and amassed together to form proximal rudstone and distal floatstone layers. This kind of sedimentation is recognized in the uppermost part of the Lowville Formation at certain localities in the embayment (e.g., Locs 1, 8, 42, and 43).

Aggradation of the bioclastic and oolitic sand shoals would occasionally reach the intertidal to supratidal zone, thus creating a restricted lagoon behind them. Fine-grained bioclastic wackestone and mudstone (CLF4) accumulated in the lagoon. Poorly developed mudcracks in the lagoonal mudstone lithofacies indicate shallowing of the lagoon with

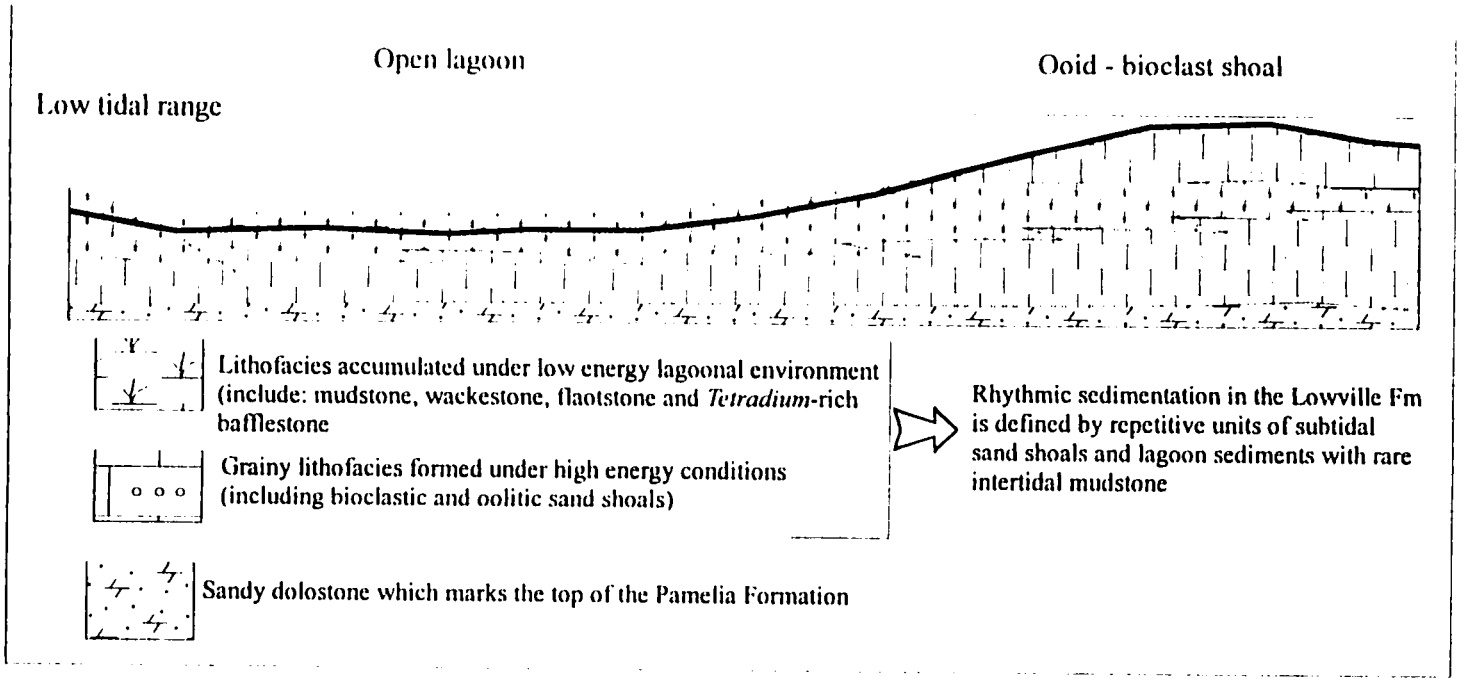


Fig. 5.6 Ooid and bioclast sand shoals and open lagoon environments dominated the Ottawa Embayment during Lowville deposition.

environmental conditions becoming intertidal.

Seaward migration of the shoals during relative sea-level fall was accompanied by similar shifting of the lagoon, whereas relative sea-level rise promoted landward shifting of the respective depositional environments. This caused repetitive stacking of shoal - lagoon sediments. The rhythmites in the Lowville Formation grade from subtidal shoals to lagoonal facies, and locally intertidal flats. The base of each rhythmite documents an erosional, transgressive surface. Although it is evident that certain bars were entirely bioclastic and others entirely oolitic, the stratigraphic relationship and coexistence of bioclasts and ooids within both CLF6 and CLF7 lithofacies indicate that the two were associated with each other and could develop mixed bars. This is comparable with the subtidal oolitic - bioclastic bars of the Middle Mississippian Salem Limestone of the Illinois Basin (Carozzi 1989).

The Lowville Formation in the Ottawa Embayment consists of at least four general rhythmic sedimentary packages (Fig. 4.27). However, certain sections with one or two more thinner rhythmic units may occur. These are interpreted to have originated as either shoal sands migrating over finer sediments of local inter-shoal accumulations, or spillover tongues (e.g., tempestites) intercalating with finer lagoonal sediments.

Chaumont Formation

The Chaumont Formation is almost exclusively made up of bioturbated bioclastic peloidal wackestone to packstone lithofacies (CLF8). The lithofacies was deposited in a calm to moderately agitated, open marine environment. This is suggested by predominance of poorly-washed, fine- to medium-grained wackestone and packstone facies; extensive (mostly horizontal) bioturbation; lack of wave- and-or current-generated sedimentary structures; and a high diversity, open-marine fauna. The comparable SMF9 of Flügel (1982) is diagnostic of shallow marine waters with open circulation below (but close to) wave base (Wilson 1975;

Flügel 1982; Tucker and Wright 1990).

This facies is also recognized to occur in the Chaumont Formation of upstate New York (Walker 1972; 1973). Walker (1972; 1973) describes the Chaumont Formation as consisting of "level bottom" facies, that is a sediment bank consisting of thick to very thick, thoroughly horizontal burrow-mottled, bioclastic, peloidal packstone to mudstone (biomicrite, pelmicrite to micrite). Walker (1972) also referred to biota in this environment as "level bottom marine community", dominated by calcareous algae, stromatoporoidea, rugose and tabulate corals, nautiloides, and brachiopods. Walker interpreted that bottom-level facies accumulated under subtidal, normal marine conditions. Lithologic and fossil similarities between the Chaumont Formation in the Ottawa Embayment and Walker's bottom level facies and fossil community further underscore subtidal marine conditions below wave base. In this environment, abundant infaunal deposit feeders destroyed most of previous sedimentary structures (if any) and produced homogenous burrow-mottled sediment. Presence of local well-washed coquina layers may indicate storm accumulation. Although no current or wave bedforms are recognized throughout the Chaumont Formation, an upward increase in energy is indicated by: (1) an upward increase in grain size accompanied by decrease in matrix content and decrease in burrows; and (2) predominance of wave- and/or current-created sedimentary structures in the conformably overlying Bobcaygeon Formation. The Chaumont Formation (correlative with the Ottawa-type calcarenites of Barnes 1964; 1967) passes laterally into the lower Bobcaygeon Formation in the western part of the Ottawa Embayment (i.e., west of Carp, see Barnes 1964; 1967). This indicates that the depositional environment passed laterally into and above wave-base, thus becoming more agitated. Thus, the upper part of the Chaumont Formation in eastern localities (east of Carp) becomes coeval with the lower part of the Bobcaygeon Formation.

CHAPTER SIX

DIAGENESIS OF THE BLACKRIVERAN SUCCESSION IN THE OTTAWA EMBAYMENT

Introduction

Despite numerous previous studies of the Blackriveran succession in the Ottawa Embayment, the post-depositional diagenetic evolution of these rocks has remained poorly understood. Steele-Petrovich (1984) superficially addressed the diagenesis of the succession in the upper Ottawa Valley. She indicated that neither marine nor vadose cements were present in these rocks and accounted for lithification of these rocks by meteoric phreatic cementation. She also reported some burial diagenetic features (e.g., stylolites). From petrographic and geochemical analyses of the Blackriveran formations (Pamelia, Lowville and Chaumont Fms) in the Ottawa Embayment, the post-depositional history includes marine, vadose, meteoric phreatic and burial cements; and, early syngenetic and later shallow to deep burial dolomitization, with the former confined to the Pamelia Formation and the latter preserved in all three formations. Diagenetic features of the Pamelia, Lowville and Chaumont formations, with their relative timing and possible environment of origin, are shown in figures 6.1, 6.2, and 6.3, respectively. This chapter discusses the general attributes of diagenesis of the limestone and dolostone strata in the Blackriveran succession.

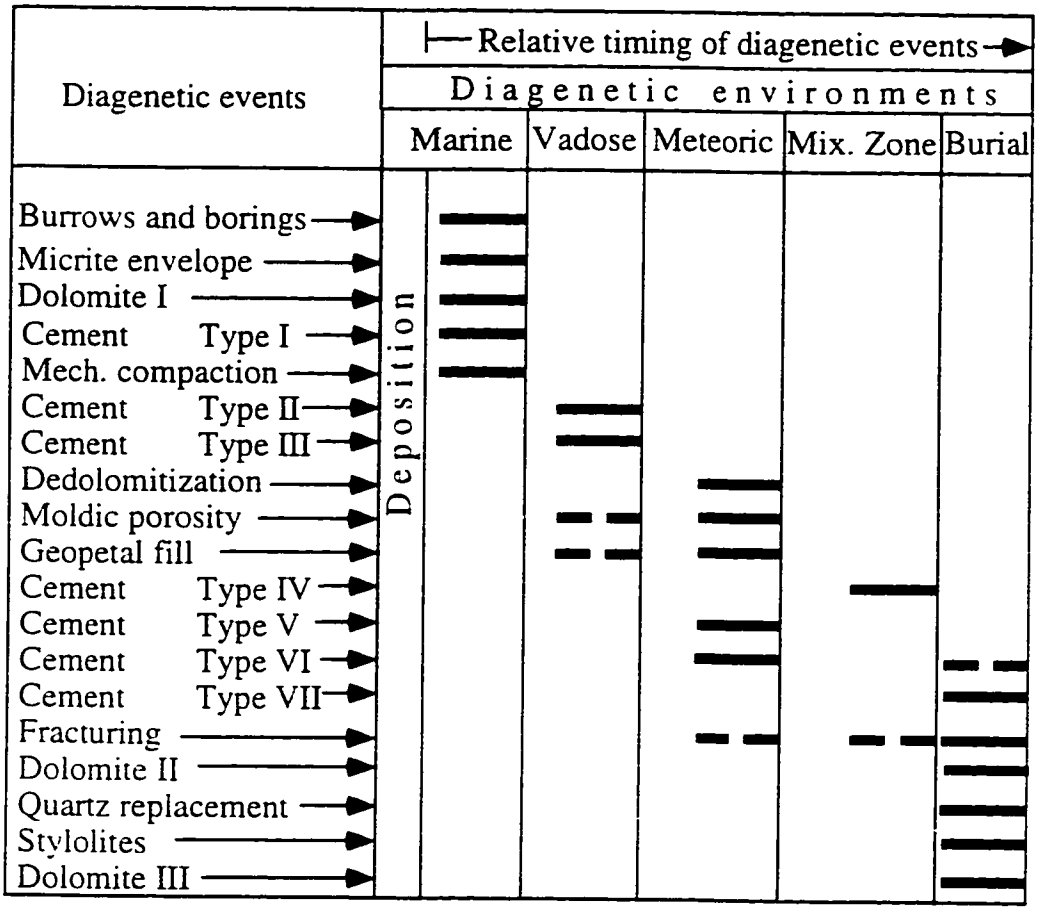


Fig. 6.1 Diagenetic events, their relative timing and environment as interpreted from petrographic study of the Pamelia Formation in the Ottawa Embayment. Dashed lines indicate possible occurrence of the diagenetic event in that environment.

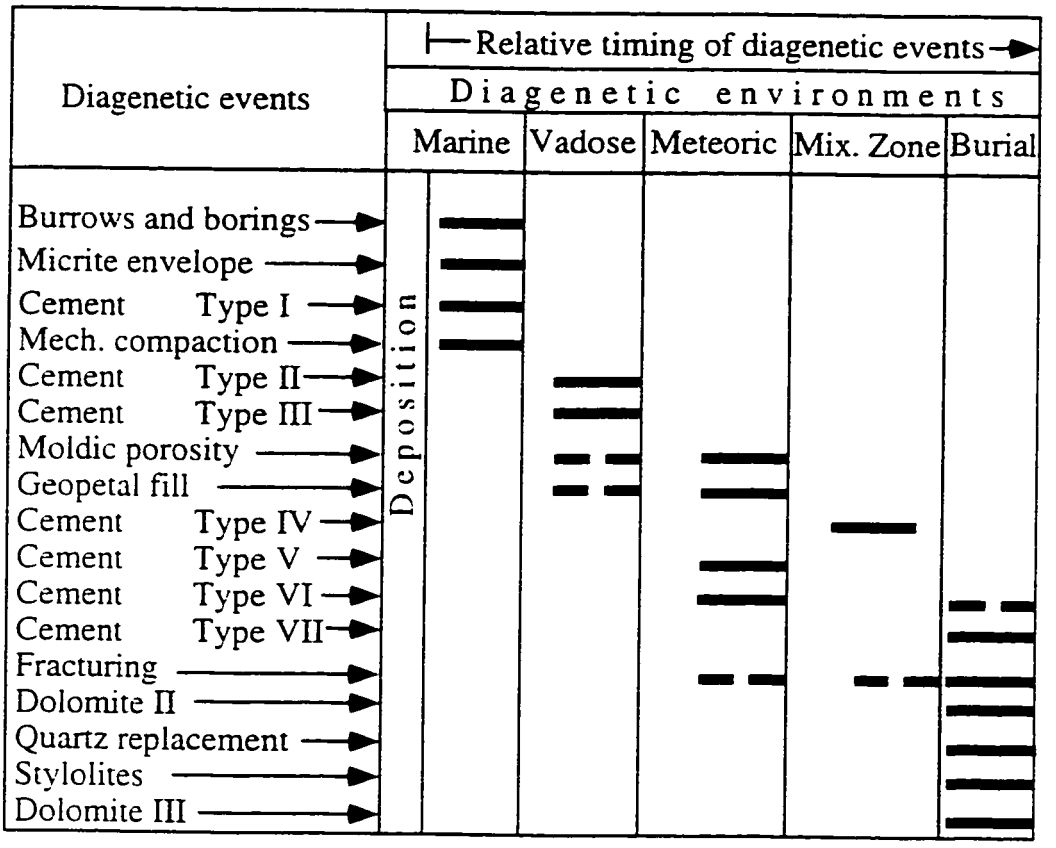


Fig. 6.2 Diagenetic events, their relative timing and environment as interpreted from petrographic study of the Lowville Formation in the Ottawa Embayment. Dashed lines indicate possible occurrence of the diagenetic event in that environment.

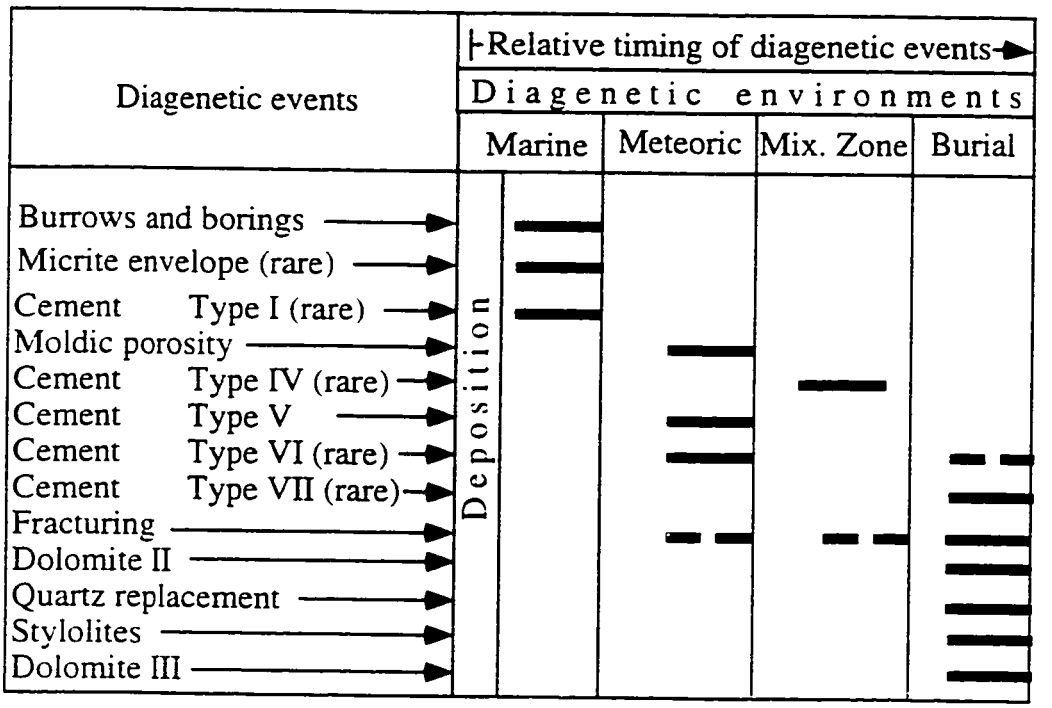


Fig. 6.3 Diagenetic events, their relative timing and environment as interpreted from petrographic study of the Chaumont Formation in the Ottawa Embayment. Dashed lines indicate possible occurrence of the diagenetic event in that environment.

Diagenetic features in limestone

Micrite envelope

Micritization of surfaces of framework grains (mostly bioclasts) is common in grainstone and packstone lithofacies of the Blackriveran succession. It usually forms a thin (5 to 70 μm thick) coating to the clasts (Fig. 6.4), and retains the original outline of the framework clast. Micrite envelopes do not develop (or are poorly developed) on framework grains in micrite-rich lithofacies (e.g., mudstone and wackestone lithofacies).

Burrows

Different types of burrows occur in the Blackriveran rocks (see chapters 3 and 4) of the embayment. They include vertical (*Skolithos*, Fig. 4.2b), subvertical (*Psilonichnus*, Fig. 4.6c), U-shaped (*Diplocraterion*, Fig. 4.2b), and horizontal (*Planolites* Fig. 4.2a) burrows. Some boring of bioclasts has also been noted. Burrows are filled by fine-grained bioclasts, micrite, peloids, anhedral calcite spar, and-or anhedral to subhedral dolomite rhombs. In most cases, burrows associated with the fine crystalline dolostone lithofacies (CLF1, see Chapter 4) are filled by detrital quartz.

Cement types

Seven types (I to VII) of calcite cements are recognized to occur within the Blackriveran strata of the Ottawa Embayment. Petrographic attributes of these cements as well as their diagenetic environments are summarized in Table 6.1. Details of these calcite cements are described in the following paragraphs.

Type-I: Fibrous calcite

This cement forms as an isopachous encrustation on framework grains in oolitic and bioclastic grainstone and packstone (Fig. 6.5). It also encrusts intraparticle porosity of some

Fig. 6.4 Leached bivalve shells and refilled by calcite spar. Outline of the bioclasts is preserved by micrite envelope. Lowville Fm. at Loc. 34, Francon northern quarry, Blackburn Hamlet, Gloucester. Scale bar is 300 μm.

Fig. 6.5 Isopachous Fibrous calcite cement (F, Cement Type I) occurs around ooid and bioclast grains. This cement is followed by prismatic calcite cement (P, Cement Type IV, see below). Lowville Fm. at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 100 μm.

F

Cement type	Crystal type and size	Geometry	Staining	Cathodo-luminescence	Diagenetic Environment
I	Fibrous, 10-15μm long & <15 μm wide.	Isopachous rim	Pink	dull-red to non-luminescent	Marine
II	Very fine anhedral, < 5μm.	Pendant microspar aggregates	Brownish red	Non-luminescent	Vadose
III	Very fine anhedral, < 5mm.	Mensicus micro-spar aggregates	Brownish red	Non-luminescent	Vadose
IV	Prismatic: 60 to 120 μm long & < 40 μm wide.	Isopachous to irregular rim	Pink	Dull brown to non-luminescent	? Mixing zone
V	Blocky, anhedral, < 60 μm.	Inter- and intra-granular mosaics	Pink	Dull-red to non-luminescent	Meteoric phreatic (shallow burial)
VI	Blocky, anhedral, 30 μm - > 4 mm.	Inter- and intra-granular mosaics, but centre-ward relative to Type-V	Pink	Dull-red to orange, poor zonation	Meteoric phreatic (shallow burial but deeper than Type-V)
VII	Blocky, anhedral, 30 μm - > 4 mm.	Inter- and intra-granular mosaics, but centre-ward relative to Type-VI	Blue	Dark brown to non-luminescent	Burial (deeper than Type-VI)

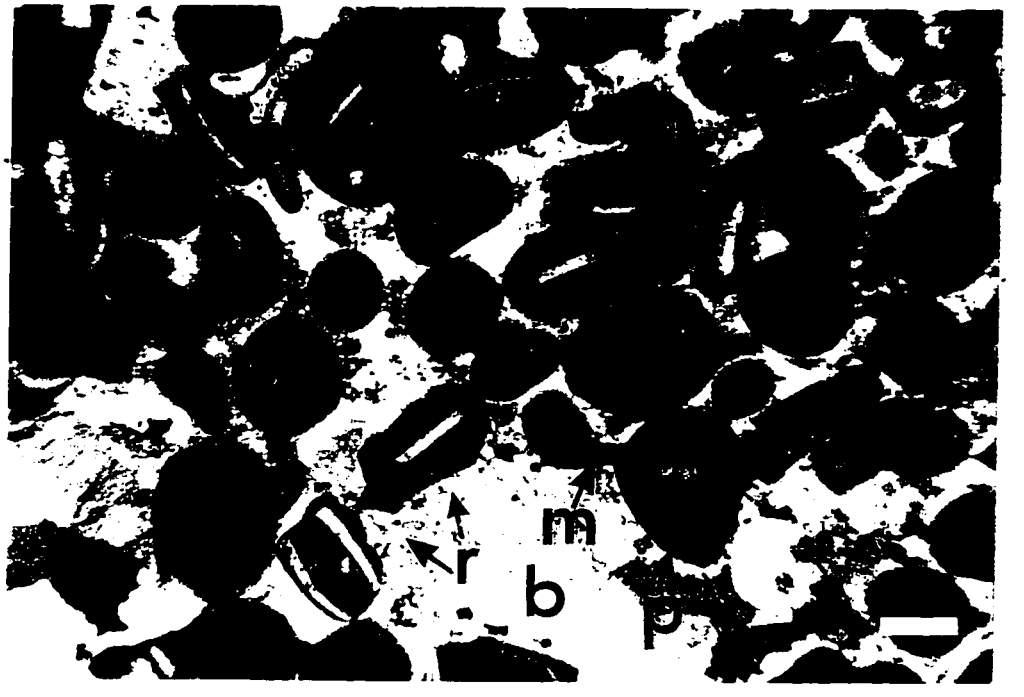
Table 6.1 Summary of petrographic descriptions of the various types of cements of the Blackriveran strata of the Ottawa Embayment. Diagenetic environments of these cements are also shown.

shells (e.g., ostracods). Fibrous crystals (Tucker and Wright 1990) are columnar in shape, 10 to 50 μm long, and usually less than 15 μm wide. They have scalenohedral or needle-like terminations. Isopachous, radiaxial fibrous calcite (Kendall 1985; Tucker and Wright 1990) with crystals up to 20 μm wide and about 40 μm long is less common. Fibrous calcite cement shows a pinkish stain and displays a dull red- to non-luminescence character. Fibrous calcite cement predates all other types of cements, but it post-dates formation of micrite envelopes. Type-I cement commonly occurs in the lower, usually grainy (oolitic and-or bioclastic) part of rhythmites in the Pamelia and Lowville formations. However, it occurs less frequently in finer-grained lithofacies, usually restricted to within articulated ostracod shells. This cement is also present in the rare bioclastic grainstone facies of the Chaumont Formation.

Type-II: Pendant cement

This type of cement, although not common in the studied sections, extends beneath framework grains (Fig. 6.6), and is characterized by very fine (<5 μm in diameter), anhedral microspar aggregates. It is brownish-red in colour when viewed with plane light. Cement Type-II is non-luminescent. It postdates fibrous calcite cement. Pendant cement occurs in the Pamelia and Lowville formations. In the case of the Pamelia Formation, cement Type-II occurs locally in lithofacies below dolostone intervals of T-2 and T-6, as well as below the sandstone layer of T-3.

Fig. 6.6 Pendant (p, Cement Type II) and meniscus (m, Cement Type III) cements are locally present in oolitic grainstone lithofacies. Note that prismatic rim (r) and blocky (b) calcite cements postdate the pendant and meniscus cements. Lowville Fm., at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 300 μm.


m
r
b
p

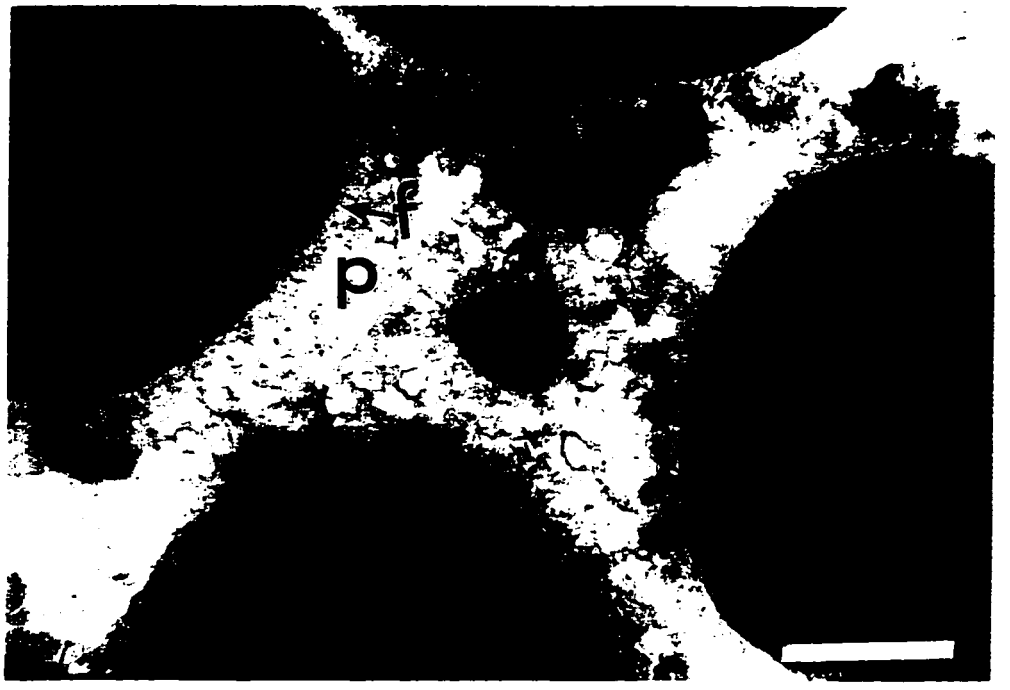
Type-III: Meniscus calcite

Meniscus cements are characterized by a thin layer of micrite which bridges adjacent grains (Fig. 6.6). It is petrographically similar to cement Type-II. Its relationship with Type-I cement is not clear from the available thin sections. However, it is usually associated with the pendant cement and appears to have formed at the same time.

Type-IV: Prismatic calcite

This type of cement forms continuous to discontinuous, isopachous to irregular rims that drape over fibrous calcite cement, or where the latter is absent, around framework particles of grainy lithofacies. It occurs uncommonly along the internal walls of bioclast molds, always forms the earliest cement in this pore space. The prismatic calcite consists of limpid crystals, 60 to 120 μm long and up to 40 μm wide (Fig. 6.7). The crystals show flat to scalenohedral terminations, and have a pinkish colouration when stained. Type-IV cement is usually non-luminescent but may locally show a succession of, first, dull brown then non-luminescence. Prismatic calcite cement postdates Type-I through Type III cements, and formation of moldic porosity. Type-IV cement occurs frequently in medium- to coarse-grained lithofacies (e.g., bioclastic and oolitic grainstone and packstone) of the Pamelia and Lowville formations, usually found in the lower part of rhythmic units. However, like Type-I cement, it may also occur in intraskeletal (e.g., articulated ostracod shells) porosity within other lithofacies, as well as in the Chaumont Formation.

Fig. 6.7 Prismatic calcite cement (P, Cement type IV) fills most of intergranular spaces of an oolitic grainstone. This cement postdates fibrous (f) calcite cement which forms a thin isopachous layer around the ooid grains. Lowville Fm., at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 100 μm.


f
p

Type-V: Equigranular blocky calcite - A

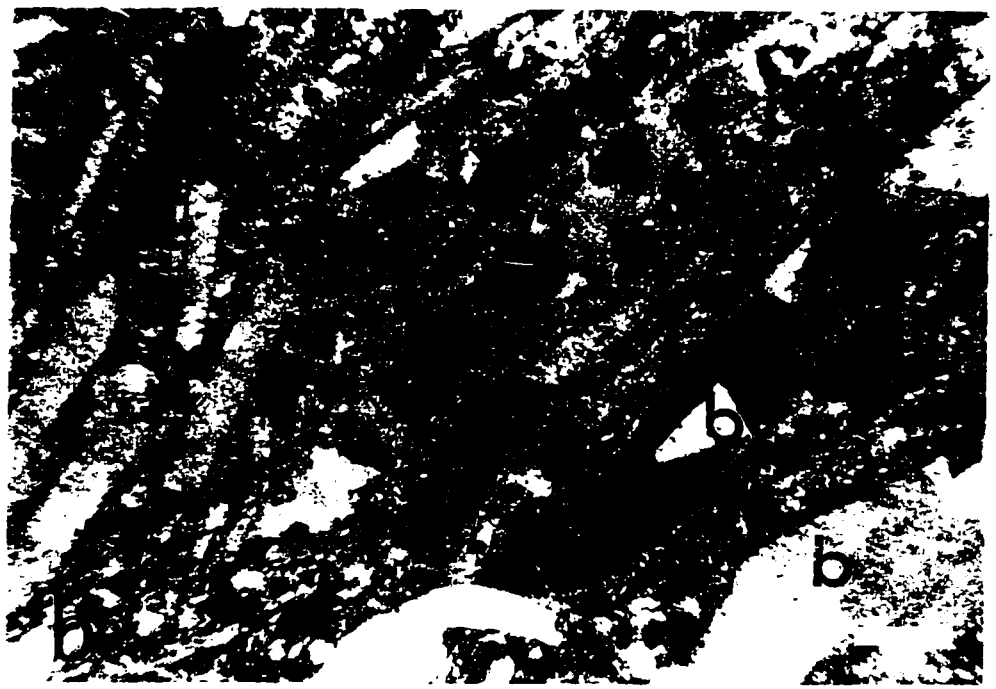
This cement fills intergranular as well as intragranular (including shell mold) pore spaces. It is preferentially developed in rocks with relatively fine intergranular porosity (e.g., medium- to fine-grained lithofacies), and consists of fine to very fine crystalline (< 60 μm), anhedral, equant blocky calcite (Figs 4.13b, 6.8a). Calcite crystals form interlocking mosaics with compromise boundaries. This cement stains pink. Using cathodoluminescence, the cement is dull red to non-luminescent. Type-V cement post-dates formation of micrite envelopes, Type-I to Type-III cements, and probably Type-IV cement. The temporal relationship between Type IV and Type-V cement is not clear. Type-IV cement usually follows Type-I without Type-V cement intervening, Type-V cement probably postdates Type-IV cement. The former cement also postdates leaching of metastable clasts as it too fills biomoldic porosity (see below).

Type-VI: Equigranular blocky calcite - B

This cement occupies inter- and intragranular porosity, moldic pores (e.g., leached shells of bivalves, *Tetradium* corals, and gastropods), and fracture porosity. It consists of coarsely crystalline (30 μm to over 4 mm wide) anhedral, clear, blocky (sparry) calcite (Figs. 6.4, 6.8b). The crystal size usually increases toward the centre of the pore space. Crystal size gradation with Type-V cement makes it difficult to set a limit between the two cements. However, this gradation does not occur where Type-VI cement is in contact with Type-IV cement. Like Type-V cement, Type-VI cement stains a pink colour. Rare poikilotopic fabric is associated with Type-VI cement, and shows petrographic attributes similar to those of Type-VI cement. Using cathodoluminescence, Type-VI cement is commonly dull red to

Fig. 6.8a Fine crystalline, equant blocky calcite (Cement Type V, b) fills most of intergranular spaces of a bioclastic, oolitic grainstone lithofacies. Note that this cement postdates fibrous (f) calcite cements. Unit II of the Pamelia Fm., at Loc. 24, Scott St. Transitway, Ottawa. Scale bar is 300 μm.

Fig. 6.8b Coarse blocky calcite cement (Cement Type VI, b) fills bivalve moldic spaces as well as intergranular porosity. Unit V of the Pamelia Fm. at Loc. 47, Macleod quarry, Cornwall. Scale bar is 300 μm.



orange colour, and seldom shows irregular, poorly developed zonation of red to (locally bright) orange luminescence. In general, the luminescence increases from crystal centre to periphery. This cement postdates Type-IV and Type-V cements, leaching of metastable bioclasts, and formation of fractures. Type-VI cement is present in all limestone lithofacies of the Blackriveran strata of the embayment. However, it occurs most frequently in the medium- to coarse-grained lithofacies (e.g., bioclastic and oolitic grainstone and packstone) of all three formations. In finer-grained lithofacies, this cement fills either intragranular spaces (e.g., ostracods) or fractures.

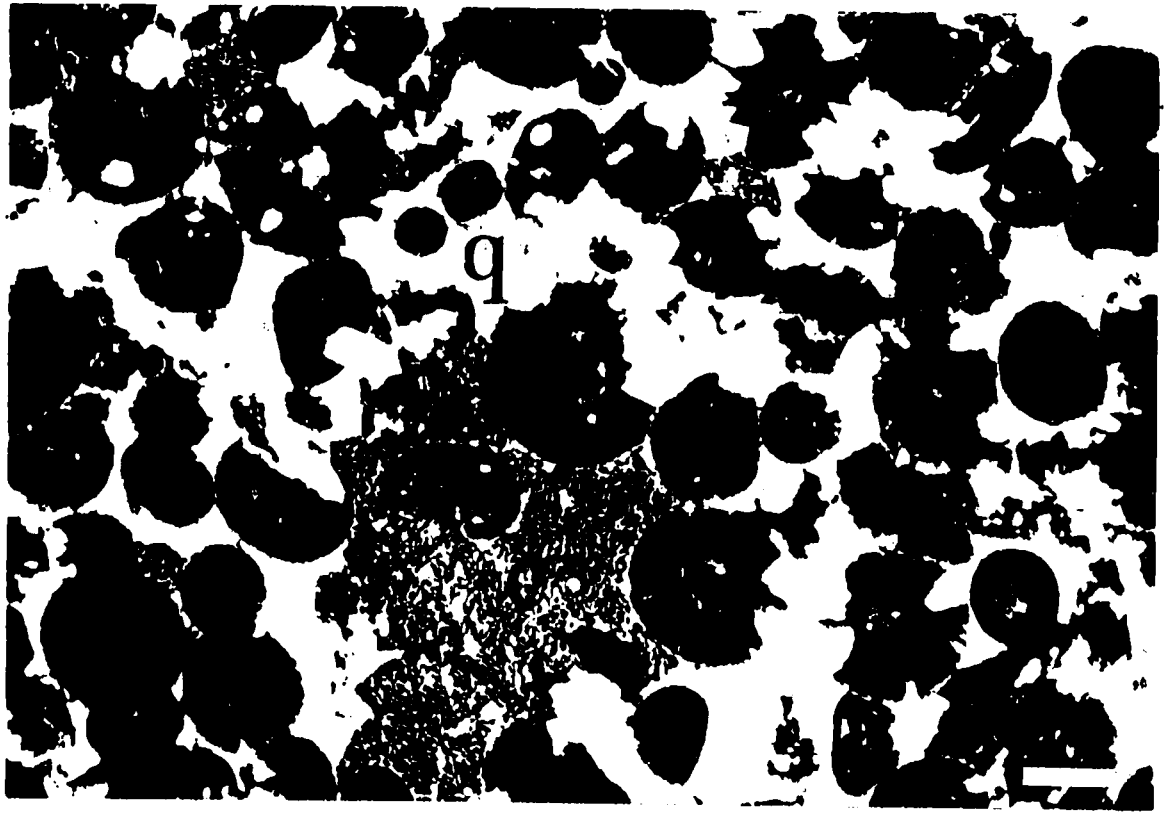
Type-VII: Equigranular blocky calcite - C

Type-VII cement is petrographically similar to the Type-VI cement, with the major difference being its blue (Fe-rich) stain (Fig. 4.13b), and a dark brown- to non-luminescence. Precipitation of Type-VII cement post-dates formation of some stylolites. Type-VII cement is less common than Type-VI cement, and the former always occurs towards the centre of pore spaces. Type-VI and Type-VII cements occur in the same stratigraphic intervals.

Quartz replacement

Quartz, replacing framework grains as well as cement, is recognized but not common in the Blackriveran strata. Quartz forms subhedral to anhedral crystals (up to 250 microns long) (Fig. 6.9). Quartz replacement is less common in the Pamelia and Lowville formations compared to the Chaumont Formation. In the former, quartz replacement occurs in cement Type-VI (and probably Type-VII cement) as well as oolites (Fig. 6.9). In the Chaumont Formation, quartz replacement is seen in bioclasts, particulary brachiopods and crinoids.

Fig. 6.9 Quartz (q) replacing pre-existing calcite (c) cement (Type-VI). Note that authigenic quartz crystals also replace part of ooid grains. Unit II of the Pamelia Fm. at Loc. 47, Macleod quarry, Cornwall. Scale bar is 300 μm.


q

Moldic porosity

Biomoldic porosity is common within the Blackriveran section. Affected bioclasts include bivalves (Figs. 4.12a, 6.4, 6.8b), *Tetradium* corals (Fig. 6.10a), calcareous algae (Fig. 4.12b) and gastropods (Fig. 6.10b). The outline of the leached grains is usually preserved by micrite envelopes. Leached pore spaces are filled by various types of cements, especially Type-IV through Type-VII cements. Some leached *Tetradium* corals and (rarely) bivalves are filled by peloids, micrite or fine-grained bioclasts.

Geopetal fill

Intragranular and moldic geopetal fill has been observed in a few of the limestone facies. Where only partial sediment fill occurred, calcite cement fills the remaining part of the void space. Geopetal sediment fill consists of grey silt to sand size crystals and grains. The finer silt-size sediments are recrystallized. Lamination and normal grading from sand to silt is characteristic of these geopetal fillings (Fig. 6.11a). Another type of sediment fill is characterized by a uniform, thin micrite layer that drapes the lower surface of moldic porosity (Fig. 6.11b). This geopetal micrite is lighter in colour than the micritic matrix of the host rock, and usually follows the irregular micropaleotopography at the base of the available pore spaces (Fig. 6.11b).

Compaction features

Mechanical compaction

Evidence of minor mechanical compaction is found locally, and includes breakage of ooids and bioclasts. The breakage postdates precipitation of fibrous calcite cement (Type-I

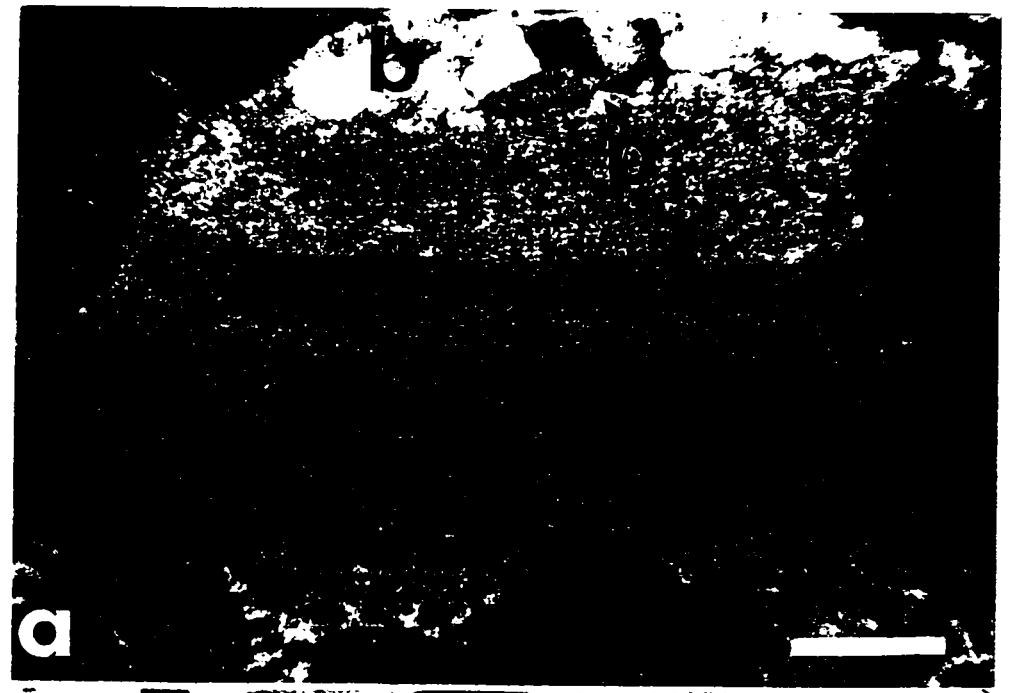
Fig. 6.10a Moldic porosity developed in *Tetradium* corals and refilled by cement Type-VI. Calcite-refilled *Tetradium* coral branches are vertical to horizontal, and were referred to as "typical birdseye effect of the Lowville Formation" or *Phytopsis tubulosum* in the past (e.g. Young 1943a; Wilson 1932; Raymond 1931). Lowville Fm. at Loc. 16, Riverside Dr., Ottawa. Scale bar is 1000 μm.

Fig. 6.10b Moldic porosity developed in bivalves and gastropods and refilled by both cement Type-VI and Type-VII (relatively darker crystals, arrows). Lowville Fm. at Loc. 16, Riverside Dr., Ottawa. Scale bar is 1000 μm.

b

Fig. 6.11a shows laminated and graded geopetal sediment filling probably in a burrow hole. The uppermost part of the void space is filled by Type-VI cement (b). Poorly developed prismatic calcite (cement Type-IV, p) may occur between the top of the geopetal fill and Type-VI cement. Lowville Fm. at Loc. 16, Riverside Dr., Ottawa. Scale bar is 600 μm.

Fig. 6.11b shows a thin layer (arrows) of secondary fill which drapes along depression zones of what appears to have been *Tetradim* coral molds. Note relics of *Tetradium* corals. Lowville Fm., at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 600 μm


b
a

b

cement) but predates remaining diagenetic features that are later than the fibrous calcite cement. Evidence of the mechanical compaction has been found in the Pamelia and Lowville formations.

Stylolites and other chemical compaction features

Chemical compaction features include stylolites, linear, concave-convex and sutured grain contacts. Stylolites are common throughout the various lithofacies of the Blackriveran strata whereas the other features are usually confined to medium- to coarse-grained packstone and grainstone lithofacies (e.g., oolitic and bioclastic grainstone and packstone). Sutured and stylolitic grain contacts are restricted to grainstone lithofacies (Fig 6.12a). Most stylolites are characterized by a thin (3 μm) sinuous, horizontal layer of insoluble clay minerals (Fig. 6.12b). In certain lithologies, where the carbonate host rock is rich in quartz clasts, stylolites form thick (up to 200 μm) sinuous layers with high concentration of quartz particles. The stylolites postdate all other diagenetic features except some fractures and their fracture-filling blue-stained calcite (Type-VII cement) and dolomites (Dolomites II and III, see below).

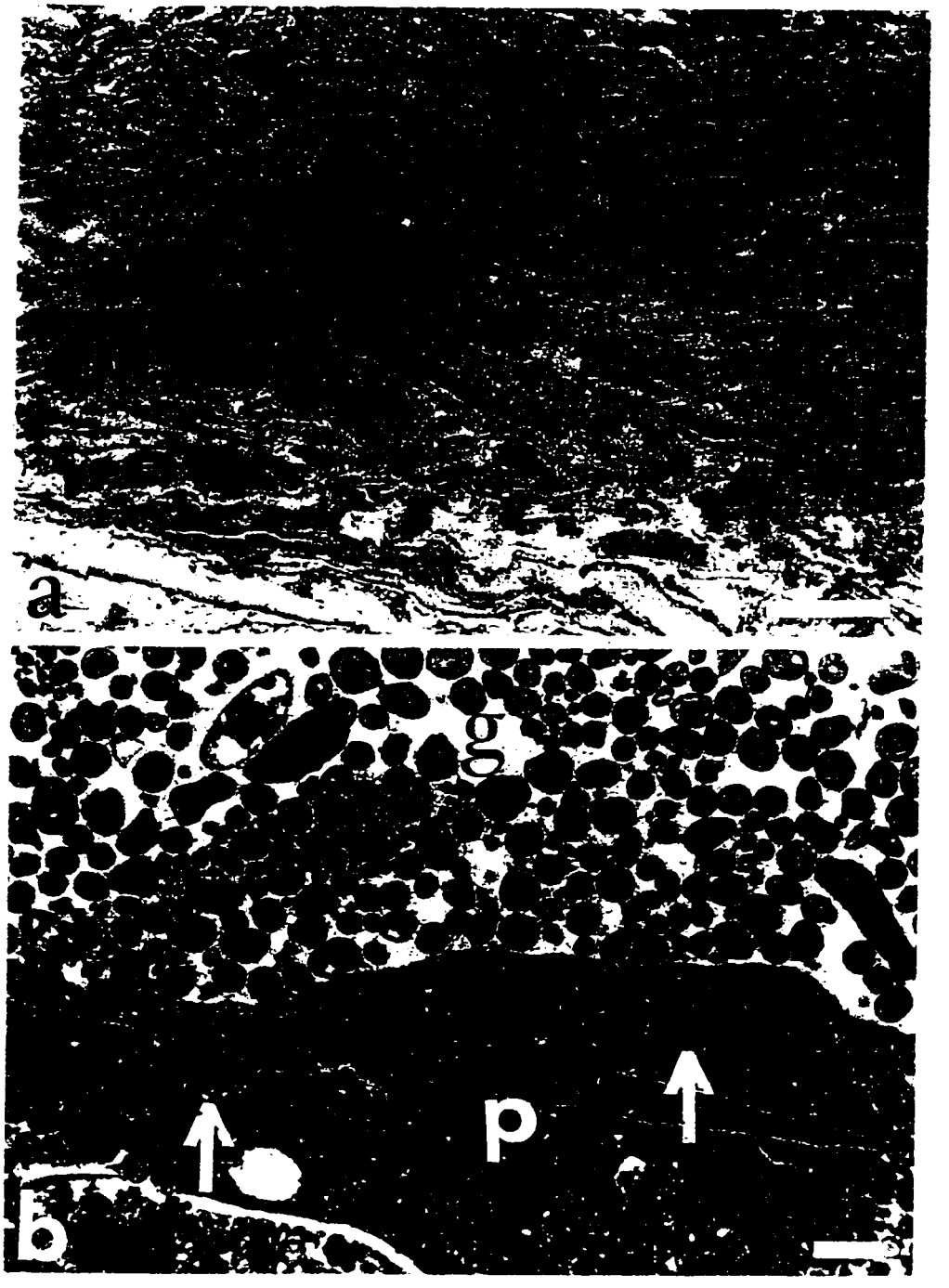
Geochemical analysis of cements

Microprobe analysis

Fourteen samples selected from medium- to coarse-grained lithofacies (CLF6 & CLF7) of the Pamelia and Lowville formations were polished for microprobe analyses. Elements (Ca, Mg, Fe, Sr, Na, and Mn) of three cement types (fibrous calcite = Type I,

Fig. 6.12a Suture and stylolitic grain contacts in algal (?Phylloid) grainstone. Note that stylolitic surfaces are horizontal to subhorizontal. Unit II of the Pamelia Fm. at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. Scale bar is 1000 μm.

Fig. 6.12b Oolitic packstone overlain by oolitic grainstone. The two facies are separated by a ? hardground, incrusted surface. A horizontal stylolite, marked by a thin sinuous residual clay (arrows), runs horizontally in the lower packstone lithofacies. Unit VI of the Pamelia Fm. at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 1000μm.


a
g
p
Б

prismatic calcite = Type IV, and equigranular blocky calcite = Type VI & Type-VII) were examined to identify potential vertical or lateral stratigraphic changes in geochemistry of these cements, and to provide geochemical support for petrographically-determined diagenetic realms for the various types of cements. Analytical data are shown in Appendices 2a, 2b, and 2c. Most of the analyzed points show elemental contents below their respective detection limits. The values of the most significant elements are plotted in a binary figure (Fig. 6.13). The Mg versus Fe (6.13a) and Mn versus Fe (6.13b) plots compare values of the three cements whereas the Mg versus Fe (6.13c) plot compares elemental values of Type-VI and Type-VII cements from different sections within the Ottawa Embayment.

The binary plots 6.13a and 6.13b show no obvious discrimination among the various types of cements based on Mg and Mn contents. However, change in Fe content identifies three groups: Group 1 contains Fe values below the detection limit. There are 87 samples along the Mg axis equivalent to 68.5% of the total number of points. Group 2 contains samples with Fe values less than 1500 ppm. Group 3 contains Fe values of more than 1500 ppm. Both Type-I (fibrous calcite) and Type-IV (prismatic calcite) cement occur in Group 1 and Group 2. Data points comprising Group 3 are from cements that stain blue and have non-luminescence: that is, they are Type-VII cements. Blocky calcite cement with Fe less than 1500 ppm (in groups 1 and 2) stained pink and showed red to orange luminescence suggesting Type-VI. The Mg versus Fe binary plot (Fig. 6.13c) shows the distribution of the blocky calcite cement according to locality and lithologic unit. There is no obvious geochemical separation on this basis.

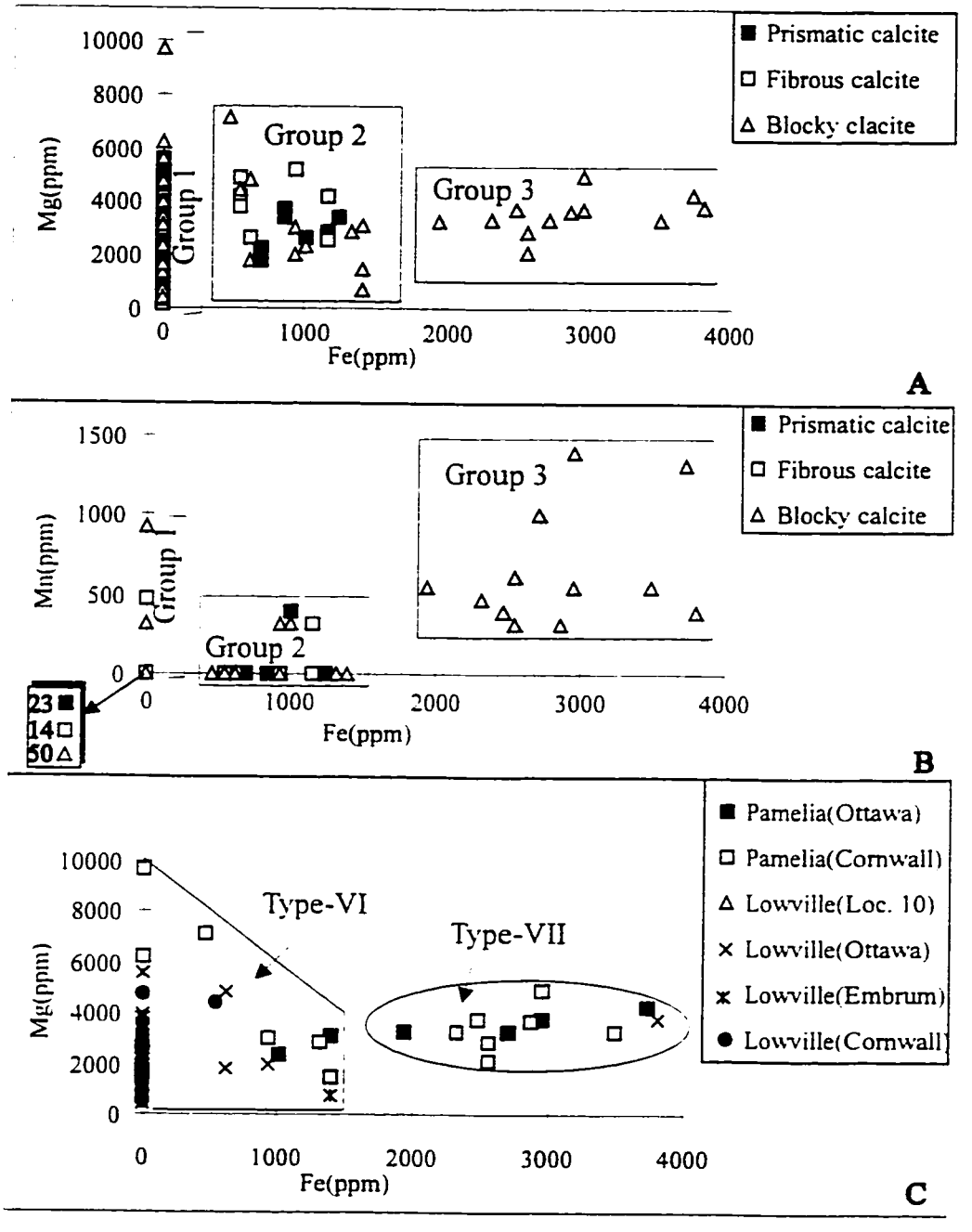


Fig. 6.13 Binary diagrams showing Fe, Mg, and Mn concentrations of the fibrous (cement Type-I), prismatic (Type-IV), and blocky (Type-VI and Type-VII) calcite cements of the Pamelia and Lowville formations.

Interpretation

Diagenetic features, and their relative timing (Figs. 6.1, 6.2, 6.3) suggest that the post-depositional history of the Blackriveran strata in the Ottawa Embayment evolved from marine through locally vadose to burial diagenetic environments.

Micrite envelopes and fibrous calcite cement are the earliest marine diagenetic signatures which formed while the sediments were still in contact with their embryonic marine water. Micrite envelopes are attributed to micritization of grain surfaces at the site of sedimentation (Flügel 1982; James and Choquette 1990b; Tucker and Wright 1990). The micrite layer is formed by endolithic (boring) micro-organisms, boring into the surface of the bioclasts (Flügel 1982; James and Choquette 1990b; Tucker and Wright 1990). Absence of a micrite envelope around grains within mudstone and wackestone lithofacies suggests that the presence of fine-grained sediments impedes colonization of micro-organisms.

Early, minor mechanical compaction is indicated by broken oolite cortices and bivalves. The relative age of the mechanical compaction suggests that some compaction occurred during shallow burial, but early cementation by Type-I cement probably decreased its maximum potential.

Fibrous calcite cement (Type-I) typically forms in active marine or marine-phreatic zones (Shinn 1969; Longman 1980; Flügel 1982; Harris et al., 1985; Molenaar et al. 1988; James and Choquette 1990b; Tucker and Wright 1990). However, original mineralogy (aragonite, high-Mg, or low-Mg calcite) of fibrous calcite cements in ancient rocks is not well known. Many researchers (e.g., Assereto and Folk 1976; Loucks and Folk 1976; Longman 1980) have used the shape of the fibrous calcite crystal terminations to distinguish an aragonite versus high Mg-calcite precursor mineralogy. These authors point out that aragonite crystals show square-ended fibres, and their alteration to low-Mg calcite could preserve this fabric. Lack of square terminations in isopachous fibrous calcite rims in

Blackriveran strata may preclude an aragonitic origin and, therefore, I suggest a high Mg-calcite precursor. Sandberg (1985) argues that, like aragonite ooids and bioclasts, calcitization of aragonite cements will thoroughly obliterate the finest textural elements of the original aragonite cement even if the replacement occurs under closed system. Therefore, preservation of the original fibrous texture would indicate a non-aragonitic origin, and possibly a high Mg-calcite.

Brand and Veizer (1980) and Veizer (1983) documented that sediment and cement formed in a marine environment are relatively rich in Sr and Na, and poor in Fe and Mn, reflecting composition of oxygenated sea water. However, textural maturity of the marine products during diagenesis favours a decrease in Sr and Na, and increase in Fe and Mn concentrations in the diagenetic products. The low Sr- and Na-contents and locally elevated Fe content of the fibrous calcite suggest that diagenetic alteration has modified the original marine cement chemistry. Despite this diagenetic alteration, the cement maintained its original fibrous texture suggesting a magnesian-calcite origin, since if it were of aragonite origin the fibrous texture would have been destroyed by the latter diagenetic alteration (Sandberg 1985).

Presence of pendant and meniscus cements in certain layers beneath supratidal dolostone and the sandstone layer (T-3) of the Pamelia Formation suggests that these cements developed in a vadose diagenetic realm (Longman 1980; Flügel 1982; Moore 1989; James and Choquette 1990c), with an overlying surface exposure caused by relative sea-level drop. Similarly, the geopetal silt confined in certain layers of the Pamelia and Lowville formations are probably related to similar periods of subaerial exposure. It is also probable that, during these stages of sea-level fluctuation (accompanied by meteoric water flushing into the sediments), many metastable grains were (at least partially) dissolved.

Cementation within a possible marine-meteoric mixing zone is suggested by the

presence of prismatic calcite cement (Type-IV cement). On the basis of Type-IV morphology and its age relationship with Type-I, Type-IV cement precipitated from a less saline pore water than Type-I cement (Folk 1974). This implies that the diagenetic fluid was probably a mixture of predominantly marine water with some meteoric mixture. Prismatic calcite cements are considered as products of marine-meteoric mixing zones elsewhere (Moore and Druckman 1981; Druckman and Moore 1985). However, the marine water component is predominant in the diagenetic marine-meteoric fluid (Folk 1974). The poor- to non-luminescent character of Type-IV cement may also support pore water dominated by marine water. Local luminescence zonation within Type-IV cement may indicate fluctuation in the pore water chemistry due to temporal changes in marine-meteoric water mixtures.

Successions of cement types V through VII, all equigranular in texture, suggest a diagenetic continuum with progressive burial (James and Choquette 1990c). Type-V cement post-dates Type-I to Type -IV calcite cements, dissolution of the metastable bioclasts, fills fractures, and predates Type-VI cement, Type-VII cement, and stylolites. It is, therefore, the earliest burial cement within a meteoric phreatic burial realm (Flügel 1982; James and Choquette 1990c; Tucker and Wright 1990). Petrographic similarities between Type-V and Type-VI cements, their gradational nature suggest that they probably precipitated from a similar diagenetic fluid, but their crystal size difference results from differences in available pore space. Petrographic and chemical attributes of Type-VII cement (e.g., blue staining, non-luminescence and relatively higher Fe-content, Fig. 6.13), its age relationship with Type-VI cement and some stylolites suggest deeper burial setting (Scholle and Halley 1988; Choquette and James 1990). The poikilotopic fabric associated with Type-VI cement is also interpreted to be a burial diagenetic feature (Tucker and Wright 1990).

Burial depth of the Blackriveran strata of the Ottawa Embayment appears to be deep (> 300 m). Based on Conodont Alteration Index (CAI), Legall et al. (1981) showed that CAI

of conodonts from eastern Ontario range 2.5 to 3; indicating a burial temperature of 90°C to 120°C. Such range of temperature gives an approximate overburden of 2800 to 3200 m (Nowlan and Barnes 1987). However, Legall et al. (1981) indicated that the CAI range from eastern Ontario is high compared to southern Ontario, suggesting that faulting along Ottawa - Bonnechère graben could have controlled the high CAI values. So that, the burial depth of the Blackriveran strata is probably less than the estimated overburden thickness but still within the range of deep burial depth (> 300 m).

Diagenesis and origin of dolomite

Introduction

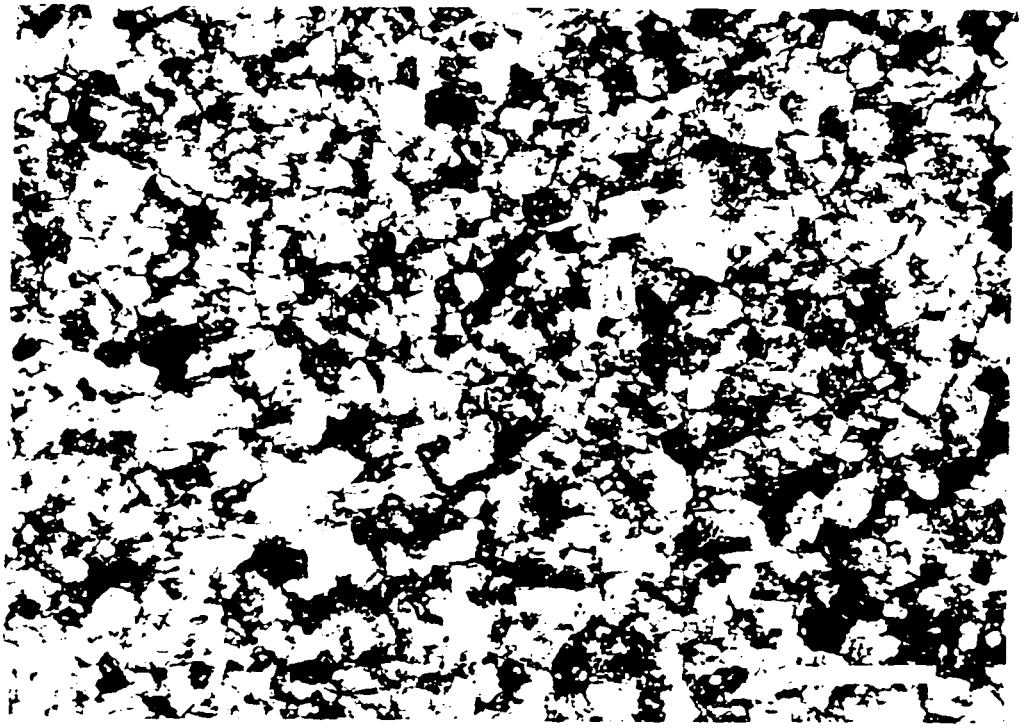
Three generations of dolomite, based on crystal size, texture and petrographic characteristics, are recognized in the Blackriveran succession of the Ottawa Embayment. These dolomite types are: (1) mosaic of fine crystalline dolomite (Dolomite I), (2) fine to medium crystalline, isolate rhombohedra (Dolomite II), and (3) coarse crystalline, void-fill dolomite (Dolomite III). Petrographic and geochemical descriptions of these dolomites, as well as their origin, are presented in the following sections.

Dolomite I

Petrography

Dolomite I is characterized by homogenous, very fine (micron-sized) to fine (decimicron-sized, usually < 70 μm), interlocking euhedral to subhedral (planar-e and planar-s; Sibley and Gregg 1987) crystals that form an interlocking mosaic (Figs. 4.5b, 6.14). The dolomite crystals are colourless or stain light purple, and are non-luminescent. However,

Fig. 6.14 Thin section photomicrograph showing fine, euhedral to subhedral (planar-e to planar-s) interlocking mosaic dolomite crystals that characterize Dolomite I. Unit IV of the Pamelia Fm. at Loc. 44, Cruickshank quarry, Winchester - Morrisburg area. Scale bar is 400 μm.



the dolomite crystals often show cloudy, locally bluish centres of probable calcite mineralogy representing dedolomite (see below). In addition, space between dolomite crystals is filled by very fine (usually < 10 μm), anhedral, unstained, limpid crystals of probable dolomite. However, these very fine crystals may also be calcite, unstained due to their small crystal size. Type-V through Type-VII cements are present in Dolomite I but are usually rare and fill fractures, biomolds and evaporite molds. Dolomite I, therefore, forms a groundmass that predates other generations of dolomites (Dolomite-II and Dolomite-III), pink and blue calcite cements (Type-V, VI, & VII cements), fractures, moldic porosity, stylolites and other compaction features. Dolomite I is the most predominant dolomite type (> 95%) and is exclusively confined to the Pamelia Formation. It is the prevailing constituent of the thick dolostone intervals (e.g.,T-1) which form the CLF1 lithofacies that forms top of rhythmic units in the Pamelia Formation. See chapters 3 and 4 for sedimentologic details.

Dedolomitization

Partial dedolomitization has affected Dolomite I. Dedolomitization occurred along crystal borders and cleavage surfaces. Dedolomitized zones stain purple. The rhombohedral fabric of the original dolomite crystals is generally preserved suggesting a mimic replacement.

Geochemistry

X-ray diffraction analysis of these dolomites illustrate that Dolomite I is non-stoichiometric, with 51.88 to 58.75 mol % $CaCO_3$. It is also poorly ordered. Major (Ca and Mg) and minor (Fe, Mn, Na, and Sr) elements of the dolomite were analyzed and the results

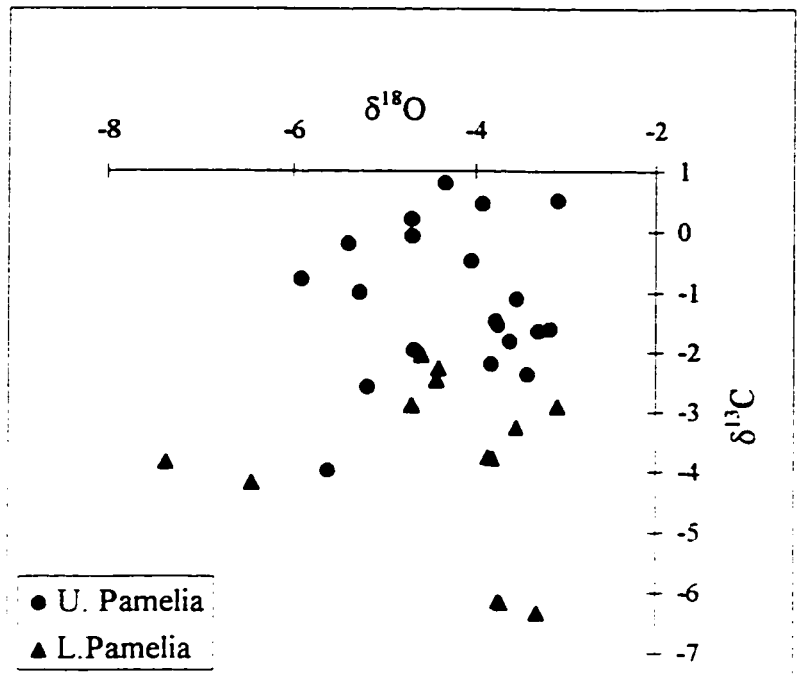
are shown in Appendix 3a. The results show considerable range in $CaCO_3$ content, some clearly defining some calcite - dolomite mixtures. This is most likely caused by dedolomitization. Oxygen and carbon isotopes of 33 samples were also analyzed (see Appendix 3b). Dolomite I has $\delta^{18}O$ values between -8.04 ‰ and -3.06 ‰, relative to Pee Dee Blemnite (PDB), and $\delta^{13}C$ values of between -6.34 ‰ and 0.8 ‰, relative to (PDB). Figure 6.15a shows a binary plot of $\delta^{18}O$ versus $\delta^{13}C$. No significant isotopic differences are observed within the Pamelia Formation between the Ottawa and Cornwall-Morrisburg areas. However, dolostone from the Lower Member of the Pamelia Formation from both regions show more negative ^{13}C values when compared with the dolostones from the Upper Member of the formation (Fig. 6.15a).

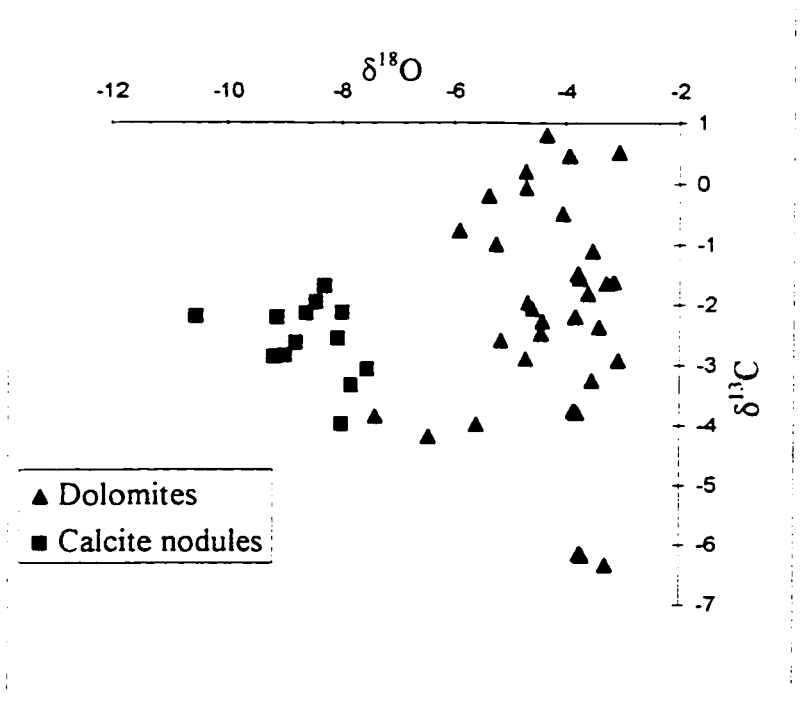
Interpretation

Dolomite I is interpreted to have formed syngenetically within a hypersaline sabkha environment. This is already inferred from field evidence, which includes an association with desiccation cracks, birdseye structures, evaporitic crystal molds, calcite and celestite nodules. Moreover, beds of Dolomite I occur at the top of the shallowing-upward cycles, contain relatively high terrigenous quartz grains, and are associated with stromatolites and other peritidal lithofacies (see chapters 3 & 4). Petrographic attributes, such as fine to very fine crystals and the non-luminescence character, support a penecontemporaneous origin for these dolomites (La Porte 1967; Textoris 1968). A modern analogue is dolomite forming along the Trucial coast of Abu Dhabi and Qatar (Illing et al. 1965; Morrow 1982a; b; Machel and Mountjoy 1986). The fine crystalline fabric preservation in many ancient dolomites is directly analogous to, and most likely related to, the fine-grained dolomitic sediments that

Fig. 6.15a Binary diagram showing $\delta^{18}O$ versus $\delta^{13}C$ values of samples from the dolostone lithofacies of the Pamelia Formation.

Fig. 6.15b Binary diagram plotting $\delta^{18}O$ versus $\delta^{13}C$ values of calcite samples from the calcite nodules and samples from the host rocks. Note the net $\delta^{18}O$ separation between the two groups, indicating that the calcite nodules precipitated from diagenetic fluid isotopically lighter in ^{18}O with respect to the fluids that precipitated the hosting dolomite rocks.


δ18O
-8
-6
-4
-2
1
0
-1
-2
-3
-4
-5
-6
-7
δ13C
U. Pamelia
L.Pamelia


δ18O
-12
-10
-8
-6
-4
-2
1
0
-1
-2
-3
-4
-5
-6
-7
δ13C
Dolomites
Calcite nodules

form today as early replacement of aragonite in the upper peritidal (high intertidal and supratidal) zones of modern carbonate tidal flats of the Persian Gulf sabkhas, as well as Caribbean dolocrusts (Illing et al. 1965; Morrow 1982a).

Petrographically and stratigraphically similar dolostone facies of Blackriveran age in Kingston and upstate New York (Textoris 1968; Peterson 1969; Mukherji 1969; Walker 1972; 1973; Cameron and Mangion 1977; Noor 1989; McFarlane 1992) as well as in the Ottawa Embayment (Sawford 1972; Steele-Petrovich 1984; Williams 1991), are also interpreted to have a syngenetic supratidal origin.

Geochemical analysis of Dolomite I also supports penecontemporaneous origin relative to sedimentation. Wadleigh and Veizer (1992) and Qing and Veizer (1994) have analyzed oxygen and carbon isotopic compositions of Lower Paleozoic brachiopod shells in order to determine the isotopic signature of calcite precipitated from Lower Paleozoic marine water. It is assumed by these authors, as well as Brand (1989), that the $\delta^{18}O$ and $\delta^{13}C$ values of brachiopod shells reflect ambient marine chemistry.

From Figure 2 of Qing and Veizer (1994), $\delta^{18}O$ of Blackriveran brachiopod shells ranges from -6 ‰ to -4 ‰ PDB. Since the majority of brachiopods live in a normal marine environment, and assuming a paleo-temperature of 25°C, marine calcite with a $\delta^{18}O$ value ranging from -6 ‰ to -4 ‰ would have precipitated from a marine water that had $\delta^{18}O$ values of -4 ‰ to -2 ‰ SMOW. These values are estimated from Figure 6.22 of Tucker and Wright (1990, p. 311) that plots equilibrium relationship between $\delta^{18}O$ of calcite, temperature and $\delta^{18}O$ of water. Values in this figure are based on Epstein et als' (1953) expression modified by Craig (1965): $t(°C) = 16.9-4.2(\delta c-\delta w) + 0.13(\delta c-\delta w)^2$, where δc is the $\delta^{18}O$ value (in PDB) of CO_2 produced by reaction of $CaCO_3$ in phosphoric acid at 25°C,

and δw is the $\delta^{18}O$ value (in PDB) of CO_2 in equilibrium with water at 25°C. Using these $\delta^{18}O$ values for a diagenetic fluid, at 25°C, a dolomite would have an $\delta^{18}O$ value ranging between about -3 ‰ to -1 ‰ PDB (Tucker and Wright 1990). These values are also estimated from Figure 8-16 of Tucker and Wright (1990, p. 383) that plots $\delta^{18}O_{dolomite}$ versus temperature for various $\delta^{18}O_{water}$ values. However, pore-water temperature of the present-day supratidal flats and sabkhas (e.g., the Trucial coast of the Arabian Gulf) varies from 25°C to 40°C (Patterson and Kinsman 1982; Tucker and Wright 1990). Shinn (1986) has also shown that surface temperatures of the supratidal zones with profoundly sun-heated hypersaline lagoonal waters along the Trucial Coast oscillate between 40°C and 50 ℃. Using these temperatures as paleo-temperature values for the Blackriveran supratidal (hypersaline) environments, the possible $\delta^{18}O$ values for Dolomite I are shown in Table 6.2.

There is a good overlap in the $\delta^{18}O$ range calculated for 40°C and 50°C (-3 ‰ to -7.5 ‰) and the $\delta^{18}O$ values determined for Dolomite I (compare $\delta^{18}O$ values in Fig. 6.15 vs $\delta^{18}O$ values in Table 6.2). This suggests that Dolomite I could be syn-sedimentary and formed very early in a supratidal environment. However, other factors may influence the $\delta^{18}O$ range in values.

As mentioned earlier, terrigenous content is relatively higher in the dolostone lithofacies of the Pamelia Formation than in limestone facies. The siliciclastic input was likely related to relative sea-level fall. Coincident with progradation of shorelines, siliciclastic detritus is increased and there is a basinward shift in freshwater aquifer (Tucker and Wright 1990). It was probably during these events when evaporite nodules in the dolostone lithofacies were (at least partially) dissolved and enriched the Ca^{-2}-content in the pore water. High Ca^{-2}/Mg^{-2} ratio probably favoured local dedolomitization of Dolomite I

$\delta^{18}O$ of Blackriveran marine water (SMOW)	$\delta^{18}O$ (PDB) of dolomite at 25°C	$\delta^{18}O$ (PDB) of dolomite at 40°C	$\delta^{18}O$ (PDB) of dolomite at 50°C
-2 ‰	-1 ‰	-3 ‰	-4 ‰
-4 ‰	-3 ‰	-5 ‰	-7.5 ‰

Table 6.2 Possible $\delta^{18}O$ values for dolomites precipitating from Blackriveran marine water at various paleo-temperatures. The marine $\delta^{18}O$ values are estimated from Figure 6.22 of Tucker and Wright (1990) by using Qing and Veizer's (1994) $\delta^{18}O$ values of Blackriveran brachiopods and a paleo-temperature of 25°C.

crystals (Evamy 1967). Dedolomitization is favoured under near-surface (< 50°C) diagenetic conditions (De Groot 1967).

$\delta^{13}C$ values of marine carbonate rocks are virtually constant from Cambrian to Tertiary, fluctuating about 0 ‰ relative to PDB (Faure 1977, p. 497). However, analyzed dolomite samples show $\delta^{13}C$ values which range from +0.8 ‰ to -6.34 ‰ PDB (Appendix 3b) and most of them are below zero. This implies some diagenetic alteration has occurred. This alteration may be attributed to an atmospheric or organic-derived CO_2 source, incorporated into supratidal to shallow intertidal syngenetic dolomites. Another possibility is that some values represent incorporated dedolomite formed from diagenetic fluids enriched in ^{12}C. Lower $\delta^{13}C$ values in dolostones of the Lower Member with respect to the Upper Member of the Pamelia Formation probably reflects accumulated diagenetic effects induced by periodic fresh water flushing into the rock during lower Pamelia time.

Calcite Nodules in Dolomite I

Field attributes and relationship with host rock

The calcite nodules consist of coarse crystalline, white and pink calcite. They occur within the supratidal dolostone lithofacies (CLF1, see Chapter 4) of the Pamelia Formation. Nodules are spherical to lenticular in shape, and about 1 to 8 cm long (Fig 4.7). Collapse breccia from the host rock is locally present around and-or inside the calcite nodules.

Petrography

Calcite nodules consist of coarse (up to 5 mm) crystals of equant, anhedral calcite mosaics. The crystal size generally increases towards the centre of each void space. The

calcite crystals stain blue to purple and have a dull luminescence. Minor celestite crystals are intergrown with calcite.

Geochemical comparisons between calcite nodules and host rock

The minor elements (Fe, Mn, Na, and Sr) of 13 calcite nodules as well as their oxygen and carbon stable isotopes were analyzed. The results of the trace elements and stable isotope analyses are shown in Appendix 4. Figure 6.15b shows the $\delta^{18}O$ versus $\delta^{13}C$ of bulk samples from the calcite nodules and the host dolostone. The $\delta^{13}C$ of the calcite nodules (-3.99 ‰ PDB to -1.7 ‰ PDB) are approximately within the $\delta^{13}C$ range of the dolomites but their $\delta^{18}O$ values are more depleted than those of the dolomites (Fig. 6.15b).

Interpretation

Calcite nodules hosted by syngenetic dolomites are interpreted to have originated as filling of molds created by dissolution of evaporite nodules (gypsum and-or anhydrite). Such evaporite nodules are common in the Holocene dolomite sabkha of the Trucial Coast, Abu Dhabi (McKenzie et al. 1980; Machel and Mountjoy 1986) and of the Qatar Peninsula (Illing et al. 1965). The fact that collapse breccia fragments occur within calcite nodules suggests that fragmentation occurred prior to or during precipitation of the calcite. Blue to purple colour and dull luminescence of the nodule calcite suggest presence of a low Mn/Fe ratio (Pierson 1981). From this, calcite precipitated from a diagenetic fluid with high iron content in a reducing environment (James and Choquette 1990c). The calcite that forms the present nodules was probably precipitated from the same diagenetic fluid from which precipitated Type- VII cement. The evaporites could have been (at least partially) leached at the same

time that bioclastic molds formed. Indurated and (partially) lithified syngenetic dolomites probably preserved the evaporite molds until the latter were filled by the blocky calcite in a burial diagenetic environment.

Formation of celestite is common in hypersaline sediments (Mukherji 1969; Veizer et al. 1978; Flügel 1982, p. 473). Veizer et al. (1978) stated that formation of celestite "is related to early diagenetic replacement of metastable Sr-rich aragonite mud by low-Mg calcite or dolomite" (p. 1456). Dissolution or replacement of aragonite typically releases Sr ions into the pore water. When the pore water reaches saturation with respect to celestite, the excess Sr reacts with sulphate ions in the pore water to form celestite (Veizer et al. 1978).

Figure 6.15b shows that $\delta^{13}C$ values of the calcite nodules are within the range of the $\delta^{13}C$ values of the host dolostone, but $\delta^{18}O$ values of the former are more depleted compared with $\delta^{18}O$ values of the latter. In the carbonate rock-water system, the larger isotopic reservoir of carbon is in the rock whereas the main isotopic source of oxygen is the water. This implies that $\delta^{13}C$ of water percolating through a carbonate rock rapidly reaches equilibrium with the $\delta^{13}C$ composition of the rock whereas oxygen isotope composition of the water is transferred directly to precipitating calcite. Low $\delta^{18}O$ values in calcite forming nodules may have arisen by two pathways, occurring simultaneously or independently: (1) The calcite precipitated from a diagenetic fluid strongly buffered by meteoric water which is enriched in ^{16}O (Moore 1989; Morse and Mackenzie 1990). (2) An increase in temperature in the subsurface environment will favour preferential incorporation of the light oxygen isotope into the lattice of precipitating calcite (Moore 1989). Therefore, the calcite filling nodule molds may have formed in a deeper burial realm.

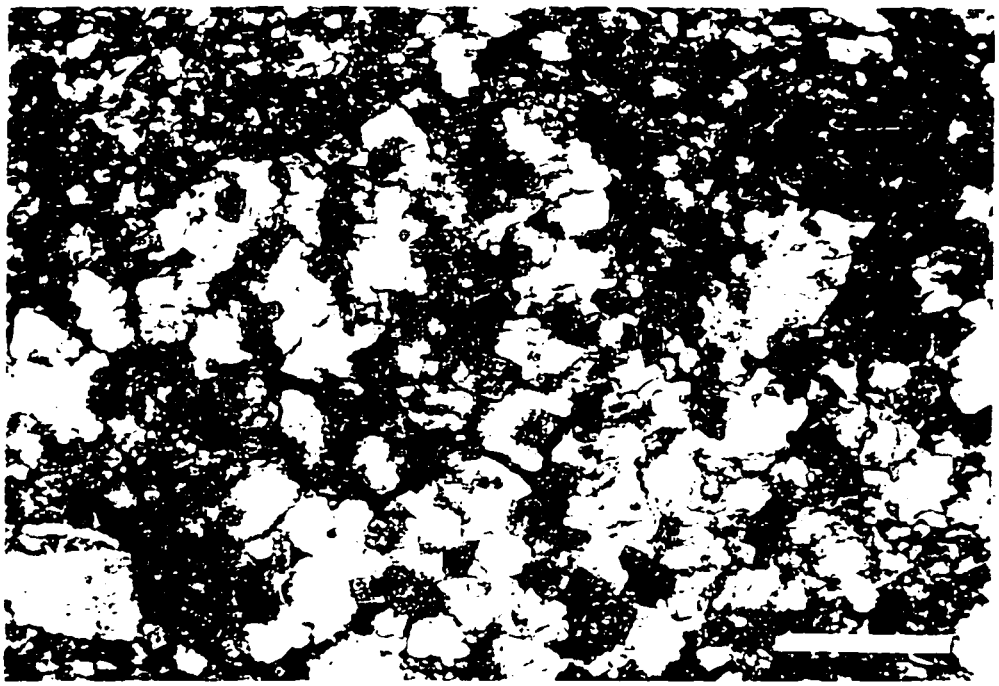
Dolomite II

Petrography

This type of dolomite is present in all the three Blackriveran formations in the Ottawa Embayment. It is volumetrically minor, and associated with various sedimentary lithofacies (e.g., thick dolostone intervals in the Pamelia Formation and the matrix of the other lithofacies units in all the three Blackriveran formations).

The dolomite rhombs in Dolomite II are characterized by isolated, euhedral crystals in the matrix of the hosting rock and in burrows (Fig. 6.16). Crystal size ranges from 20 μm to 100 μm. Crystals coalesce to form local dolomite mosaic patches a few millimetres in diameter. In plane light, the crystals are either clean and clear with minor inclusions or show cloudy appearance. Crystals of Dolomite II are colourless when stained. In the dolostone intervals of the Pamelia Formation, it is difficult to differentiate the crystals of Dolomite II from those of Dolomite I under normal petrographic microscope. However, using cathodoluminescence, crystals of Dolomite II show good zonation. Dolomite II crystals present in the Dolomite I groundmass represent less than 5% of total dolomite. The zones of the Dolomite II crystals include from the centre outward: (1) a non-luminescent core, (2) bright (red) orange, (3) dull, and (4) bright orange to (locally) dull red (with dullness increasing outward). The crystals of Dolomite II are poorly developed in the Cornwall area and show less clear distinction of overgrowth zonation. The outer surface of the zones, except the core, are fairly planar with no apparent dissolution (or corrosion). Cores show a barely visible etched outer surface.

Fig. 6.16 Photomicrograph showing Dolomite II occurring in a burrow (Chaumont Fm). It is characterized by isolated and coalescing, euhedral to subhedral dolomite crystals. Dolomite II replaces here anhedral, lighter crystals of pinkish calcite. Note the cloudy nature of the dolomite crystals. Chaumont Fm. at Loc. 34, Francon norhtern quarry, Ottawa. Scale bar is 400 μm.



The relationship between Dolomite II and stylolites shows that the dolomite spans stylolite formation.

Geochemistry

Fifty points from 8 samples collected from the Pamelia and Lowville formations were microprobed and their Ca, Mg, Fe, Mn, Na, and Sr contents were determined (see Appendix 5). Binary plots of the available geochemistry data from Dolomite II show Fe-enrichment in dolomite cements of the Pamelia Formation in the Ottawa area compared to samples from the Cornwall area (Fig. 6.17a, b). In contrast, samples from the Lowville Formation show higher Fe-content in the Cornwall area compared with samples from the Ottawa - Orleans area (Fig. 6.17a, b). On the basis of location and formation, no significant differences or trends for the Sr and Mg contents are observed (Fig. 6.17a, b, c).

Interpretation

Although total number of analyzed samples is small and may not be representative, at least three possibilities may explain regional differences in Fe distribution: (1) differences in Fe concentrations in diagenetic paleo-fluids; (2) differences in oxidation - reduction factor of the diagenetic environments; and (3) as Dolomite II is characterized by dull and luminescent zonation, analyzed points may represent zones of different Fe-contents.

Dolomite III

Petrography

Dolomite III is, volumetrically, the least important, and is a typical saddle dolomite, also called baroque (Assereto and Folk 1974).The dolomite is characterized by relatively

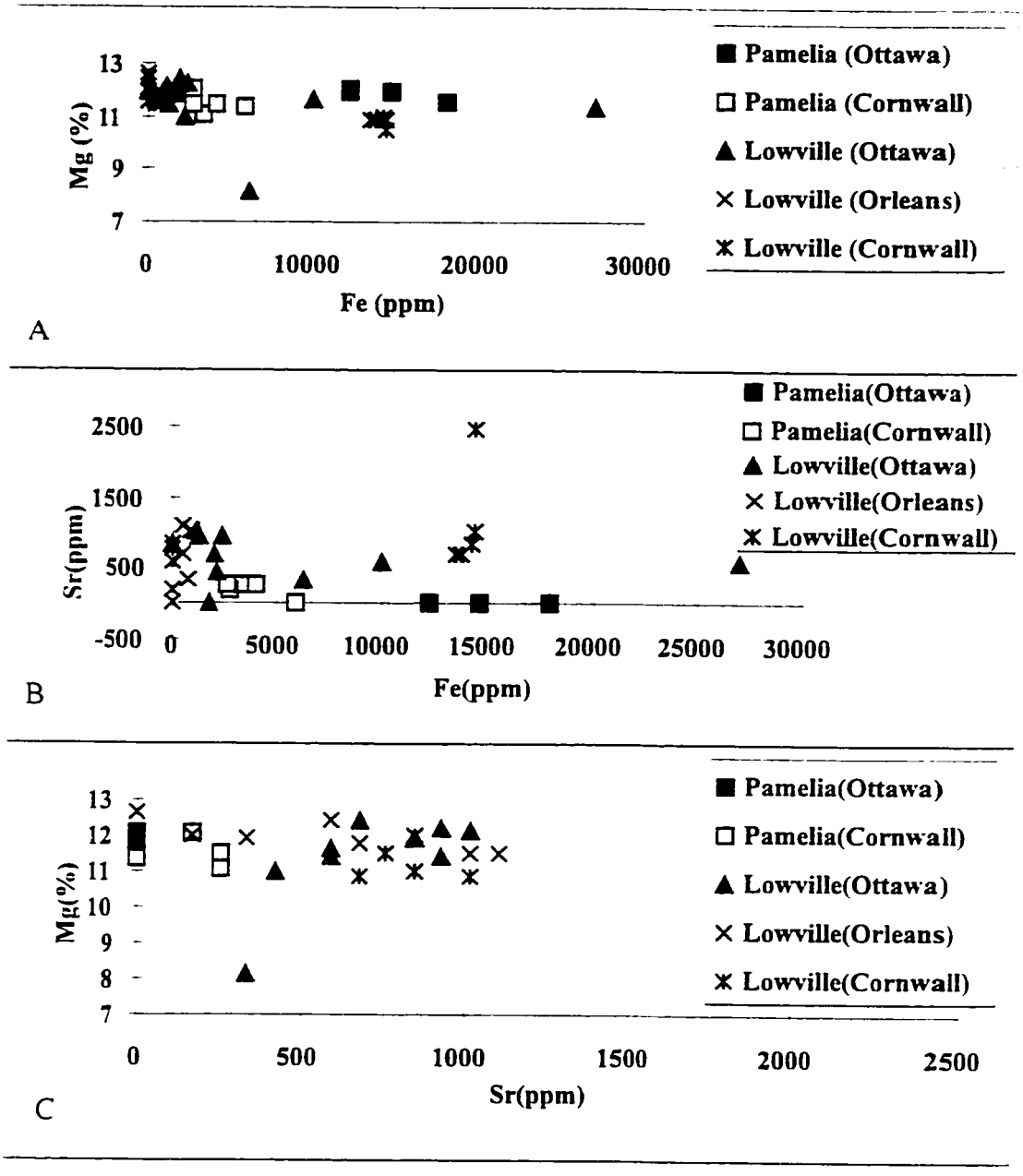


Fig. 6.17 Binary plots showing Fe, Sr, and Mg concentrations in Dolomite II.

coarse (up to 250 μm), euhedral to subhedral dolomite crystals (Fig. 6.18). The dolomite crystals have blue to purple staining, sweeping extinction, straight to curved crystal faces, and a somewhat cloudy appearance in plane light. They also display non-luminescence. Dolomite III usually fills void spaces and fractures, and is interpreted to be late-stage features. The dolomite is locally associated with, and appears to have locally replaced, Type-VII cement. However, although Dolomite III is a minor and volumetrically negligible constituent in the Blackriveran strata, it developed relatively more abundant in the dolostone intervals of the Pamelia Formation, and very rarely in other lithofacies of the succession. No geochemical analysis of these dolomites was conducted.

Interpretation

The third generation saddle dolomite (Dolomite III) is interpreted to have formed in the burial diagenetic realm (Moore and Druckman 1981; Scholle and Halley 1988). The fact that they post-date fractures as well as most of the other diagenetic events provide support that they formed during relatively late stage of alteration. Folk (1977) indicates that the baroque dolomites are diagenetic products of hypersaline brines and elevated temperature. The fact that Dolomite III is developed best in the Dolomite I lithofacies probably reflects that the latter was more capable in producing hypersaline brines due to its relatively higher content of evaporite minerals. Although a significant portion of the evaporite minerals were probably already dissolved during earlier diagenetic stages (e.g, evaporite molds later filled by calcite nodules), a high quantity of evaporites in the form minute crystals associated with Dolomite I crystals may have remained. Later dissolution of these evaporite minerals may have developed local hypersaline brines from which Dolomite III precipitated.

Fig. 6.18 Photomicrograph showing Dolomite III, (saddle dolomite, s) partially replacing calcite cement (cement Type VI) and partially filling centre-ward void space due to shelter porosity. The sample shown here stains purble. Lowville Fm. at Loc. 27, Beechwood Ave., Ottawa. Scale bar is 1000 μm.

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CHAPTER SEVEN

LITHOSTRATIGRAPHY OF THE TRENTONIAN SUCCESSION IN THE OTTAWA EMBAYMENT

Introduction

The Blackriveran portion of the Ottawa Group in the Ottawa Embayment is conformably overlain by the Trentonian succession (upper Ottawa Group). Raymond (1913) originally divided the Trentonian strata into four formations which are, in ascending order: Rockland, Hull, Trenton and Picton. These subdivisions were based on faunal zones, and later workers (e.g., Wilson 1946; Kay 1937; 1942) modified Raymond's (1913) nomenclature but still based their subdivisions of the rock succession on faunal distribution (Table 7.1).

Lithostratigraphic investigations of the upper Ottawa Group in the Ottawa Embayment (this study) showed a different stratigraphic arrangement compared to the previous interpretations. After visiting Liberty's (1969) type sections in south-central Ontario (Lake Simcoe area) and studying the available literature, the adoption of a modified version of Liberty's (1969) lithostratigraphic terminology seemed justified. The proposed nomenclature is somewhat different from that proposed by Liberty (1967a; b; 1969) and the most recent work that adopted Liberty's nomenclature (e.g., Williams and Telford 1986; Williams 1991; Johnson et al. 1992). Instead of the tripartite subdivision of the stratigraphic column (i.e., Bobcaygeon, Verulam and Lindsay formations), four formations are recognized in the Ottawa Embayment. They include, in ascending order, Bobcaygeon, Hull, Verulam and Lindsay formations. Williams' (1991) upper and lower boundaries of the Bobcaygeon Formation as well as the lower boundary of Uyeno's (1974) Hull Formation are redefined.

Table 7.1 Chart showing correlation of the various stratigraphic terms applied for the Trentonian strata in the Ottawa Embayment. B.R. = Blackriveran.

Stage	Edenian	Black-riveran
Raymond 1914	Colling-wood Fm	B.R. Group Leray Fm
Wilson 1946 Faunal zones	Eastview	Ottawa Formation Leray
Barnes 1964; 1967	Eastview Fm	B.R. Group Chaumont Fm
Uyeno 1974		Ottawa Group Leray Fm
Williams & Telford 1986 Williams 1991	U	Ottawa Group Bobcaygeon Fm Lower A
Liberty 1967a		Simcoe Group Bobcaygeon Fm
This study	U	Ottawa Group Chaumont Fm

Stage	Trentonian			
Raymond 1914	Trenton Group			
Wilson 1946 Faunal zones	Middle Phase		Upper Phase	
Barnes 1964; 1967	Ottawa Limestone Megagroup Trenton Group			
Uyeno 1974	Hull Fm Lower	Hull Fm Upper		
Williams & Telford 1986 Williams 1991	Middle	Upper	Verulam Fm	Lindsay Fm Lower
Liberty 1967a	Verulam Fm			
This study	Bobcaygeon Fm Lower	Upper	Hull Fm	Verulam Fm Lindsay Fm Lower

Stage	Rocklandian	Kirkfieldian	Shermanian	Cobourgian
Raymond 1914	Rockland Fm	Hull Fm	Trenton Fm	Picton Fm
Wilson 1946 Faunal zones	Rockland	Hull	Sherman Fall	Cobourg
Barnes 1964; 1967	Rockland Fm	Hull Fm	Sherman Fall Fm	Cobourg Fm
Uyeno 1974	Rockland Fm		Sherman Fall Fm	Cobourg Fm
Williams & Telford 1986 Williams 1991				
Liberty 1967a				
This study				

My work substantially redefines Williams' (1991) Bobcaygeon and Verulam formations as well as Uyeno's (1974) Hull Formation. New lateral relationships between the redefined Hull and Verulam formations are also shown. The Lindsay Formation is accepted as defined by Williams (1991).

In the following sections, the origin of the adopted nomenclature and brief lithologic attributes of type sections are described. Lithostratigraphic description of the upper Ottawa Group formations in the embayment, their correlation with equivalent strata in the nearby regions (e.g., southern Ontario, New York and Montreal area), as well as general depositional environments are also presented.

The Bobcaygeon Formation

Origin

The Bobcaygeon Formation was initially proposed by Liberty (1969) for the beds overlying Gull River Formation in Lake Simcoe area. Liberty (1969) revised the type section of the Middle Ordovician strata in the Lake Simcoe area, and modified Okulitch's (1939) nomenclature and formation boundaries. Liberty's (1969) Bobcaygeon Formation consisted of three members: (1) a lower member (unit C) of thickly bedded grey, fine- to medium-crystalline, crinoidal limestone (unit C1) uncommonly overlain by thin calcarenite beds (unit C2), (2) a middle member (unit D) of fine-grained, grey and brown, sparsely fossiliferous limestone, and (3) an upper member (unit E) of grey, fine- to medium-grained limestone interbedded with fine- to medium-grained (granular) calcarenites, rare brown mudstone and bluish grey crystalline limestones.

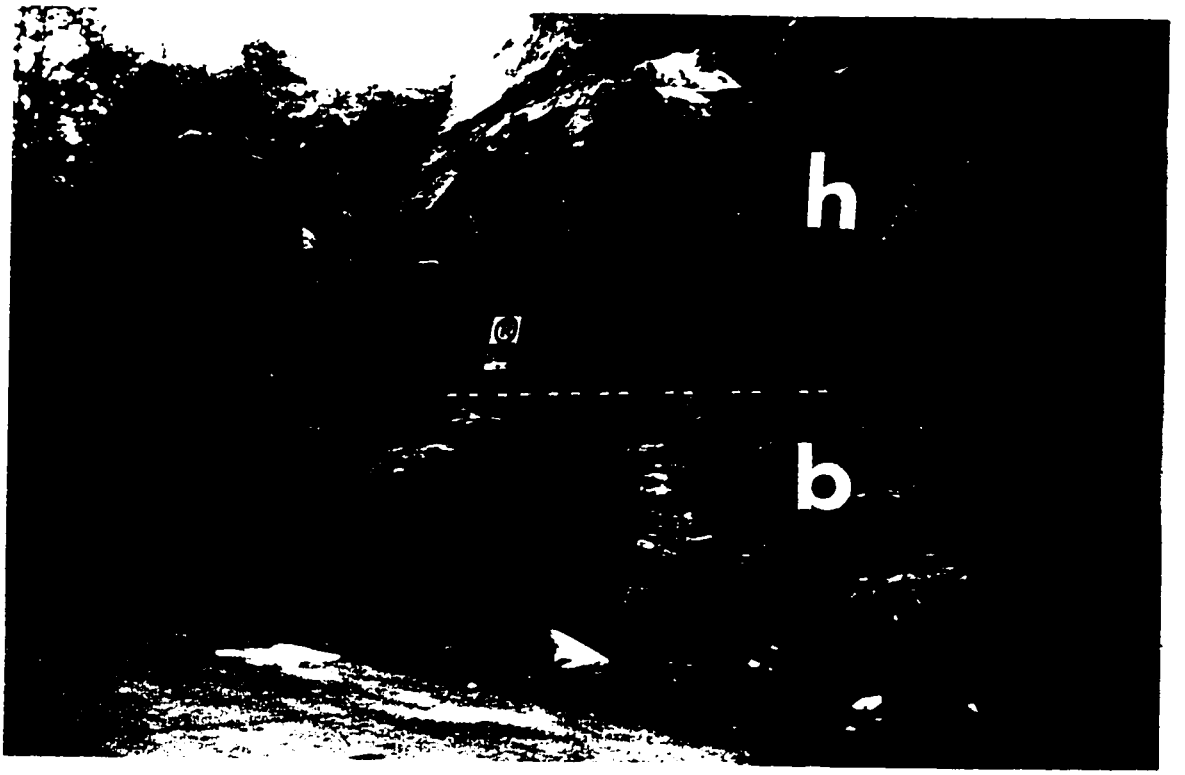
Stratigraphy

The Bobcaygeon Formation is conformably underlain by the Chaumont Formation and disconformably overlain by the Hull Formation. Attributes of the lower boundary are already discussed in Chapter 3. The upper boundary of the Bobcaygeon Formation is characterized by an extensive erosional surface, and abrupt lithologic changes. The erosional surface is defined by either truncation of the uppermost beds of the Bobcaygeon Formation with rip-up clasts incorporated with the overlying Hull Formation (e.g., Loc 13, Lac des Fees at St. Jean-Bosco, Hull) or a well-developed hardground surface (e.g., Loc. 7, Highway 7 near Stittsville). This contact separates lower medium (brownish) grey, thin to medium beds of medium- to fine-grained grainstone and packstone of the Bobcaygeon Formation and very thick, light grey, coarse-grained grainstone beds of the overlying Hull Formation (Fig. 7.1).

None of the mapped sections in the Ottawa Embayment provides a complete section through the formation, with the exception of the Russell well (Loc. 41, see Fig. 7.2). However, two adjacent sections (Locs. 7 & 8) display a total of about 41 metres of the Bobcaygeon Formation, with a portion missing from the middle of the upper part of the formation (Fig. 7.3). A total thickness of about 55 metres is measured from the Russell well (Loc 41, see Fig. 7.3).

The formation can be divided into lower and upper members. The lower member has a total thickness of about 21 metres at Locality 8, and increases to about 25 metres in the Russell well (Loc. 41). It is characterized by thin to thick (5 to 40 cm, rarely up to 80 cm thick) interbeds of very coarse- to medium-grained, bioclastic grainstone and packstone, and fine-grained bioclastic peloidal wackestone. The grainstone is light grey (usually the very coarse- crystalline grainstone) to medium brownish grey (usually the medium-crystalline grainstone) whereas the wackestone become more brownish grey to dark brown. Colour of

Fig. 7.1 Field photograph showing Bobcaygeon (b) - Hull (h) contact. This contact is defined by an abrupt lithologic change of thin to medium, bioclastic packstone to grainstone of the Bobcaygeon Fm overlain by thick, crinoidal grainstone beds of the Hull Fm. The no-parking sign is about 2 m high. Loc. 29: St Laurent Blvd (near Brittany Road), Ottawa.


h
b

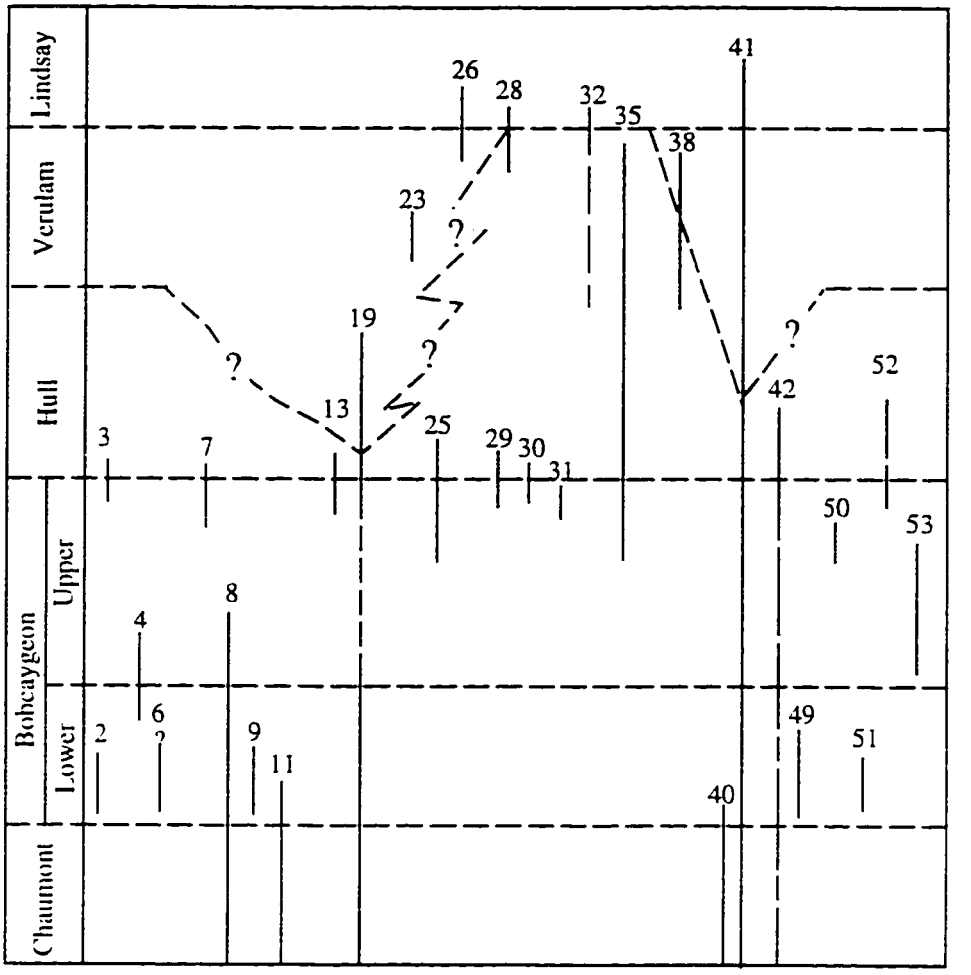
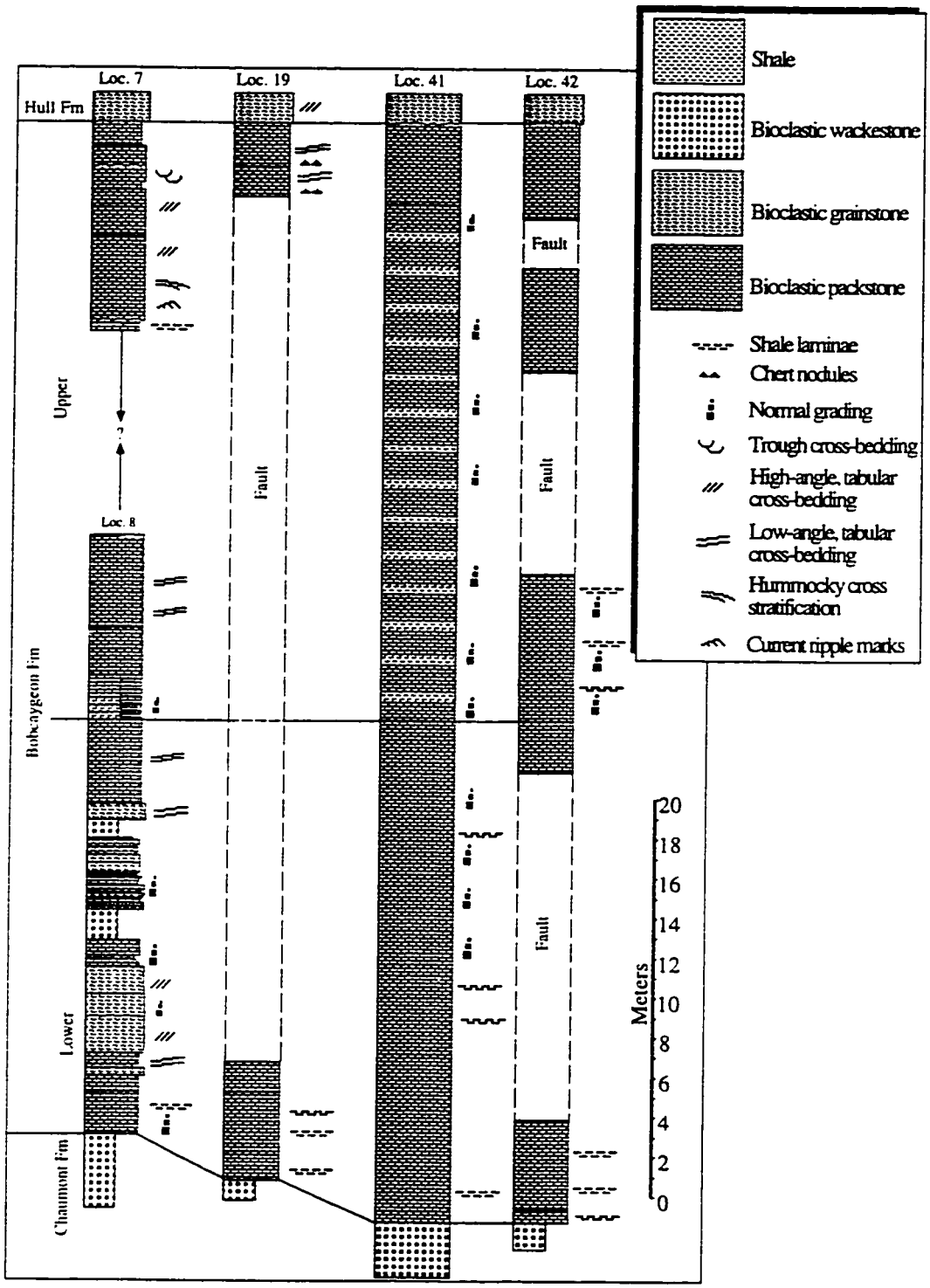


Fig. 7.2 Vertical distribution of sections showing Trentonian strata in the Ottawa Embayment. Vertical dashed intervals represent sections removed by faults. Most of the Hull and Verulam formations appear to be Lateral equivalent but their relationship is not clear (see text for more details). Loc. 2 Clay Bank quarry, McNab. Loc. 3 = Pakenham quarry, Pakenham,Loc. 4 = Kinburn quarry, Kinburn. Loc. 6 = West Carleton quarry. Almonte, Loc. 7 highway 7, ~ 1 km south of wheere 417 splits , Stittsville,Loc. = 8 Clarke quarry, Stittsville, Loc. 11 = Fallowfield quarry, Nepean, Loc. 13 = Lac des Fees at St. Jean-Bosco. Hull. Loc. 19 = McCarthy Rd. at Walkley Rd., Ottawa. Loc. 23 = Victoria Island, Ottawa, Loc. 25 = Scott St. Transitway (east of Tunny's Pasture), Ottawa, Loc. 26 = Rideau Falls, Ottawa. Loc. 28 = Quarry in Beechwood cemetry, Ottawa, Loc. 29 = St. Laurent Blvd (~ 150 m south of Brittany Rd), Ottawa, Loc. 30 = Brittany Rd at St. Laurent Blvd., Ottawa. Loc. 31 = Quarry Rd., Ottawa, Loc. 32 = Aviation Parkway (nothern outcrop), Ottawa, Loc. 35 = Farncon quarry (southern quarry), Blackburn Hamlet, Gloucester, Loc. 38 = Tenth Line at St. Joseph Blvd, Orleans, Loc. 41 = Russell well, Russell County, Loc. 42 = Embrun quarry, Embrun, Loc. 49 = Duval quarry, Dunvegan, Glengary Township. Loc. 50 = Gauther quarry, St. Isidore de Prescott, Prescott, Loc. 51 = Leroux (Skye) quarry, Bernardin, Prescott, Loc. 52 = Cliftondale (McAlpine) quarry, Vankleek Hill, Loc. 53 = L'Orignal quarry, L'Orignal village.

Fig. 7.3 Correlation of four sections showing the Bobcaygeon Fm. The formation is divided into lower and upper members, the lower part of the upper member is characterized by interbedded shale and various limestone lithofacies. The interbedding is defined by a gradational nature from bioclastic grainstone and packstone through wackestone and-or mudstone to calcareous shale. The vertical profile of the sections represent indentation due to weathering. Locality 41 is the Russell well core and no weathering profile is shown. Other localities include: Loc. 7 = Highway 7 near Stittsville; Loc. 8 = Clarke quarry, Stittsville (just east of Loc. 7); Loc. 19 = McCarthy Rd at Walkley, Ottawa; Loc. 42 = Embrun quarry at Embrun, Russell Township.


Loc. 7
Loc. 19
Loc. 41
Loc. 42
Hull Fm
Upper
Loc. 8
Bobcaygeon Fm
Lower
Chaumont Fm
Fault
Fault
Fault
Fault
Meters
20
18
16
14
12
10
8
6
4
2
0
Shale
Bioclastic wackestone
Bioclastic grainstone
Bioclastic packstone
Shale laminae
Chert nodules
Normal grading
Trough cross-bedding
High-angle, tabular cross-bedding
Low-angle, tabular cross-bedding
Hummocky cross stratification
Current ripple marks

weathered surfaces change from brownish grey in the finer-grained lithofacies to light grey in the coarser-grained units. Thin beds to laminae of calcareous dark shale and fine sandstone are interbedded in the limestone beds in the lower part of the member. Large and small scale tabular cross-bedding (Fig. 7.4), normal as well as inverse grading, stylolites, lateral pinch-outs, and scoured surfaces are common in the member. Syneresis cracks are also observed on certain layers. The wackestone beds show horizontal burrows and thin shaly interlaced partings. The latter lithofacies represents minor "Chaumont-type lithology" interbedded within the typically coarser lithofacies of the Bobcaygeon Formation (Fig. 7.4).

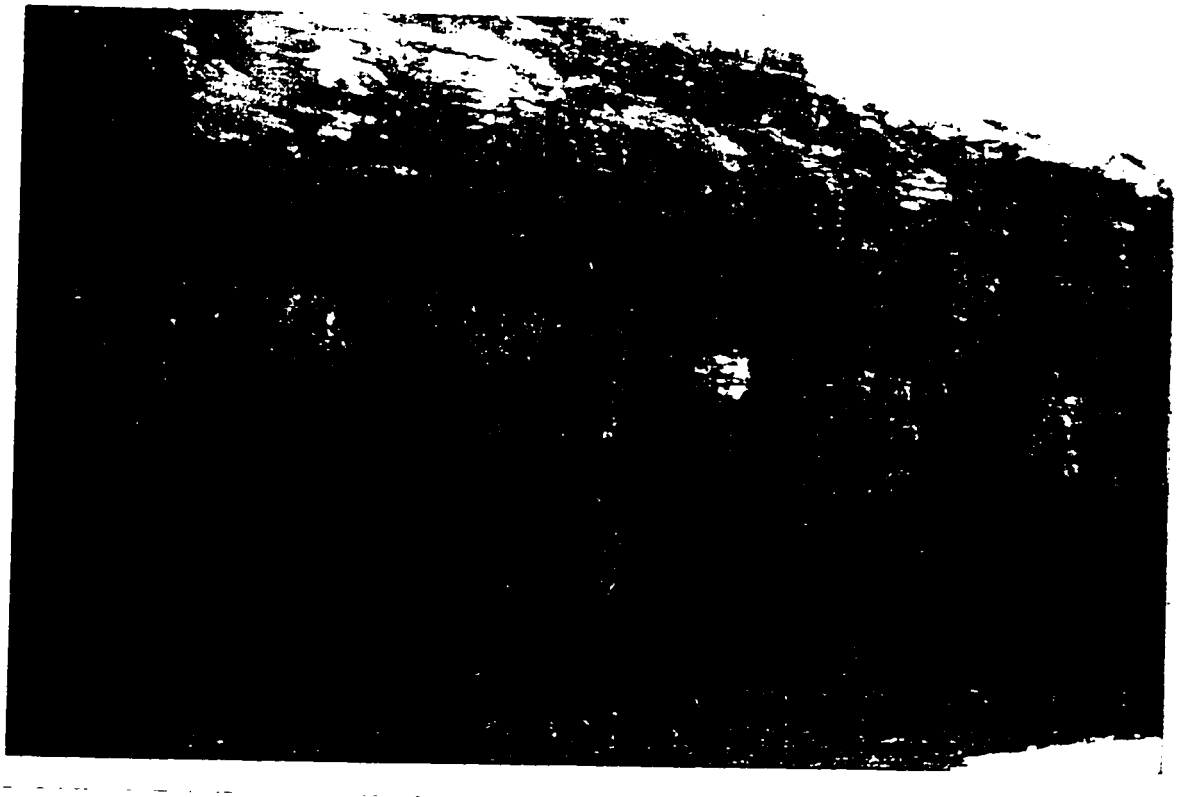
Coarser-grained beds of grainstone and packstone are more abundant in western localities (e.g., Locs. 1, 8, 11) whereas the fine-grained bioclastic peloidal wackestone (the Chaumont-type lithology) increases in abundance (although never dominate) toward east within the Ottawa Embayment (e.g., Locs. 41, 42). Repetitive units, inversely graded units of fine-grained, laminated mudstone, through massive to thinly laminated medium-grained packstone, to coarse-grained, sometimes cross-bedded grainstone, are present in the middle of the member at Locality 8 (see Appendix 1, section 8).

The lower member is moderately fossiliferous and contains brachiopods, trilobites (*Isotelus* sp.), crinoids, bryozoans, orthocones, gastropods, solitary and colonial corals.

The upper member of the Bobcaygeon Formation is about 30 metres thick in core from the Russell well (Loc. 41). The lower boundary of the member is seen in four sections (Locs. 4, 8, 41 & 42, Fig. 7.2). It is placed at the base of repetitive couplets of thin to medium bioclastic packstone grading to wackestone and thin shale conformably overlying thick bioclastic packstone of the lower member. The upper boundary of the member is already described above as the upper boundary of the Bobcaygeon Formation.

The upper member begins with thin to medium (3-15 cm thick), normally graded

Fig. 7.4 Medium to thick beds of dark to light grey, coarse-grained, bioclastic packstone to grainstone form the lower part of the Bobcaygeon Fm. Note the prominent cross-bedding nature in the lower half of the picture suggesting a migrating channel (or subaqueous dunes). Note also the thick dark brownish grey beds (between the arrows); these beds are characterized by highly burrowed, fine to medium-grained bioclastic peloidal packstone to wackestone reflecting a Chaumont-like lithology. Measuring stick is 1.2 m long. Loc. 8. Clarke quarry, Stittsville.



units, from medium grey bioclastic grainstone to packstone and wackestone. Thin (1 to 5 cm thick) dark shale interbeds are also common (Fig. 7.5). Eastern localities of the embayment contain more, and thicker, shale interbeds or interlaminae in the lower part of the member. Erosional surfaces are quite common in the unit. The upper part of the member is characterized by medium brownish grey, normally grading bioclastic (and locally intraclastic) grainstone and packstone with uncommon shale interbeds. Thin beds of dove grey *Tetradium*-bearing mudstone are locally present in the highest portion of the member (e.g., within the highest 3.5 m at Loc. 7, as well as in Loc. 31). Where these mudstone beds are not preserved, fragments of *Tetradium* corals occur within some grainstone and packstone beds. Lenses of black chert (up to 10 cm long) are often present in the upper two metres of the member. Rare, thin beds of coarse-grained bioclastic rudstone (brachiopod coquina) are present in the member at some localities (e.g., Loc.7). Rib-up clasts, overturned *Tetradium* corals, hummocky cross stratification, and rare, big (~20 cm x 15 cm) silica-cemented bioclastic grainstone nodules (Fig. 7.4) are locally seen in the upper part of the member.

Fossils are abundant in the upper member and include: brachiopods (*Rafinesquina* sp. and others), crinoids, bryozoans (both dome-shaped *Parasopora* sp. and branching bryozoans), trilobites, and gastropods. Rare *Tetradium* sp. and *Columnaria* sp. corals are also present. Well preserved conodont fauna have been collected from a 4-kg rock sample from the uppermost part of the formation (~ 15 cm below the Bobcaygeon-Hull contact) at Locality 19 (McCarthy Road-cut, Ottawa). The conodont fauna include: *Belodina compressa* (Branson and Mehl), *Coelocerodontus*? sp., *Drepanoistodus suberectus* (Branson and Mehl), *Panderodus gracilis* (Branson and Mehl), *Paroistodus* sp. cf. P. *mutatus*, *Phragmomdus undatus* Branson and Mehl, *Plectodina aculeata* (Stauffer), *Pseudobeloidina? dispensa*

Fig. 7.5a Thin to medium interbeds of bioclastic packstone to mudstone and calcareous shale form the lower part of the upper member of the Bobcaygeon Fm. Field book is 18.5 cm long. Loc. 42 = Embrun quarry, Embrun, Russell County.

Fig. 7.5b A close look of Figure 7.5a showing details of a normally grading (packstone to calcareous shale) rhythmic units which form the lower part of the upper member of the formation. Marker pen is 14 cm long. Loc. 42 = Embrun quarry, Embrun, Russell County.

a

b

(Glenister), *Pseudobeloidina inclinata* (Branson and Mehl)?, *Pseudooneotadus*? sp., *Staufferella*? sp., and *Walliserodus*? sp. or *Ansella* sp. (McCracken 1995).

The age of the Bobcaygeon Formation, based on the conodont fauna, is bracketed by *Phragmodus undatus* and by *Plectodina aculeata* or *Belodina compressa*. Their interval range defines the *Phragmodus undatus* Zone to *Plectodina tenuis* Zone (Sweet 1984) and implies an estimated age of Rocklandian to early Shermanian (McCracken 1995).

Sedimentary structures common in both members of the Bobcaygeon Formation include: horizontal and tabular cross-bedding, scoured surfaces, lateral pinching-out of the beds, normal grading, channel-fills, wave and current ripple marks, and stylolites.

Correlation

The revised Bobcaygeon Formation includes beds of the original upper Rockland "formation" and the lower member of Uyeno's (1974) Hull Formation (Table 7.1). The Chaumont - Bobcaygeon boundary is diachronous becoming stratigraphically older in western localities within the Ottawa Embayment. In western localities the contact coincides with the Leray - Rockland contact of Wilson (1946; Table 7.1), and may occur at or below the Blackriveran - Rocklandian time line. In eastern localities, the Blackriveran - Rocklandian boundary occurs within the Chaumont Formation. The latter formation's contact with the overlying Bobcaygeon Formation occurs higher in the Rocklandian stage (see Chapter 3, Fig. 3.26). Based on Williams (1991), the redefined Bobcaygeon Formation correlates with his unit B [a coarse-grained bioclastic grainstone to rudstone, equivalent to Barnes's (1964; 1967) "calcarenite shoal facies" in localities west of Carp] and Williams's (1991) middle member of the Bobcaygeon Formation (see Fig. 3.26). The boundary between

the two members of the Bobcaygeon Formation presented here is correlative with Williams' (1991) lower - middle member contact (Table 7.1).

Correlation of the Bobcaygeon Formation in the Ottawa Embayment with its equivalents in the nearby regions of south-central and southeastern Ontario (Lake Simcoe and Kingston regions respectively), upstate New York and southwestern Quebec (Montreal area) is shown in Fig. 7.6.

The Hull Formation

Origin

The Hull Formation was initially proposed by Raymond (1914) and described as "light grey, coarse-grained limestone with shale partings. ... Characterized by numerous crinoids and cystids" (p. 346). In the same report Raymond (1914) stated that, "the name Hull is proposed for the strata which at Ottawa, Belleville and in Central Ontario, carry the well-known crinoid fauna" (p. 349). This gives a dual interpretation of lithostratigraphic and biostratigraphic origin. Uyeno (1974) redefined the formation on lithologic basis. He pointed out that, unlike the terms Sherman Fall, Kirkfield and Rockland, the name Hull never gained any popularity as a time term. Therefore, Uyeno (1974) retained and redefined it as a lithostratigraphic term. Uyeno (1974) proposed a section at an abandoned quarry (Canada Cement Co. Ltd) in the city of Hull, Quebec, as a type section for the Hull Formation. Neither the lower nor the upper boundary of the formation is exposed at Uyeno's type section. However, he described the upper boundary from a nearby outcrop. Uyeno's Hull Formation consisted of a lower member of thin to medium bedded, dark brown to brownish

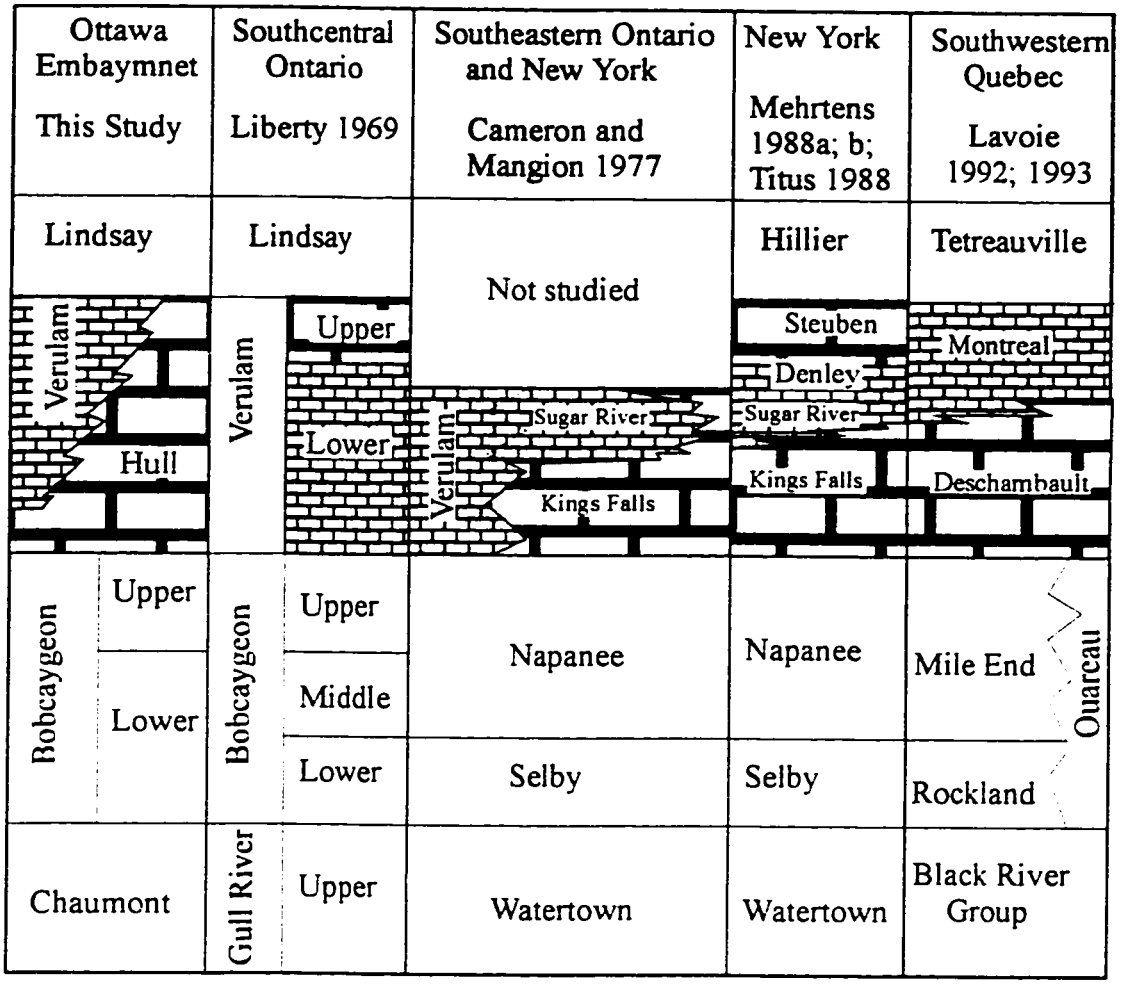


Fig. 7.6 Regional correlation chart of the Trentonian succession of the St. Lawrence Platform in Ontario, southern Quebec, and upstate New York. Note that units of Hull-like lithology occur in various stratigraphic levels within the stratigraphic range equivalent from the top of Bobcaygeon Formation and base of the Lindsay Formation.

grey, very fine to medium grained, pure to argillaceous limestone and an upper member of medium to thick, sometimes cross-bedded, medium to coarse-grained, pure limestone.

Retention of the name Hull

Williams (1991) suggested abandoning the term Hull because of absence of a defined lower boundary. Thus, Williams (1991) and later work (e.g., Johnson et al. 1992) lumped the Hull, Rockland and Chaumont beds under the term Bobcaygeon Formation (Table 7.1).

After mapping sections exposing upper Ottawa Group strata in the Ottawa Embayment, it has become clear that two distinct lithostratigraphic units are laterally equivalent with one another, and occur between strata of typical Bobcaygeon and typical Lindsay lithologies. One of the units is lithologically similar with the Verulam Formation of Williams (1991, see below) whereas the other one shows a distinct lithology of thick, coarse-crystalline crinoidal grainstone. The latter unit is hereby called the Hull Formation, and my work revises the boundaries of the Hull Formation of Uyeno (1974).

The revised Hull Formation is restricted to Uyeno's (1974) upper member. This redefinition is adopted after the following factors were acknowledged. (1) Although Uyeno (1963, as reported in Sawford 1972) has described the lower boundary of the Hull Formation in an unpublished M.Sc thesis, his later publication (Uyeno 1974) does not satisfactorily describe the lower boundary. This could be due to the lack of a significant lithologic break between the Rockland "formation" and the lower member of Uyeno's Hull Formation. In fact, no such lithologic break is recognizable until one reaches the contact between lower and upper members of Uyeno's Hull Formation (or the Bobcaygeon - Hull contact of my work). (2) Uyeno's lower member of the Hull Formation has more lithological affinities with the

Rockland "formation" than with the upper member of his Hull Formation. (3) Uyeno's lower member of the Hull Formation is laterally continuous and extends over the underlying Rockland "formation" within the Ottawa Embayment, whereas the upper member is not spatially continuous and passes laterally into the Verulam Formation (see below). (4) The boundary between Uyeno's lower and upper members of the Hull Formation is marked by an extensive erosional contact and an obvious lithological change. These points justify the separation of Uyeno's (1974) lower and upper members of the Hull Formation into two different lithologic units. The lower member is incorporated within the underlying beds under the term Bobcaygeon, whereas the name Hull is retained and applied to the upper member of the original Hull Formation.

Stratigraphy

The Hull Formation, as redefined here, overlies the redefined Bobcaygeon Formation and underlies both the Verulam and the Lindsay Formation. However, where the Hull Formation is overlain by Verulam Formation, the former is usually a relatively thin unit (e.g., 2.2 m. thick at Locality 19) which separates the Bobcaygeon from the Verulam Formation. This scenario suggests that most of the Hull Formation is laterally equivalent with the Verulam Formation. The lower boundary of the Hull Formation is recognized at ten widely separated localities within the embayment (Locs. 3, 7, 13, 19, 25, 29, 30, 35, 41, & 42, see Fig. 7.2). It is characterized by an erosional contact which separates lower, thin to medium beds of the Bobcaygeon Formation and overlying thick beds of coarse-grained (locally intraclastic) bioclastic grainstone of the Hull Formation. The upper boundary of the formation is seen at five different localities; at three of these, the Hull is overlain by the

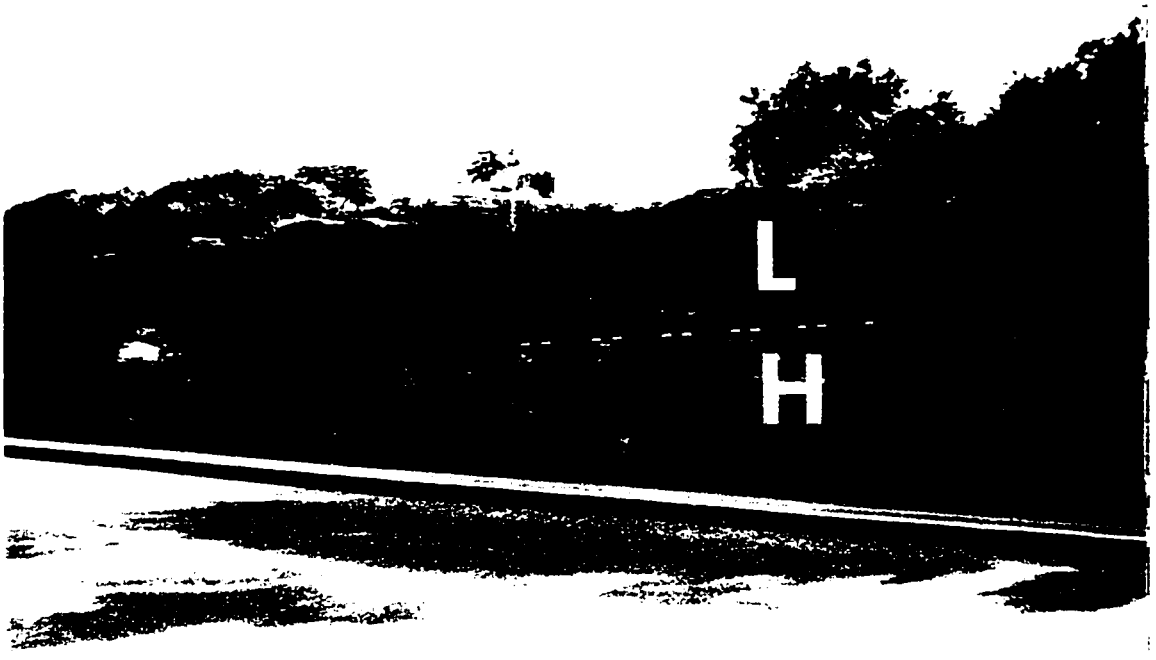
Verulam Formation (Locs. 19, 38, & 41) whereas the remaining two expose a Hull - Lindsay contact (Locs. 28 & 35, Fig. 7.2). The upper boundary of the Hull Formation is easily recognizable by a strong lithologic contrast with overlying strata. In the case of the Verulam Formation, medium bedded, fining-upward grainstone to wackestone with thin shale interbeds succeed the thickly-bedded, coarse-grained, pure grainstone of the Hull Formation. On the other hand, when the Hull is followed by the Lindsay Formation, the latter shows thin to medium beds of nodular, bioclastic wackestone to packstone with thin shale interbeds (Fig. 7.7a, b).

From the mapped sections, the Hull Formation has a minimum thickness of 2.2 metres at Locality 19 and an estimated maximum thickness of about 38 metres (Locs. 32, 35, & 41). The section at the southern Francon quarry (Loc. 35) exposes an incomplete, but continuous section of 35.8 metres of the Hull Formation. Another section along the Aviation Parkway (Ottawa, Loc. 32) shows a fault-interrupted section exposing the Hull - Lindsay contact (Fig. 7.7a, b). Due to homogenous lithologic attributes of the Hull Formation (see below), it is quite difficult to recognize marker bed(s) to allow correlation among the various sections of the formation within the embayment. However, both of the above mentioned sections show alternating thick and thin to medium beds of the formation. These are used for tentative correlation between the two sections (Fig. 7.8).

The Hull Formation consists of medium to thick (15 - 60 cm, locally >1 m thick) beds, coarse-grained, well washed, fossiliferous grainstone. Packstone beds are present but less common. The grainstone and packstone are light and medium (locally brownish) grey, and weather whitish grey and (locally medium brownish) grey, respectively. The formation is usually shale-free but rare and thin dark shale may occur locally along stylolitic surfaces.

Fig. 7.7a Hull (H) - Lindsay (L) contact at Locality 32 (norhtern outcrop at Aviation Parkway, Ottawa). The contact is sharp with abrupt lithologic change of thick, clean, crinoidal grainstone of the Hull Fm overlain by thin to thick beds of nodular, bioclastic packstone to wackestone with thin shale interbeds. Measuring stick is 1.2 m long.

Fig. 7.7b A close look of the Hull (H) - Lindsay (L) contact shown in Figure 7.7a. Note both bed-thickness and lithologic changes across the boundary. Hammer is 25 cm long. Locality 32 = Aviation Parkway, Ottawa.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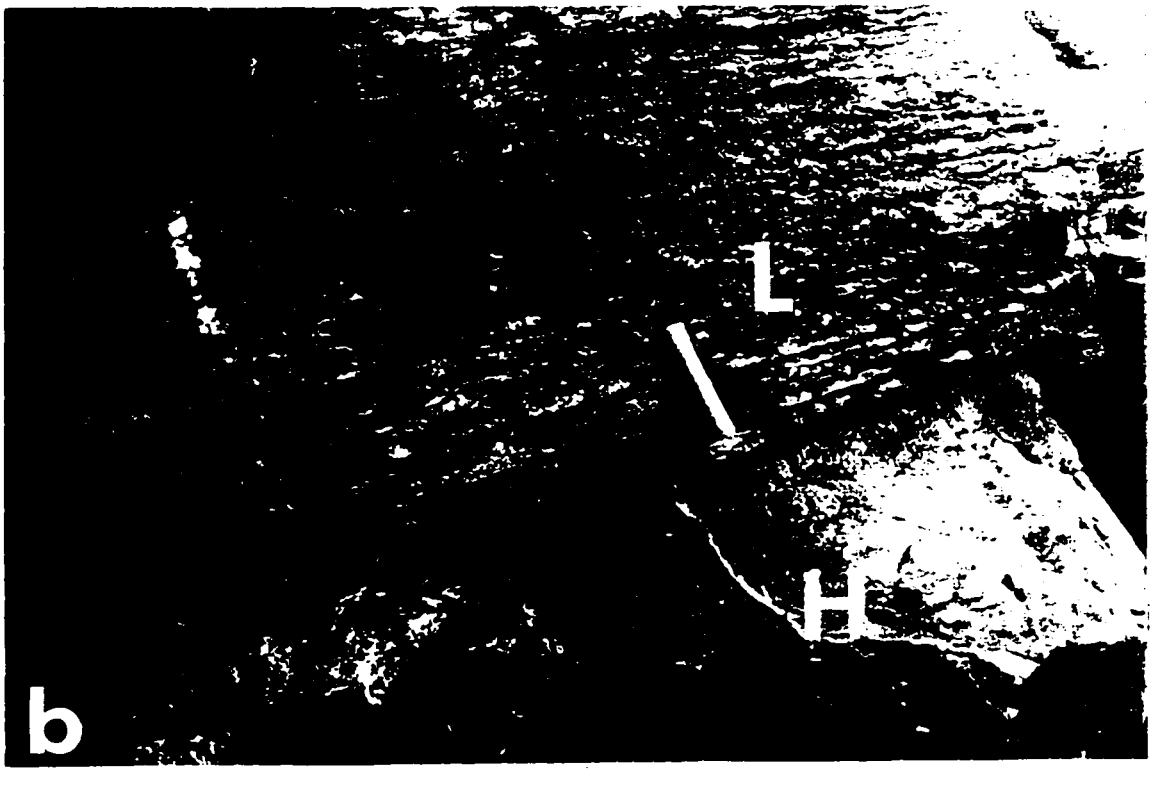
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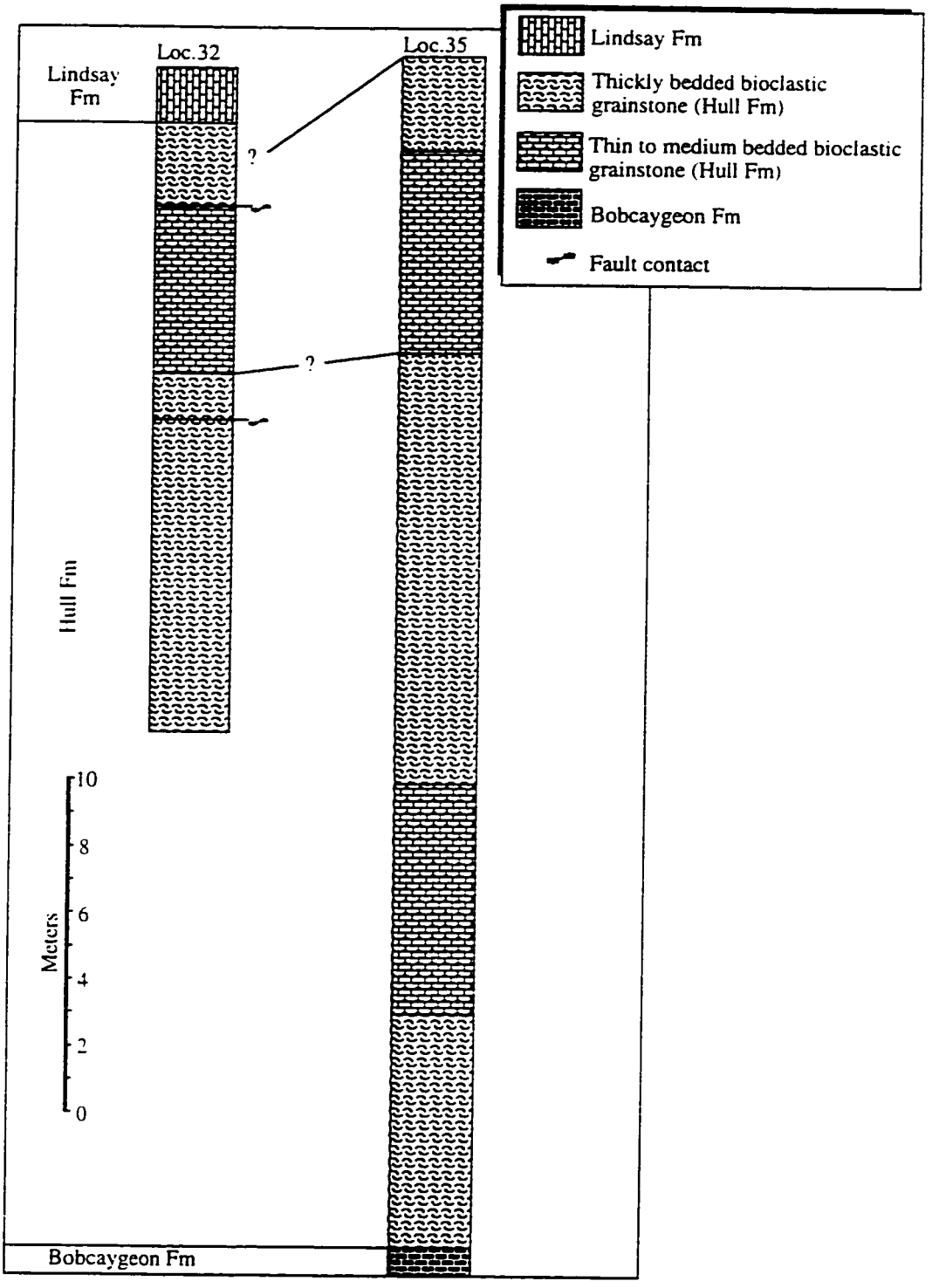

Fig. 7.8 Tentative correlation between two sections Loc. 32 = Aviation Parkway, Ottawa and Loc. 35 = Francon southern quarry, Blackburn Hamlet, Gloucester) which show the Hull Fm. Mapped sections which expose the Hull Fm do not provide reliable marker bed(s) for correlation, and the correlation shown in this figure is based on apparent similarities in bed thicknesses.

Black chert nodules are locally present, but silicification of certain biota (e.g., brachiopods and crinoids) appears to be more common. Large (up to ~ 8 cm long) rip-up intraclasts are locally present near the lower erosional contact of the formation.

The beds of the formation are well- to poorly-defined and show certain degree of both vertical and lateral amalgamation. Stylolitic bedding-contacts are common. Other common sedimentary structures include planar- and (high- & low-angle, tabular & sigmoidal) cross-bedding (Fig. 7.9), scoured and erosional surfaces, and wave and current ripple cross-laminations. Vertical and horizontal burrows are often present in the less common packstone lithofacies. The horizontal burrows are more common along bedding surfaces.

The abandoned quarry at Pakenham (Loc. 3) exposes the Bobcaygeon - Hull contact. At this locality, a 25-cm thick, medium- to coarse-grained intraclastic, bioclastic grainstone, with prominent trough cross-laminations, forms the basal unit of the Hull Formation. This is followed by thickly bedded, medium brownish grey, bioclastic packstone. The unit is characterized by abundant horizontal burrows and erosional surfaces. Thin lenses of coarse-grained bioclastic grainstone which usually occur on the erosional surfaces, are also present within these thick beds. The Hull beds of this locality can be easily mistaken with the Chaumont Formation (see Barnes 1964; 1967; 1968; Kay 1968a; Sinclair 1968). However, after careful microfacies analysis and correlations with other sections in the embayment, it became evident that this section contains the Bobcaygeon - Hull contact (Figs. 7.2, and 7.10, Appendix 1, section 3).

The Hull Formation is very fossiliferous, crinoids being the most abundant fauna. Other fossils include branching and domal (*Parasopora* sp.) bryozoans, brachiopods (e.g., *Rafinesquina* sp), orthocones, bivalves, trilobites, solitary (rugosa) and colonial (*Columnaria*

Fig. 7.9 The Hull Fm is characterized by clean, coarse-grained bioclastic grainstone to rudstone with prominent tabular to sigmoidal (swaly?) cross-bedding. Beds shown in this photo belong to the lower Hull Fm. Hand lense is 6 cm long. Loc. 30 = Brittany Rd at St. Laurent Blvd., Ottawa.

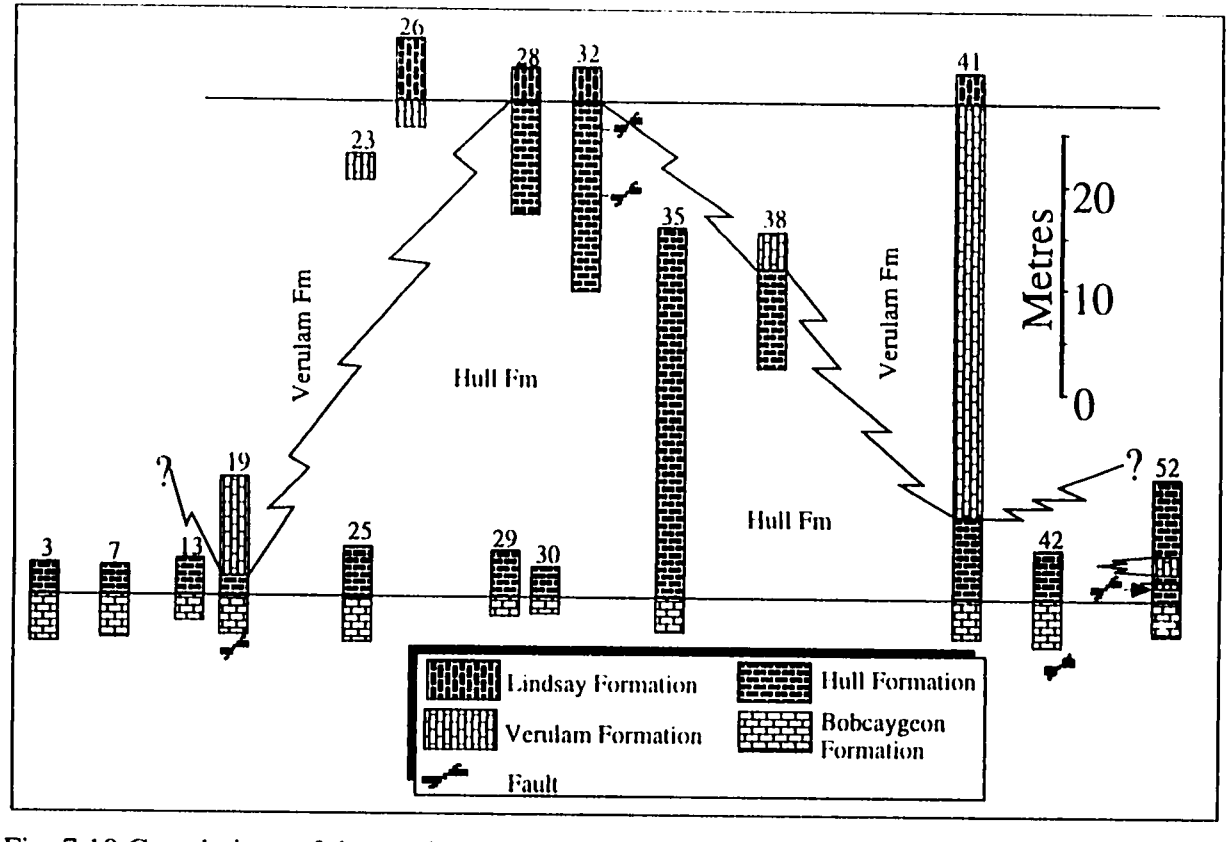

Fig. 7.10 Correlations of the sections exposing Hull and Verulam formations. Note the lateral relationship between the two formations. Note also that the Verulam Fm is probably missing where the Hull Fm is in contact with the Lindsay Fm. Sections are arranged from west to east but their horizontal distribution is not in scale. See Fig. 7.2 for section names and locations.

sp.) corals, and oncolites. Fossils are abraded and fragmented. A 4-kg rock sample collected from about 10 cm below the Hull - Lindsay contact at Locality 32 gave a fairly preserved conodont fauna which include: *Belodina compressa* (Branson and Mehl), *Curtognathus* sp., *Drepanoistodus suberectus* (Branson and Mehl), *Erismodus* sp., *Panderodus gracilis* (Branson and Mehl), *Phragmodus undatus* Branson and Mehl, *Plectodina aculeata* (Stauffer), and *Pseudobelodina inclinata* (Branson and Mehl)? (McCracken 1995).

The age range of the Hull Formation is determined by the presence of *Phragmodus undatus* and *Belodina compressa*. The concurrent range biozone ranges from *Phragmodus undatus* Zone to *Plectodina tenuis* Zone (Sweet 1984), implying Rocklandian to early Shermanian age for the strata (McCracken 1995).

Correlation

The revised Hull Formation is equivalent with the upper part of Wilson's (1964) middle phase of her Ottawa Formation. It is also correlative with Uyeno's (1974) upper member of the Hull Formation, and the upper member of Williams' (1991) Bobcaygeon Formation.

In southeastern Quebec (e.g., Montreal area), the redefined Hull Formation is lithologically correlative with the Deschambault Formation. Biostratigraphic correlation (using conodont fauna) between Hull and Deschambault was previously recognized by Poole et al. (1970) and Globensky and Jauffred (1971). This correlation was rejected by Uyeno (1974) suggesting that his Hull Formation was biostratigraphically (using conodont fauna) correlative with units D and E of Liberty's (1969) Middle and Upper members of the Bobcaygeon Formation.

As mentioned above, the Hull Formation is laterally equivalent with the Verulam Formation. The Hull - Verulam stratigraphic interval in the regions of south-central and southeastern Ontario, upstate New York and southwestern Quebec shows interbedding of various lithologies similar to those of Hull and Verulam formations in the Ottawa Embayment. Regional correlations of the Hull - Verulam stratigraphic interval is shown in Figure 7.6, and further discussed under the Verulam section.

The Verulam Formation

Origin

The Verulam Formation was initially described by Liberty (1955, 1969) for beds occurring between the Bobcaygeon and Lindsay formations in the Lake Simcoe area. Liberty (1969) divided the Verulam Formation into two members. The lower member (~ 52 m, unit F1 of Liberty 1969) consists of grey to brownish grey, fine- to medium-grained argillaceous limestone with thick interbeds of grey, medium crystalline crinoidal limestone and thinner beds of shale in its upper part. The upper member (~ 8 m, unit F2 of Liberty 1969) "consists of brownish grey and grey, fine- to coarse-crystalline bioclastic, crinoidal limestone... with minor amounts of argillaceous limestone and granular fragmental limestone" (Liberty 1969, p.52). Williams (1991) recognizes that his Verulam Formation in the Ottawa Valley is lithologically similar to Liberty's (1969) lower member of the Verulam Formation but could not recognize Liberty's upper member of the formation characterized by the distinctive calcarenite beds.

Stratigraphy

Although most of the Hull Formation is laterally equivalent with the Verulam Formation, beds of Hull-lithology usually separate the underlying Bobcaygeon from the Verulam Formation. The Verulam formation is always conformably overlain by the Lindsay Formation. Where the Hull Formation is in contact with the Lindsay Formation (e.g., Locs. 28 & 32), the Verulam Formation may be missing (see Figs., 7.2 and 7.10).

The lower boundary of the Verulam Formation is exposed at three localities (Locs. 19, 38 & 41). At Localities 19 and 41, only 2.2 m and 8 m, respectively, of Hull lithology separates the Bobcaygeon Formation from the Verulam Formation. The Hull-Verulam boundary is characterized by an abrupt change from the coarse-crystalline grainstone of Hull to thin and medium beds of interbedded grainstone, packstone, and shale. The lateral thinning of the Hull Formation (the thinnest known section of the Hull Fm is that of Loc. 19) may pinch out, implying a direct contact between Verulam and Bobcaygeon formations.

The upper contact of the Verulam Formation is observed at two localities (Locs. 26 and 41). Thin to medium beds of bioclastic grainstone and packstone with shale interbeds of Verulam Formation are succeeded by thin to thick beds of medium grey, nodular, bioclastic packstone with thin shale interbeds of the Lindsay Formation.

No outcrop with a complete thickness of the Verulam Formation was found during my study. A core from the Russell well (Loc. 41) exposes an apparent complete thickness of about 40 m. The Verulam Formation consists of thin to medium beds (2-40 cm) of fine to coarse grained bioclastic packstone and grainstone that are interbedded with thin (usually < 10 cm thick) dark grey (calcareous) shale. The fresh surfaces of the packstone and grainstone lithofacies are medium to dark brownish grey and medium grey, respectively. The

colour usually changes with the grain size; coarser-grained units are lighter grey in colour. Weathered surfaces change from greyish brown (packstone facies) to light grey (grainstone facies). The shale content is prominent (~ 5 to 10% in volume) in the lower part of the formation but decreases upsection where little or no shale interlamination is observed.

The fossil content of the formation is moderate to high, and includes brachiopods, bryozoans (branching and domal), crinoids, trilobites, gastropods and bivalves. Two rock samples, 4 kg each, from about 15 cm and 9.3 m above the base of the Verulam Formation at Locality 19 offered similar, fairly preserved conodont fauna. The fauna includes: *Belodina compressa* (Branson and Mehl), *Drepanoistodus suberectus* (Branson and Mehl), *Panderodus gracilis* (Branson and Mehl), *Phragmodus undatus* Branson and Mehl, *Plectodina aculeata* (Stauffer), *Plectodina* sp., *Polyplacognthus ramosus* Stauffer, and *Pseudooneotodus mitratus* (Moskalenko) (McCracken 1995).

The lower age limit of the conodont fauna is marked by *Phragmodus undatus* and *Polyplacognathus ramosus*, whereas the upper limit is provided by *Plectodina aculeata* or *Belodina compressa*. These species occur within the *Phragmodus undatus* Zone to *Plectodina tenuis* Zone, and indicate Rocklandian to early Shermanian age.

Diagenetic features recognized under microfacies analysis include: micrite envelope, algal borings, stylolites, fractures, pyritization of certain fossils, and precipitation of various generations of cement.

Hummocky and swaly cross stratification, lateral pinching-out and amalgamation of beds, horizontal burrows and trails, normal gradation, and scoured and undulating surfaces are typical of the Verulam Formation. Horizontal burrows and trails are more abundant in the shale as well as along bedding planes. Thin interbeds of bioclastic packstone and shale

show a nodular appearance but are local and uncommon.

Correlation

Correlation with previous work within the Ottawa Embayment

The Verulam Formation, as defined in my work, is lithostratigraphically correlative with that of Williams (1991) except that I extend the lower boundary to the revised Hull Formation. Liberty (1967a) suggested that the Verulam Formation in the Ottawa Valley is correlative with the original Hull Formation. He applied the term Verulam to the "Hull beds", and defined the formation to include "...strata between typical Rockland lithology and the base of typical Cobourg lithology" (P.50). These strata included both upper and lower members of the original Hull Formation as well as strata of Verulam lithology occurring within the defined interval (Table 7.1). My work considers that the lower member of the original Hull Formation belongs to the Bobcaygeon Formation. Therefore, the remaining portion of Liberty's (1967a) Verulam Formation becomes correlative with the Hull and Verulam formations of my work (Table 7.1). Correlations with the work of Raymond (1914), Wilson (1946), and Barnes (1964; 1967) are also shown in Table 7.1.

Hull - Verulam relationship

The Hull and Verulam formations can be found at different sections to be in contact with the Lindsay Fm, and appear to show complementary thickness variations within the embayment. Thus, the two formations are likely laterally equivalent to each other (Figs. 7.2 & 7.10). Two explanations are possible: (1) either the two formations were deposited contemporaneously as shoal and inter-shoal deposits, respectively (this study), or, (2) the

Verulam Formation filled paleotopographic depressions after the Hull was deposited (Dix et al. 1997b). Available geologic data support the former possibility: (1) one section, Locality 28, preserves what appears to be interbedded Hull and Verulam lithologies (Fig. 7.11); (2) available conodont data (McCracken 1995) do not indicate significant age differences between the two formations; and, (3) interbedded Hull and Verulam lithofacies are documented in other places along the St. Lawrence Platform (see below).

Regional correlation of the Hull - Verulam succession

The Verulam Formation in the Ottawa Embayment is lithostratigraphically correlative with the lower member of the Verulam Formation (unit F1 of Liberty 1969) in the Lake Simcoe area. This correlation is also recognized by Williams (1991). The coarsely crystalline upper member of the Verulam Formation (unit F2 of Liberty 1969) in the Lake Simcoe region has lithologic affinity with the Hull Formation in the Ottawa Embayment. This upper part of the Verulam Formation probably represent an extended "tongue" of the Hull build-up in south-central Ontario (Fig. 7.6).

Cameron and Mangion (1977) show that the Verulam Formation in southeastern Ontario (Kingston area) becomes laterally equivalent with the Kings Falls and Sugar River formations at the international border (Fig. 7.6, see also their Fig. 2). Nevertheless, interpretation of the available literature suggests that the Verulam-Hull succession correlates with the rock succession ranging from the upper boundary of the Napanee Limestone to the lower base of the Hillier Formation in upstate New York (Fig. 7.6). The latter rock-interval includes the Kings Falls, Sugar River, Denley, and Steuben formations (Kay 1968b; Mehrtens 1988a; b). The Kings Falls and the Steuben formations are thickly bedded, coarse-

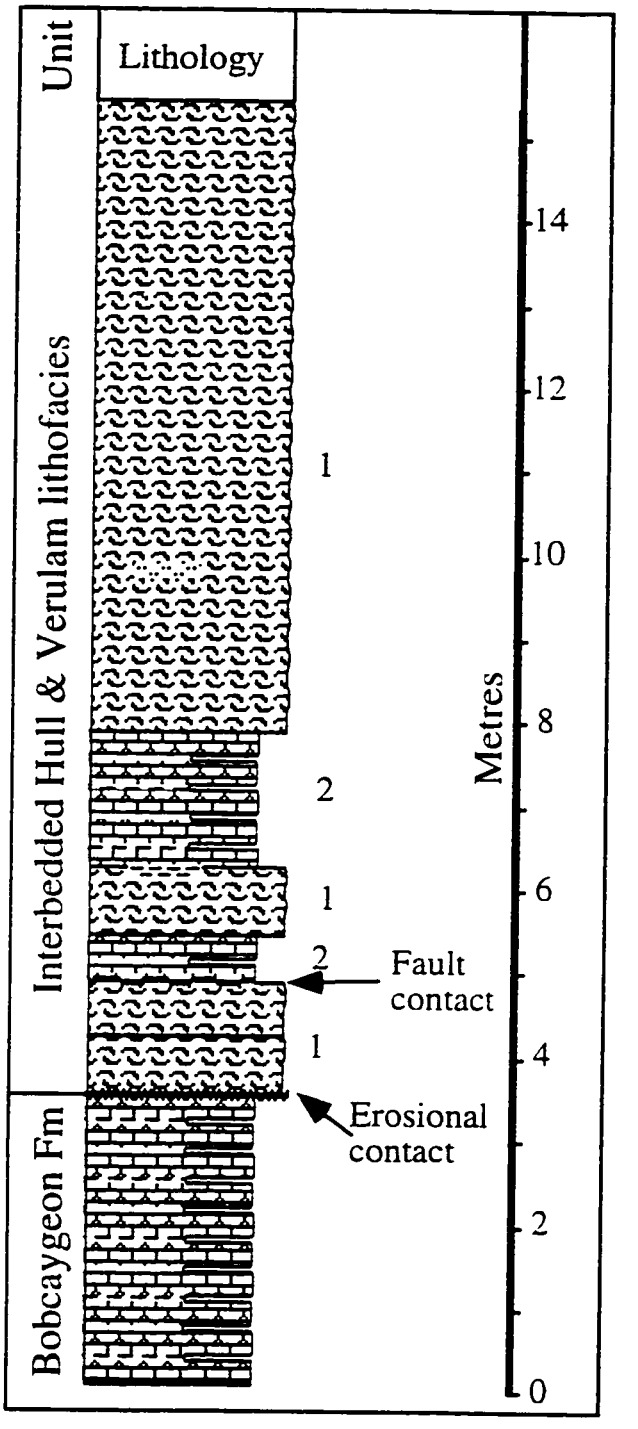

Fig. 7.11 Interbedded lithofacies of the Hull (1) and Verulam (2) formations at locality 52, Cliftondale (McAlpine) quarry, Vankleek Hill,. This interbedding suggests that the Hull and Verulam formations are laterally equivalent and represent prominent sand-shoals (Hull Fm) and intershoal (Verulam Fm) deposits.

crystalline, crinoidal limestones (Kay 1968b; Cameron and Mangion 1977; Titus 1988) which reflect a Hull-like lithology.

The Deschambault and Montreal formations in southwestern Quebec appear to be correlative with the Hull - Verulam succession. The Deschambault Formation is characterized by thickly bedded, coarse-grained pelmatozoan grainstone with relatively minor interbeds of wackestone, mudstone and shale (Clark 1972b; Mehrtens 1988a; b; Harland and Pickerill 1982; Lavoie 1992). Like the Hull Formation in the Ottawa Embayment, the Deschambault Formation shows marked thickness changes (e.g., 4 m in the Montreal area to about 70 m in the Trois-Rivièrs area, Lavoie 1992). The Montreal Formation in southwestern Quebec is characterized by wackestone and mudstone with coarse-grained bioclastic limestone of Deschambault-type lithology. The latter are more abundant in the lower part of the formation and decrease in prominence upsection. Millimetre- to centimetre-sized thick calcareous shale beds are also found throughout the formation. Sedimentary structures present in the formation include normal grading, planar and trough cross-laminations, and hummocky cross-laminations (Lavoie 1993). The lithologic attributes of the Deschambault and Montreal formations suggest that the lower part of the succession is dominated by lithologies correlative with the Hull Formation whereas the upper part is correlative with the Verulam Formation (Fig. 7.6).

Lindsay Formation

Origin

The Lindsay Formation was initially proposed by Liberty (1969) for a nodular

limestone unit (unit G of Liberty 1969) that overlies the coarse-crystalline, bioclastic limestone of the upper member of the Verulam Formation and underlies, black shale of the Whitby Formation. The Lindsay Formation in the type area of Lake Simcoe ranges between 61 and 56 metres thick. It consists of thin to thick (2.5 - 60 cm), "grey to greenish grey, fine-grained, argillaceous limestone" (Liberty 1969, p. 58) with thin shale (~ 5 cm thick) interbeds. A few beds, ~ 20 - 30 cm in thickness, and lenses of medium-crystalline crinoidal calcarenite are present. Irregular wispy shale partings give the formation a rubbly (nodular) weathering texture.

Stratigraphy

The Lindsay Formation in the Ottawa Embayment has received the least attention during my research. Only three localities in the Ottawa city (Locs. 26, 28, & 32) and the core from the Russell well (Loc. 41) have been examined. The sections do not show complete thickness nor preserve the upper boundary of the formation. However, Williams (1991) reports that the formation is about 30 metres thick with lateral thickness changes. Williams (1991) divided the formation into an unnamed lower member and an upper (Eastview) member which are also recognized in this study.

The lower member consists of nodular, thin to thick (5 - 55) bedded, dark grey to brownish grey, bioclastic packstone, wackestone, and mudstone with thin (< 5) dark brown shale interbeds (Fig. 7.7a, b). The weathering surface of the limestone beds varies form light to buff brown, and the shale beds remain dark to medium brown. The upper member of the formation consists of thin to medium bedded, dark grey, bioclastic packstone interbedded with thin to medium beds of dark, petroliferous calcareous shale.

Nodular bedding (Fig. 7.7b) is quite common in both members of the Lindsay Formation. Burrows and undulatory surfaces are also present but less common. The high energy sedimentary structures characteristic of the underlying Verulam and Hull formations are locally present in the lower member.

Fossils are very abundant in the lower member of the Lindsay Formation but decrease in abundance upward. The fauna in the formation include brachiopods (*Dalmanella* sp. among others), crinoids, bryozoans, gastropods, and trilobites (*Pseudogyges?* sp.) [see references mentioned in Williams (1991) for detailed description of the fossils in the Lindsay Formation]. One sample of about 1.2 kg of rock for conodont analysis was collected from about 10 cm above the base of the Lindsay Formation at Locality 32. Abundant fauna include *Belodina compressa* (Branson and Mehl), *Drepanoistodus suberectus* (Branson and Mehl), *Panderodus gracilis* (Branson and Mehl), *Phragmodus undatus* (Branson and Mehl), *Plectodina aculeata* (Stauffer), *Polyplacognathus ramosus* Stauffer, *Pseudooneotodus mitrus* (Moskalenko), and *Pseudooneotodus*? sp. (McCracken 1995).

Phragmodus undatus and *Polyplacognathus ramosus* provide the lower and upper range limits of the faunal assemblage. This biozone interval occurs within the *Phragmodus undatus* Zone to *Plectodina tenuis* Zone range (Sweet 1984), and indicates Rocklandian to early Shermanian (McCracken 1995).

Correlation

The Lindsay Formation boundaries of this study are equivalent to those defined by Williams (1991). Although Williams correlated the lower member of the Lindsay Formation in the embayment with Liberty's unit F (see p. 75 of Williams 1991: the correlation shown

on this page does not conform with those shown in other parts of his report), my work suggests that the lower member of the Lindsay Formation in the embayment is correlative with the Lindsay Formation of Liberty (1969, unit G) in the Lake Simcoe area (Fig. 7.6). In the latter region, the Lindsay of Liberty (1969) is overlain by his Whitby Formation. The Lindsay - Whitby stratigraphic interval has been revised by Russell and Telford (1983). They showed that Liberty's (1969) lower member (Craigleith Mb) of the Whitby Formation has lithologic affinity with the underlying Lindsay Formation. They proposed the name Collingwood for the member and included it in the Lindsay Formation. Similarly, the Eastview Member has lithologic affinity with the Lindsay Formation in the Ottawa Embayment, and considered here as an upper member of the formation.

In southern Quebec, the Lindsay Formation in the Ottawa Embayment becomes correlative with the Tetreauville Formation (Fig. 7.6). The latter consists of thin to medium beds of wackestone and mudstone with shale interbeds. It has a nodular to strongly wavy-bedded facies (Terrebonne facies, Clark 1972a; b; Lavoie 1993) in southwestern Quebec. This facies of Tetreauville Formation indicates continuation of Lindsay lithology into southern Quebec.

Depositional environment of the upper Ottawa Group

The Bobcaygeon to Lindsay succession in the Ottawa Embayment was deposited in a progressively deepening subtidal platform. Sedimentary structures (e.g., cross-bedding, normal gradation, scoured surfaces, etc) present in the Bobcaygeon Formation, as well as its grainy texture suggest a well agitated, depositional setting. The lack of a marked break in

sedimentation across the Chaumont - Bobcaygeon boundary and presence of certain interbeds of Chaumont-like lithology (Fig. 7.4) in the lower part of Bobcaygeon Formation suggest a transition from a calm, subtidal, below wave-base environment (Chaumont Fm, see Chaps. 4 & 5) to a highly agitated, above wave-base (or ? storm-base) subtidal setting (Bobcaygeon Fm). Tabular, steeply cross-bedded coarse-grained bioclastic dunes (Fig. 7.4) within the lower member of the Bobcaygeon Formation (Locs. 8 and 9), probably indicate subtidal migrating channels. The prevailing medium- to coarse-grained lithofacies and sedimentary structures occurring throughout the Bobcaygeon Formation suggests that medium to high energy conditions persisted during its time of accumulation. However, occasional quiet water conditions are indicated by the shale interbeds, rare Chaumont-type lithology intervals (within the lower member of the formation), and *Tetradium*-bearing mudstone in the upper member of the formation.

The very coarse-grained Hull Formation which disconformably overlies the Bobcaygeon Formation indicates an increase in the energy of the depositional environment. It is interpreted to represent thick subtidal sand-shoals (shelfal dunes) which arose above wave-base. The abundant, high energy sedimentary structures indicate unstable, shifting dunes. The abundant crinoidal fauna in the formation may also suggest dominant prolific crinoidal biostromes within a highly agitated environment. The laterally equivalent Verulam Formation accumulated in broad inter-shoal depressions. These depressions were generally below fair weather wave-base. Storms ripped up adjacent shoals of the Hull Formation creating tempestites in the deeper inter-shoal regions. This is suggested by the presence of hummocky cross stratification, pinching-out and amalgamation of the beds, horizontal trails and burrows, and normal grading in the Verulam Formation. Lithologically similar and

temporally equivalent strata of southern Ontario are interpreted to have accumulated as shoal - basin setting (Brookfield and Brett 1988).

The Bobcaygeon, Hull, and Verulam formations in the Ottawa Embayment appear to be westward continuation of the Rockland to Montreal formations in the Montreal area. This suggests that the former also accumulated in a gently sloping carbonate ramp as shown by Lavoie (1992; 1993) for the Trentonian formations in southwestern Quebec.

The Lindsay Formation defines a deeper, relatively calm subtidal platform setting, with rare storm disturbances in its lower part. This is suggested by the decrease of indicators of high energy regime while replaced by predominance of the fine- to medium-grained lithofacies, and increased abundance of shale interbeds. Similarly, correlative formations in the nearby regions (e.g., Tetreauville and Hillier formations of southern Quebec and New York, respectively) are interpreted to have accumulated in a quiet, shallow to deep shelf conditions (Clark 1972b; Titus 1988).

Lack or marked decrease in elements indicating high temperature climate (e.g., oolites, evaporite minerals or molds, chlorozoan elements) accompanied by an increase in bryomol assemblage (e.g., bryozoans and crinoids, Jones and Desrochers 1992) in the formations of the upper Ottawa Group may suggest that the depositional environment shifted from warm water tropical realm (Blackriveran Stage) to cool water temperate realm (Trentonian Stage). Trentonian strata in the neighbouring regions of southern Quebec (Lavoie 1997; 1995) and southern Ontario (Brookfield 1988) are interpreted to be temperate carbonates.

Fine-grained siliciclastics admixed in the carbonates of the Lindsay Formation may be derived from the Appalachian allochthon heralding the eventual foundering of the

platform. Fine-grained terrigenous sediments prevailed in the embayment during Post-Trentonian stages, and are represented by the thick shale successions of Billings, Carlsbad and Queenston formations. The terrigenous influx subdued the carbonate production. and eventually drowned the Trentonian carbonate platform.

CHAPTER EIGHT

STRATIGRAPHIC PATTERNS IN CHAZYAN TO TRENTONIAN STRATA, OTTAWA EMBAYMENT

Introduction

Sloss (1963) recognized that the Phanerozoic sedimentary succession of North America consisted of six cratonic stratal packages separated by inter-regional (continental wide) unconformities. He referred to these sedimentary successions as "sequences" and, subsequently (Sloss 1988) subdivided them further into "subsequences". The Early Paleozoic sedimentary rocks in the Ottawa Embayment include the Sauk and Tippecanoe sequences. The two are generally separated by an Early to Middle Ordovician lacuna across North America. These sequences are considered to be of a scale similar to 2nd-order sea-level cycles of Vail et al. (1977).

The recent work of Johnson et al. (1992) is the first which shows subdivision of the sedimentary cover of Ontario into depositional sequences. Johnson et al. (1992) divided the Paleozoic to Mesozoic sedimentary succession of Ontario into ten depositional sequences (numbered 1 to 10). Their use of the term "depositional sequence", however, is a modified version of Mitchum et al.'s (1977). They defined depositional sequences as "stratigraphic packages or intervals of genetically related sedimentary rocks which are commonly bounded by unconformities" (p. 910). Although Johnson et al. (1992) related the division of the stratigraphic succession in Ontario with broad terms of transgression and regression, details of neither sea-level change nor the stratigraphic response to the sea-level variation were presented. However, Johnson et al. (1992) listed a number of limitations to the application

of sequence stratigraphy, and indicated that their subdivision of the stratigraphic succession into depositional sequences is "subject to some skewing; based on the availability of data ..."(p. 997). Nevertheless, in the Ottawa Embayment, Johnson et al. (1992) established the first three (1, 2, and 3) depositional sequences to represent the Nepean - Beeckmantown, Rockcliffe - Ottawa Group and Billings - Queenston rock successions, respectively (Fig. 8.1).

Depositional successions

On the basis of my work, vertical facies associations within the Chazyan - Trentonian interval allow division of the stratigraphic column into several depositional successions that reflect relative changes in sea-level. Shallow marine carbonates are good indicators of sea-level fluctuation because their production is strongly controlled by water energy, temperature, and depth (Goodwin and Anderson 1985; Goldhammer et al. 1990; 1993; Jones and Desrochers 1992). Study of vertical facies association of shallow marine carbonates can, therefore, improve understanding of relative sea-level history of carbonate platforms (Gonzalez 1996). Similarly, stacking patterns and vertical facies associations are used in order to unravel relative sea-level fluctuation during deposition of the Chazyan to Trentonian strata in the Ottawa Embayment (Fig. 8.2a-d). However, relative change in sea-level is best defined for the lower four formations (Hog's Back, Pamelia, Lowville and Chaumont Fms) which have been studied in detail (Chapters 2 to 6). Only general sea-level variations are presented for the upper four formations (Bobcaygeon, Hull, Verulam and Lindsay Fms). Figure 8.2a-d shows correlation between lithology and facies curve reconstructed from the

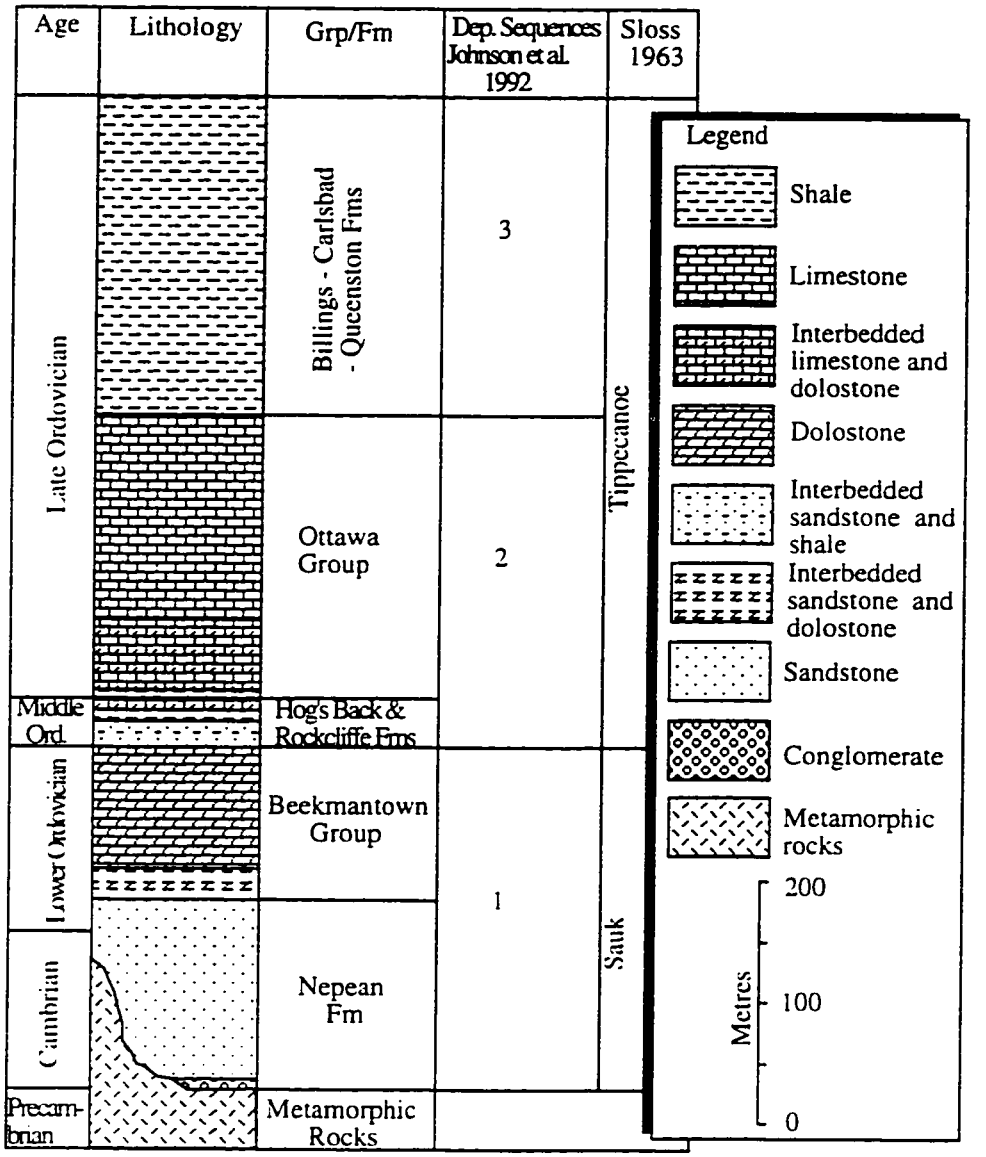

Fig. 8.1 Stratigraphy of the Paleozoic succession of the Ottawa Embayment and its subdivision into depositional sequences by Johnson et al. (1992) with correlations of Sloss's (1963) cratonic sequences.

Fig. 8.2a-d Stratigraphic succession of the Hog's Back to Lindsay formations with facies curves deducted from their depositional environments. Incorporation of the facies curve with erosional surfaces (ES), flooding surfaces (FS), prominent shale units (PSH), and prominent sandstone units (PSU) allowed to infer detailed relative sea level changes (DRSL) and general sea level changes (GRSL). Details of the depositional environments (under facies curves) are abbreviated as follows: SPT = supratidal, INT = intertidal, SBT = subtidal, ORL = open to restricted lagoon, NLT = near low tide, AWB = above wave-base, and BWB = below wave-base. The stratigraphic columns are from mapped sections that include: composite section from Prince of Wales Falls (Loc. 20, Fig. 8.2a), composite section from locations 24 and 16 (Fig. 8.2b), a section from Locality 40 (Fig. 8.2c), and Russell well (Loc. 41, Fig. 8.2d), See Appendix 1 for legend.

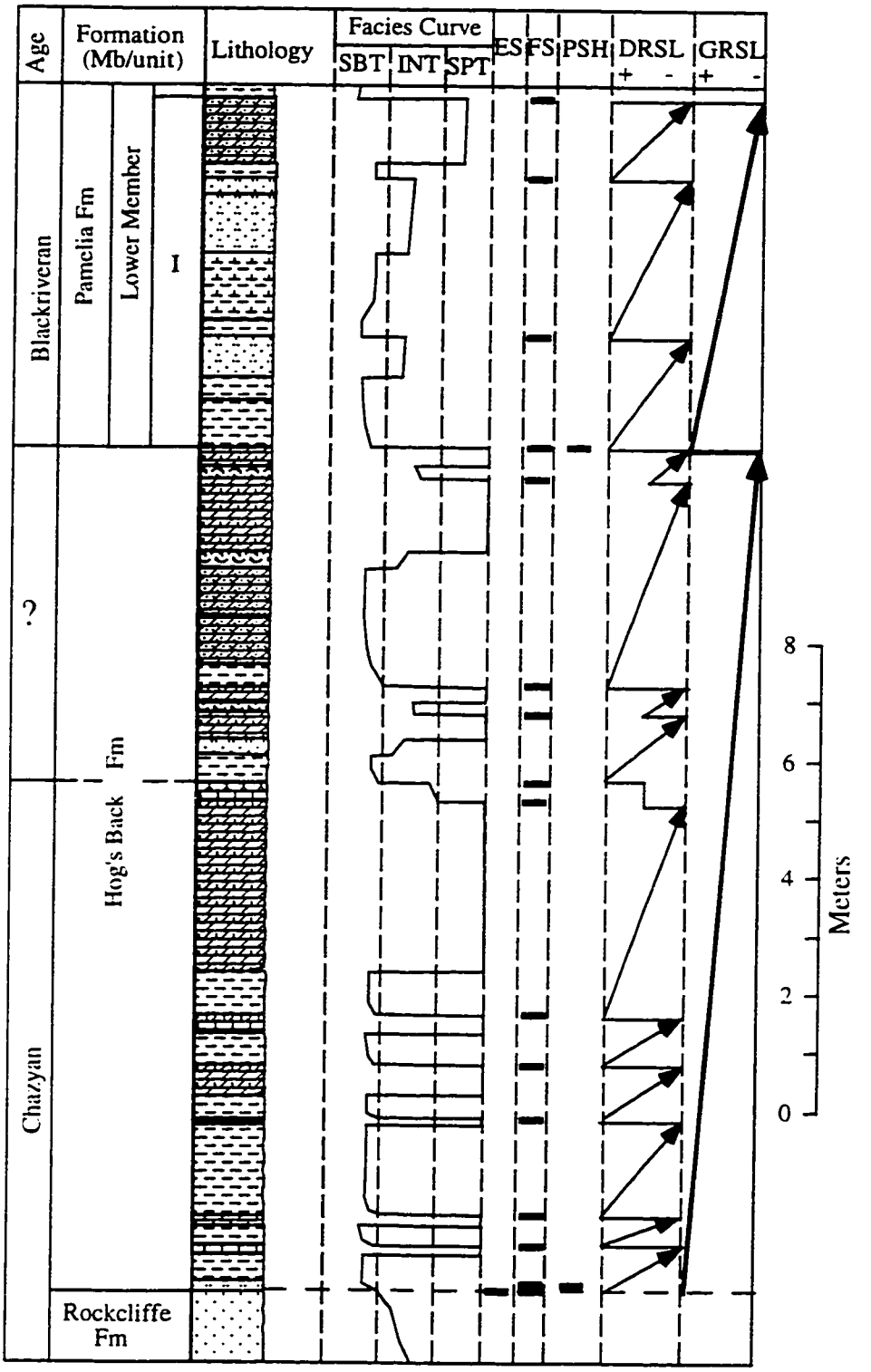
Age
Formation (Mb/unit)
Lithology
Facies Curve
SBT
INT
SPT
ES
FS
PSH
DRSL
+
-
GRSL
+
-
Blackriveran
Pamelia Fm
Lower Member
I
?
Hog's Back Fm
Chazyan
Rockcliffe Fm
8
6
4
2
0
Meters

Fig. 8.2a

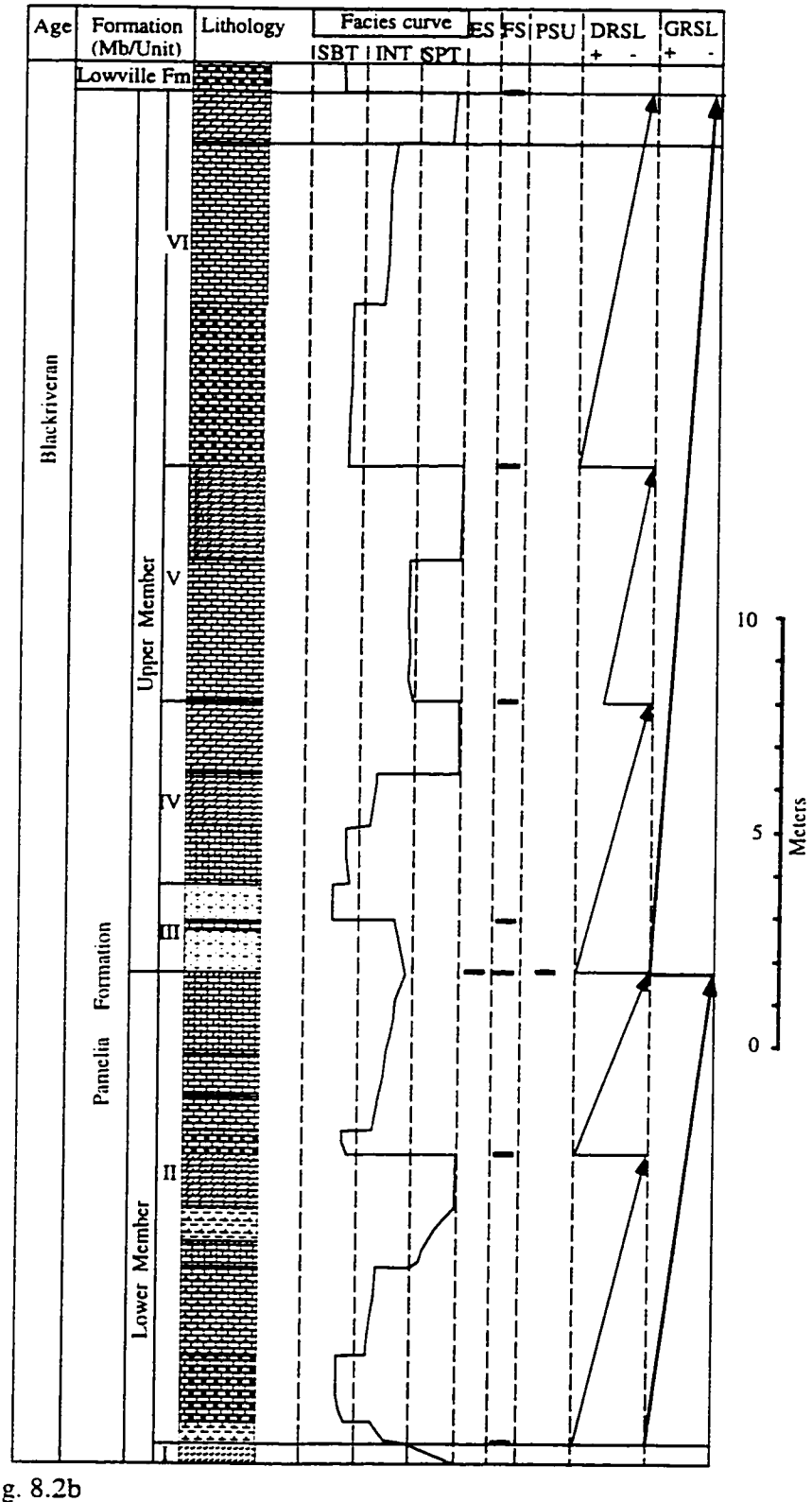
Age
Formation (Mb/Unit)
Lithology
Facies curve
ES
FS
PSU
DRSL
GRSL
ISBT
INT
SPT
+
-
+
-
Lowville Fm
Blackriveran
Pamelia Formation
Upper Member
Lower Member
VI
V
IV
III
II
I
10
5
0
Meters

Fig. 8.2b

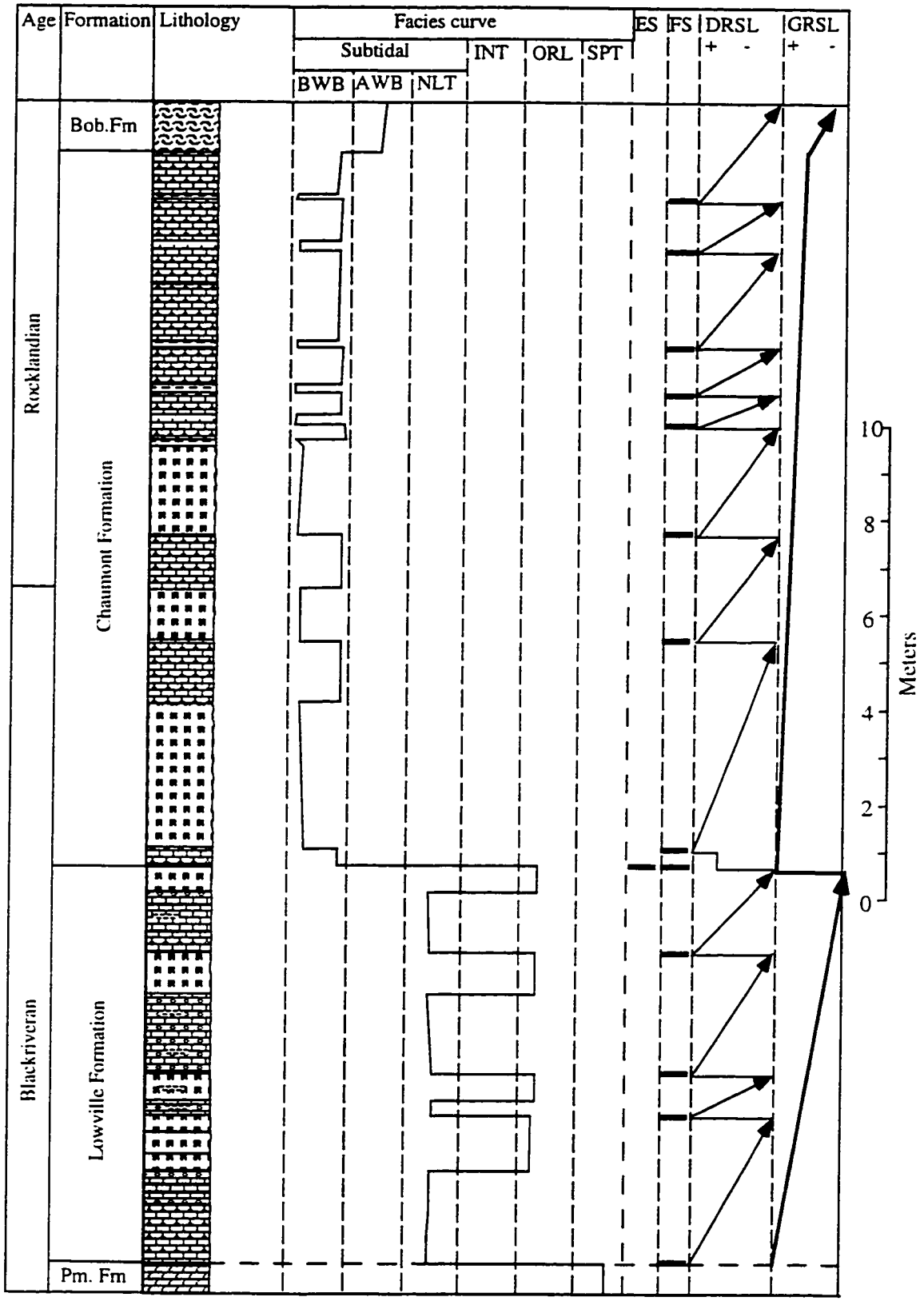
Age
Formation
Lithology
Facies curve
Subtidal
BWB
AWB
NLT
INT
ORL
SPT
ES
FS
DRSL
+
-
GRSL
+
-
Rocklandian
Blackriveran
Bob.Fm
Chaumont Formation
Lowville Formation
Pm. Fm
10
8
6
4
2
0
Meters

Fig. 8.2c

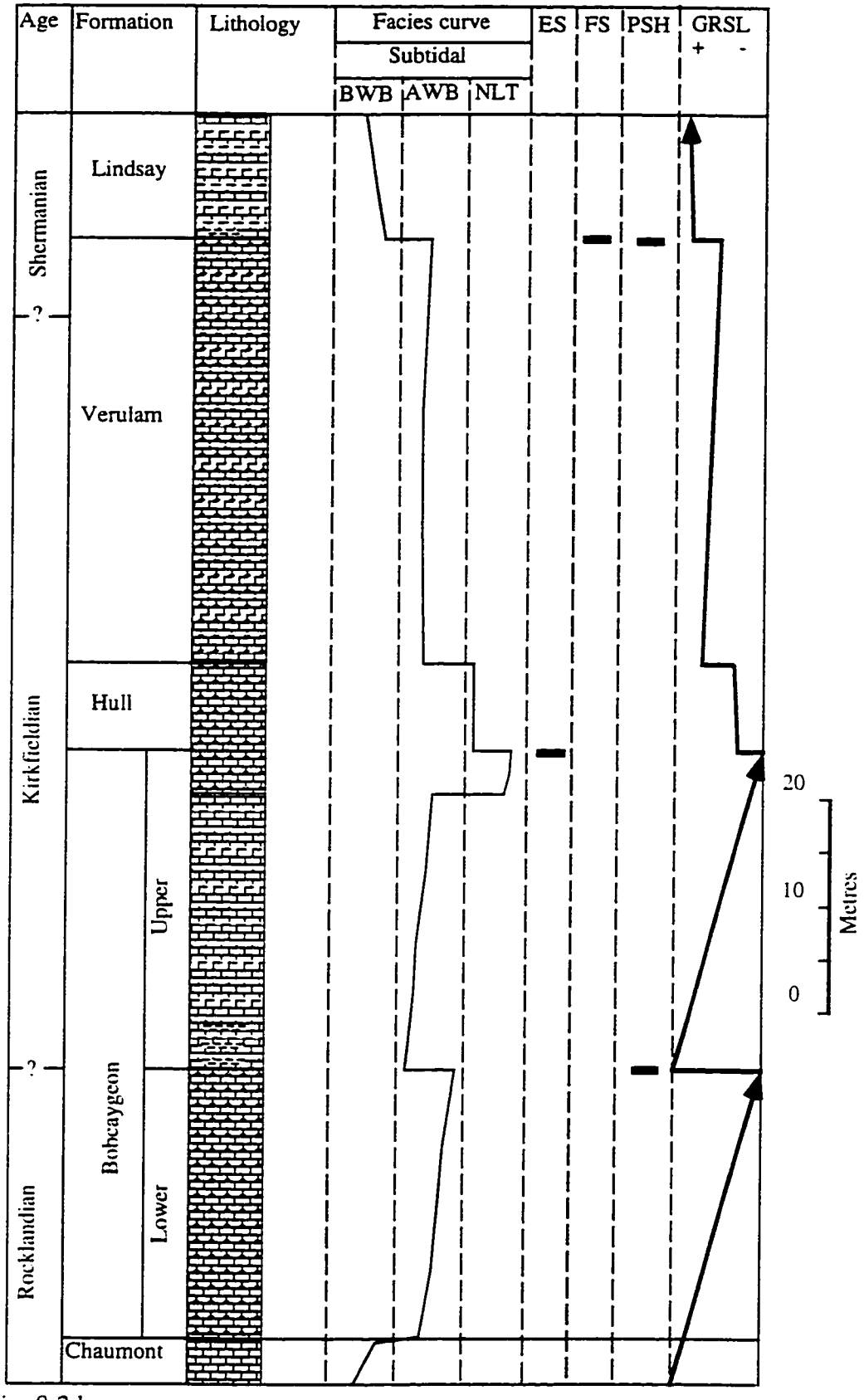
Age
Formation
Lithology
Facies curve
Subtidal
BWB
AWB
NLT
ES
FS
PSH
GRSL
+
-
Shermanian
Lindsay
Verulam
Hull
Kirkfieldian
Upper
Bobcaygeon
Lower
Rocklandian
Chaumont
20
10
0
Metres

Fig. 8.2d

depositional environments of the various facies of the studied rocks. From the facies curve [with the incorporation of other significant parameters, see Fig. 8.2a-d), deduction of detailed (where enough data is available) and general relative sea-level fluctuation trends is possible. There are a few flooding and erosional surfaces as well as shale and sandstone beds that can be correlated across eastern Ontario. The stratigraphic column is divided into three depositional successions (Fig. 8.3).

Succession One

This succession includes the Hog's Back, Pamelia and Lowville formations, and is characterized by repetitive rock packages of peritidal sediments which generally include shallow subtidal, intertidal, and supratidal facies (Fig. 8.2a-c) (Salad Hersi and Dix 1997b). The subtidal facies includes shale (TLF3), sandstone (TLF1), oolitic, bioclastic packstone and grainstone (CLF6 & CLF7) and *Tetradium*-rich, open-lagoon floatstone to bafflestone (CLF5). The intertidal facies includes sandstone (TLF1 & TLF2), microbial laminite (CLF2), intraclastic (flat-pebble breccia) packstone to rudstone (CLF3), bioclastic mudstone to wackestone (CLF4) and bioclastic grainstone to packstone (CLF6). Facies of the supratidal sediments include pure to sandy and-or calcareous dolostone (CLF1).

Most of the rhythmic units that comprise the Hog's Back and Pamelia formations contain all the three facies, but the Lowville Formation lacks the supratidal lithofacies.

The Hog's Back Formation is confined within two prominent shale units; basal shale of the lower member of the Hog's Back Formation (see Chapter 2) and shale of the basal Unit I of the Pamelia Formation (see Chapter 3). This suggests that, according to the definition of Galloway (1989), the Hog's Back Formation can be considered as a "genetic sequence".

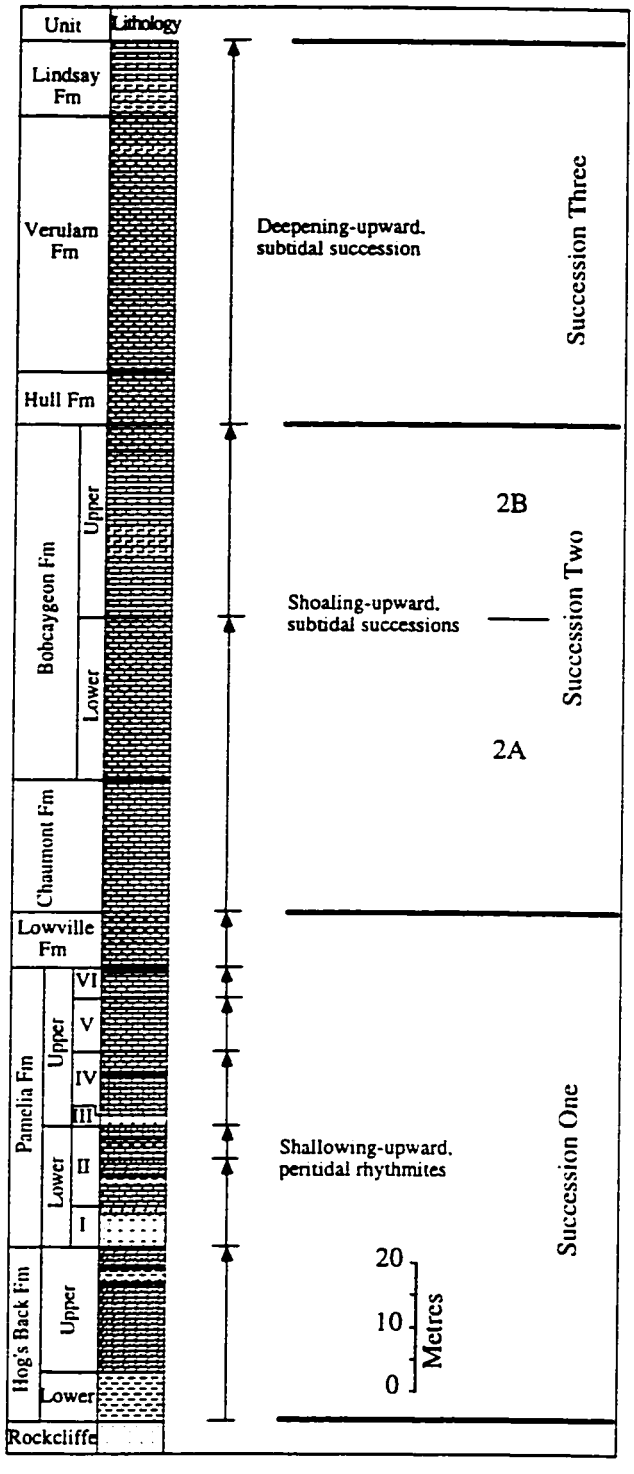

Fig. 8.3 Subdivision of the studied stratigraphic section into three successions based on rhythmic depositional patterns.

Succession Two

This succession is broadly defined and includes the Chaumont and Bobcaygeon formations (Fig 8.3). It can be divided into two sub-successions (2A & 2B), with each defined by a shoaling-upward successions characterized by relatively deep to shallow subtidal depositional settings.

The lower sub-succession (2A) includes the Chaumont and lower Bobcaygeon formations. The former is dominated by thickly-bedded, intensely-burrowed bioclastic, peloidal wackestone to packstone (CLF8) interpreted to have been formed below fair-weather wave-base (see Chapter 4). Thin- to medium-bedded shale beds within the formation (usually in the eastern part of the embayment) probably indicate further oscillation of sea-level superimposed in the overall shoaling-upward trend of the sub-succession (Fig. 8.2c). The upper part of the Chaumont Formation becomes relatively coarser indicating an upward increase in depositional energy. This is succeeded by thin- to medium-bedded, fine- to coarse-grained bioclastic grainstone to packstone of the lower member of the Bobcaygeon formation. Current-dominated sedimentary features in these rocks suggest an above-wave-base environmental setting (see Chap. 7). Thick beds of Chaumont-like lithology within the lower member of the Bobcaygeon Formation indicate occasional increase in water depth. The lower member of the Bobcaygeon Formation shows normal and inverse grading that may indicate somewhat rhythmic variation in energy. This rhythmicity is probably controlled by depositional factors (e.g., storms, energy) rather than sea-level fluctuation. However, more detailed work is needed to explain the rhythmicity within the lower as well as upper members of the Bobcaygeon Formation.

The upper sub-succession (2B) is represented by the upper member of the

Bobcaygeon Formation (Fig. 8.3). It begins with normally-grading lithofacies of bioclastic packstone, mudstone to shale. The shale becomes more abundant in the eastern part of the embayment, but generally becomes less important upsection and disappears in the upper part of the formation. In addition, grain-size and high-energy sedimentary structures are more abundant upsection (see Chapt. 7). This observation suggests a shoaling-upward depositional environment. Thin to medium beds of normally graded grainstone to packstone are dominant throughout the upper part of the Bobcaygeon Formation. Local, thin *Tetradium*-bearing mudstone beds (Lowville-type lithology) in the uppermost part of the formation were probably deposited in lagoons.

Succession Three

This succession includes the Hull, Verulam and Lindsay formations (Fig. 8.3). Unlike the other lower successions, the third succession is characterized by a deepening-upward pattern. The Hull Formation represents shallow subtidal sand shoals whereas the Verulam Formation accumulated in a relatively deeper intershoal depressions (Salad Hersi and Dix 1997c, Chapt. 7). Since the two formations are likely laterally equivalent (see Chap. 7), interbedding of Hull and Verulam lithofacies may suggest high order relative sea-level fluctuations. An ongoing M.Sc thesis by Jeff Kiernan at Carleton University is designed to define both spacial and temporal relationships of the Hull - Verulam formations. The two formations are succeeded by the Lindsay Formation. Higher shale content, lack of high energy sedimentary structures, burrows and finer-grain character of the Lindsay Formation suggest a calm, below wave-base depositional setting (see Chap. 7). Thus, Succession Three represents an overall deepening-upward nature.

Relative sea-level changes in the rock record

Change in vertical facies associations with time conveys the sense that stratigraphy is responding to interaction between sedimentary flux / production and available accommodation space (Posamentier and James 1993). Platform space available for accumulation of sediments is a function of eustatic changes and subsidence of the sea-floor (Posamentier and James 1993).

The St. Lawrence Platform developed in a foreland basin; therefore, tectonic factors and eustatic fluctuations likely both influenced sedimentation patterns. The peritidal rhythmites in Succession One may be attributed to autocyclicity where a high rate of carbonate production allowed "catch-up" of the sea floor with the sea-level (Jones and Desrochers 1992). Recurring allocyclic processes (i.e., subsidence and-or sea-level rises) enabled creation of accommodation space where a new cycle was then re-initiated. Lithofacies units in this succession suggest that, despite high-frequency relative sea-level falls and rises, the net result of these events is a deepening-upward response throughout the stratigraphic succession. This is suggested by the increase in abundance of intertidal to shallow subtidal lithofacies in the upper part of the Pamelia Formation and throughout the Lowville Formation (see Chapters 3 & 4). Facies patterns in the Chaumont Formation (the basal part of Succession 2) identify a net deepening-upward (with respect to the underlying Lowville Formation) of the depositional environment, to below fairweather wave-base or even probably below storm-base. An upsection increase in grain-size of the Chaumont Formation, followed by the coarse-grained packstone and grainstone of the Bobcaygeon Formation, indicate a change in depositional setting to being above wave or storm-base.

However, shale interbeds within the Chaumont and Bobcaygeon formations may indicate superposition of high order relative sea-level fluctuations within Succession 2. Shale interbeds probably accumulated during "lag phase" stages following relative sea-level rises (Read et al. 1986; Gonzalez 1996). During these stages, carbonate production was substantially subdued by the sea-level rises (Gonzalez 1996). Vertical facies changes of Succession 3 indicate a net depth increase of the depositional setting as suggested by the generally deepening-upward trend interpreted from the sedimentary record.

The general sea-level variation patterns of the studied rock succession indicate a deepening-upward trend throughout the Chazyan-Trentonian section. The temporal facies association reflects back-stepping of the shore-line due to an overall relative sea-level increase. This increase can be accounted for recurrent subsidences of the sea floor and-or eustatic variations. Sequence stratigraphic analysis of the studied succession requires strict stratigraphic correlations with the equivalent strata in other parts of the St. Lawrence Platform (i.e., eastern, and western St. Lawrence Platform, as well as other parts of the central St. Lawrence Platform, e.g., Montreal area). Such correlation will enable to identify platform-wide depositional factors (i.e., regional flooding and erosional surfaces, and facies changes) which are essential for sequence stratigraphic interpretations.

CHAPTER NINE

CONCLUSIONS

Eight formations are recognized to form the upper Chazyan to Trentonian succession in the Ottawa Embayment. The lowest formation, the Hog's Back Formation (new), is Chazyan in age. The upper seven formations comprise the Ottawa Group, and span Blackriveran to Trentonian stages.

The Hog's Back Formation is a distinct lithostratigraphic unit that separates rocks of typical Rockcliffe (*sensu* Wilson 1946) and Ottawa Group lithologies. It is 14.3 m thick at its type section (Prince of Wales Falls, Ottawa), and thickens to about 27 m in Russell County (~ 40 km SE Ottawa). Its lower boundary is characterized by an erosional surface overlain by a coarse-grained sandstone lag which varies in thickness from about 2 cm to 20 cm. The upper boundary of the formation is characterized by a sharp, apparently conformable contact that separates beds of upper Hog's Back Formation from dark greenish grey to black shale of the Pamelia Formation of the Ottawa Group. The lower boundary of the Hog's Back Formation is correlative with that of Wilson's (1946) St. Martin formation but, at the type locality, the upper contact lies about 5 m above that of the St. Martin formation.

The Hog's Back Formation consists of a lower member dominated by dark grey shale with minor, thin, medium grey, (dolomitic) mudstone interbeds, and an upper member dom nated by greenish grey, sandy and-or calcareous dolostone with minor interbeds of coarse-grained, pinkish, bioclastic packstone and grainstone and (rare) dark green shale. The lower 9.3 m of the formation occur below a bed rich in a Chazyan brachiopod known as *Rostricellula plena* . The age of the upper 5 m remains uncertain. Conodont fauna from the

uppermost bed of the formation define a transitional Chazyan - Blackriveran assemblage. Correlation with Chazyan strata in the upper Laval Formation (Québec) suggests the Chazy - Blackriver boundary may coincide with the Hog's Back - Ottawa Group contact.

The Ottawa Group consists of three Blackriveran (lower Ottawa Group) and four Trentonian (upper Ottawa Group) formations. The lower Ottawa Group shows good lithostratigraphic correlation with equivalent strata in upstate New York. Application of Pamelia, Lowville and Chaumont formational terms from the latter region (Cushing 1908; Cushing et al. 1910; Kay 1929) appears appropriate and has precedence over terminology applied by Liberty (1967a, 1969) from south-central Ontario. The latter terminology is not easily applicable to the Blackriveran strata in the embayment.

The Pamelia Formation (42 - 43.5 m thick) in the Ottawa Embayment conformably overlies the Hog's Back Formation and underlies the Lowville Formation. The upper boundary of the formation is placed at the upper surface of the highest (sandy) dolostone interval, which is overlain by the limestone of the Lowville Formation. The Pamelia Formation consists of two members; each one is characterized by a basal siliciclastic unit followed by carbonates. Subtle lithologic variations, and regional correlation of sandstone and sandy dolostone units, allow further subdivision into six units (I - VI).

The Lowville Formation has an average thickness of about 10 m, and its upper boundary is marked by an abrupt to erosional contact, and locally bedding with rubbly texture followed by the Chaumont Formation. The Lowville Formation is characterized by alternating units of medium- to coarse-grained intraclastic, bioclastic and-or oolitic packstone and grainstone, and bioclastic (mostly *Tetradium* corals) mudstone, wackestone, floatstone and (locally) bafflestone.

The Chaumont Formation varies in thickness from about 2 m near Arnprior (~ 50 km west of Ottawa) to about 21 m in the Russell County (~ 40 km southeast of Ottawa). It consists of thickly bedded, intensely burrowed, medium to dark brownish grey, bioclastic, peloidal wackestone to packstone. Minor shale and grainstone interbeds are locally present.

Eleven lithofacies are recognized to form rocks of the lower Ottawa Group. They include: (1) thickly bedded, highly burrowed, greenish grey, fine-grained, quartzwacke (TLF1); (2) thin to medium bedded, fine- to medium-grained (bimodal) quartz arenite (TLF2); (3) dark greenish grey to black shale (TLF3); (4) medium to thickly-bedded, light greenish grey, fine-crystalline, sandy to pure dolostone (CLF1); (5) microbially laminated mudstone; thinly-bedded/laminated stromatolite and flat-lying laminite (CLF2); (6) intraclastic (flat-pebble breccia) packstone to rudstone (CLF3); (7) bioclastic mudstone and wackestone (CLF4); (8) bioclastic floatstone to bafflestone (CLF5); (9) bioclastic packstone to grainstone (CLF6); (10) oolitic packstone and grainstone (CLF7); and (11) burrowed, bioclastic peloidal wackestone to packstone (CLF8). Lithofacies 1, 2, 4, 5, and 6 are exclusively confined to the Pamelia Formation, but other lithofacies are also present in the formation. The Lowville Formation is dominated by interbedding of lithofacies 7, 8, 9 and 10, whereas the Chaumont Formation consists mainly of Lithofacies 11. Lithofacies 3, shale, is present in all formations. The Pamelia and Lowville formations were deposited in peritidal [supratidal to shallow (above-wave-base) subtidal] environments whereas the Chaumont Formation accumulated below wave-base level.

Lithofacies in the Pamelia and Lowville formations are organized into m-scale shallowing-upward successions with distinct stacking patterns whereas no rhythmicity is observed in the Chaumont Formation. However, framework grains within the Chaumont

Formation coarsen upward suggesting a shoaling-upward succession. Rhythmic units in the Pamelia Formation are divided into two types based on their stacking patterns. Stacking pattern A, or SP-A, is characterized by a basal (transgressive) shale (TLF3) followed by thick-bedded, pervasively burrowed sandstone to dolomitic sandstone (TLF1). The other stacking pattern, or SP-B, is dominated by carbonate rocks. It generally grades from lower bioclastic and-or oolitic packstone to grainstone lithofacies (CLF6 & CLF7), through intraclastic, bioclastic (locally microbially laminated) mudstone to wackestone (CLF2, CLF3, CLF4), to (sandy) dolostone lithofacies (CLF1). Higher order rhythmics are superimposed on both types of stacking patterns. The Lowville Formation shows rhythmic units (stacking pattern C, or SP-C) characterized by subtidal (to probably deep intertidal) oolitic and bioclastic grainstone and packstone lithofacies (CLF6 & CLF7) overlain by lagoonal (*Tetradium*-rich) mudstone, wackestone, floatstone and-or bafflestone.

Petrographic (including cathodoluminescence and staining) analysis of the Blackriveran succession in the Ottawa Embayment allows recognition of successive diagenetic events that took place in marine, vadose, meteoric and burial environments. Marine signatures include: burrows, micrite envelopes, and fibrous calcite rim cement (Type-I). Minor pendant cement (Type-II) and meniscus cement (Type-III) are locally present in CLF7 lithofacies of the Pamelia and Lowville formations, suggesting precipitation in a vadose diagenetic environment. Prismatic calcite cement (Type-IV) is interpreted to have precipitated from a diagenetic fluid dominated by marine water but slightly baffered by fresh water, possibly reflecting a mixing-zone realm. Dissolution of metastable bioclasts, and precipitation of fine- to coarsely-crystalline, equigranular calcite (Type V = fine, Fe-poor; VI = coarse, Fe-poor; and, Type VII = coarse, Fe-rich) are abundant in the three Blackriveran

formations. The paragenetic succession of these cements, and their temporal relationship to other diagenetic features (e.g., other cements, fractures, stylolites), suggest they formed progressively, with greater burial, within a meteoric phreatic environment.

Three types of dolomites (Dolomite I, II, and III) are recognized in Blackriveran strata. Dolomite I consists of fine-crystalline euhedral to subhedral crystalline mosaics. Dolomite crystals are locally dedolomitized. On the basis of field, petrographic, as well as oxygen and carbon stable isotope, Dolomite I formed as syngenetic supratidal dolomite. Dedolomitization is interpreted to have occurred early in the burial history, related to dissolution of syndepostional evaporite nodules in Dolomite I. The other two dolomite generations (II & III) are volumetrically minor and occur in various lithofacies units of the Blackriveran formations. These dolomites are interpreted to be of burial origin.

A new stratigraphic division and arrangement is presented compared to previous interpretations for the Trentonian succession. The latter includes the Bobcaygeon, Hull, Verulam, and Lindsay formations. The Bobcaygeon Formation conformably overlies the Chaumont Formation. The Bobcaygeon Formation (~ 55 m thick) consists of thin to thick (~ 5 - 100 cm) bioclastic grainstone (locally rudstone) to wackestone, with shale interbeds in certain intervals. Normal grading, horizontal and cross-bedding, scoured surfaces, and channels are characteristic. The formation is disconformably overlain by the Hull Formation which contains medium to thick (15-60 cm) beds of coarse crystalline, bioclastic grainstone to packstone. The formation (~ 2 - 38 m thick) is characterized by cross-bedding, normal grading, and scoured surfaces. Although the Hull Formation overlies the Bobcaygeon Formation, most of it becomes laterally equivalent to the Verulam Formation. The latter consists of thin to thick (2 - 40 cm) beds, fine- to coarse-grained, bioclastic grainstone to

wackestone with common thin shale interbeds. Hummocky and swaly cross stratification, lateral pinch-outs, horizontal burrows and trails, and normal grading are typical of the Verulam Formation. The thickness of the formation ranges from 0 to ~ 40 m. Both Hull and Verulam formations are conformably overlain by the Lindsay Formation. The latter (~ 30 m thick, Williams 1991) is characterized by nodular, thin to thick (10-80 cm) bedded bioclastic packstone to wackestone, with local thin to medium shale beds.

The Bobcaygeon Formation was predominantly deposited in an agitated shallow subtidal environment above the wave- or storm-base level. The overlying Hull Formation represents thick subtidal sand-shoals (shelfal dunes) which probably extended occasionally up into the intertidal zone. The laterally equivalent Verulam Formation accumulated in broad inter-shoal depressions. These depressions were generally below fair weather wave-base. Storms ripped up adjacent shoals of the Hull Formation creating tempestites in the deeper intershoal regions. The Lindsay Formation defines a deeper, relatively calm subtidal platform setting. Fine-grained siliciclastics from the Appalachian allochthon are admixed heralding the eventual foundering of the platform. Similar stratigraphic patterns appear to occur in Trentonian strata in the Montreal, upstate New York, Kingston and Lake Simcoe areas. This implies regionally uniform depositional and tectonic frameworks were in place across the central St. Lawrence Platform in these areas during the Trentonian stage. The Trentonian strata in the embayment are likely westward continuation of equivalent ramp sediments in southwestern Québec (Lavoie 1992; 1993). Increase in bryomol assemblage in the Trentonian succession compared to the Blackriveran strata in the embayment as well as in equivalent sediments in the adjacent regions of southern Ontario and southern Québec may suggest that the St. Lawrence Platform shifted from warm water to cool water conditions.

Vertical stacking patterns of Chazyan through Trentonian strata identify several orders of relative sea-level changes. In general, three depositional successions are recognized on the basis of the types of stacking patterns. Succession 1 consists of the Hog's Back, Pamelia, and Lowville formations. The succession is defined by shallowing-upward rhythmic units of peritidal origin. These peritidal rhythmites are likely due to autocyclicity where a high rate of carbonate production allowed "catch-up" of the sea floor with the sea-level (Jones and Desrochers 1992). Succession 2 includes the Chaumont and Bobcaygeon formations, and is characterized by two shallowing-upward subtidal units (2A and 2B). The lower one (2A) consists of the Chaumont Formation and the lower member of the Bobcaygeon Formation; the upper one (2B) consists of the upper member of the Bobcaygeon Formation. Succession 3 includes the Hull, Verulam and Lindsay formations, and is characterized by an overall deepening-upward pattern.

The general pattern of relative sea-level changes for the Chazyan to Trentonian strata in the Ottawa Embayment is manifested by an overall deepening-upward trend with superimposition of higher order sea-level fluctuations. The vertical succession reflects back-stepping of the shore-line due to an overall sea-level rise. Although more detailed work from the other parts of the St. Lawrence Platform is needed, it can be anticipated from the available data that the overall deepening of the platform was controlled by tectonics related to the development of the Taconic foreland basin whereas the superimposed higher order fluctuations are probably due to depositional autocyclicity.

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Appendix 1

This appendix consists of geologic details of the mapped sections during my work. There are few localities (Locs. 23, 26, 33, 37, 54, 55, 56, 57, and 58), that are mentioned in the text but not mapped during my field work. These localities were mapped by previous authors and I visited all of them except Locs. 54, 55, 57, and 58. UTM coordinates of these sections are also shown in this appendix. Indentation of the sections indicates weathering profile of the respective facies.

Locality numbers and UTM coordinates of the mapped sections

Locality	Easting	Northing
1	387500	5036000
2	390450	5026600
3	399450	5020700
4	407000	5021750
5	387650	4947350
6	411200	5012550
7	423450	5010750
8	424400	5012400
9	424450	5015500
10	436100	5013700
11	436050	5014250
12	437500	5013400
13	440750	5032000
14	439000	5023000
15	441500	5024300
16	445250	5021500
17	447725	5022375
18	447500	5022750
19	446625	5023375
20	445500	5024200
21	445000	5024750
22	443500	5026750
23	Williams's Section at Victoria Island, Ottawa	
24	442000	5028250
25	443000	5028750
26	Williams' (1991) section at Rideau Falls, Ottawa	
27	448000	5033000
28	448300	5032500
29	448875	5033500
30	448875	5033650
31	449125	5033650

Locality	Easting	Northing
32	449625	5032750
33	Copeland et al's (1989) section at Rockcliffe Areoport	
34	455750	5033250
35	456250	5033000
36	456250	5034000
37	Wilson's (1946) section at east of Green's Creek, Orleans	
38	460650	5036500
39	461000	5036750
40	477000	5041500
41	469400	5017600
42	479100	5012600
43	483900	5008850
44	478700	4983150
45	512700	4987800
46	513450	4988050
47	521800	4992800
48	536350	5010200
49	521500	5021500
50	513500	5026500
51	514500	5029000
52	522750	5043250
53	518550	5049050
54	Bolton et al.'s (1989) section near Hawkesbury	

Legend for the sections of Appendix 1

		Covered
Crinoidal grainstone (thickly bedded)	Dolomitic sandstone	Wackestone
Bioclastic grainstone (thin to med. bedded)	Dolomitic limestone	Oolitic packstone and grainstone
Interbedded shales and mudstone	Calcareous dolostone	Packstone
Mudstone	Thinly interbedded shale & mudstone	Sandy shale
Sandy dolostone	Floatstone to Bafflestone	Fine-grained, burrowed quartzwacke
Bioclastic rudstone	Mudstone	Quartz arenite

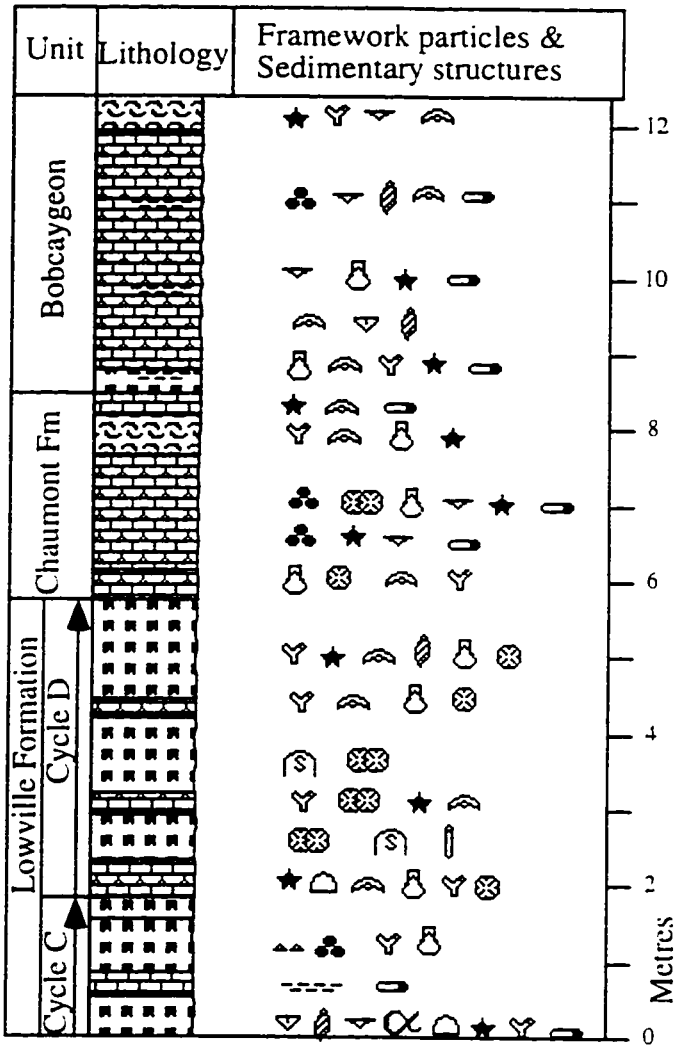
Ostracode	Peloid	Desication cracks
Crinoid	Intraclasts	Erosional surface
Trilobite	Shell fragments (undifferentiated)	Stylolites
Brachiopod	Phospatic grains	Planar (usually thin) bedding
Bivalve	Calcite nodule	Current ripple marks
Othocone	Irregular shaly parting	Hummocky cross stratification
Gastropod	Shale laminae	Wave ripple marks
Branching bryozoa	Sandstone laminae	Trough cross stratification
Tetradium Coral	Oolitic	High angle, tabular cross bedding
Rugosa corals	Calcareous or limestone laminae	Low angle, tabular Crossbedding
Other colonial coral	Dolomitic or dolostone laminae	Wavy bedding
Parasopora (bryozoa)	Flat-pebble breciia (mudchip)	Lenticular bedding
Serpulide	Pyrite	Microbial lamination
stromatolite	Chert	Normal grading
Algae (undiff.)	Detrital Quartz	Inverse grading
Stromatoporoid	Authigenic quartz	Horizontal burrows
Encrusting bryozoa	Evaporite molds	Vertical burrows
Solenopora algae	Borings	(Sinuous) horizontal and vertical burrows
Fault	Calcite-filled	*Diplocreterion*
Geopetal fill	Shelter porosity	U-shaped burrow (general)
Imbricated grains	Birdseye texture	
Mounds	Nodular texture	
	Rubbly texture	

Loc.1

Name and location of the section:
Braeside quarry,
~ 7 km NW of Amprior.

Company:
Smiths Construction Co.

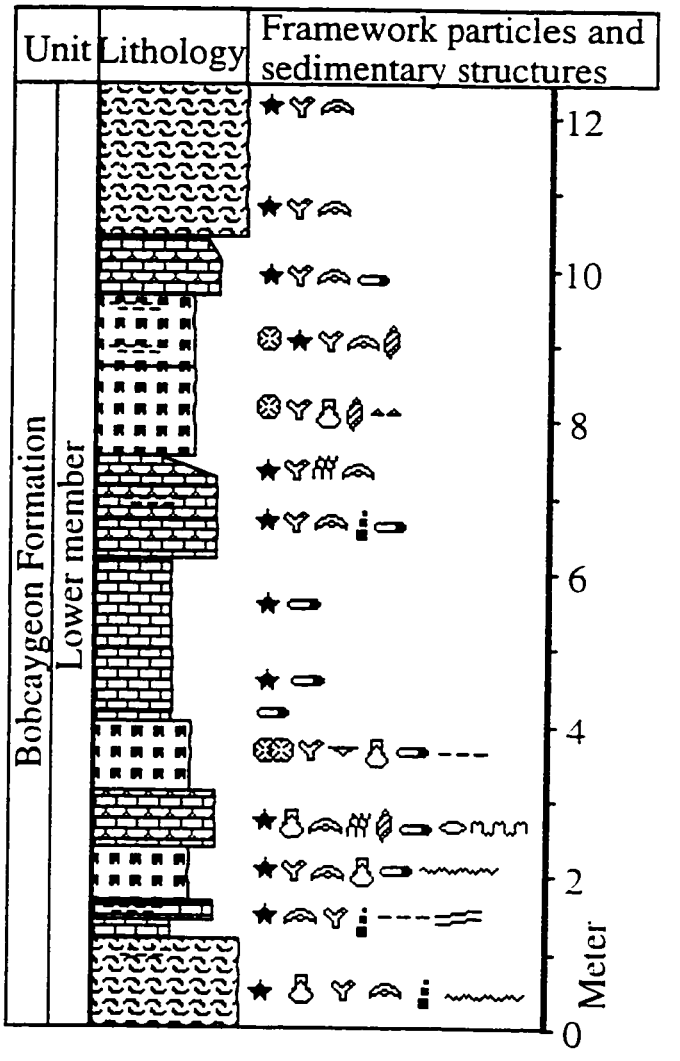
Reference:
PE-2 of Derry et al. (1991).



Loc. 2

Name and location of the section:
Clay Bank quarry,
7 km SW of Arnprior
Company:
H & H Aggregates Co.

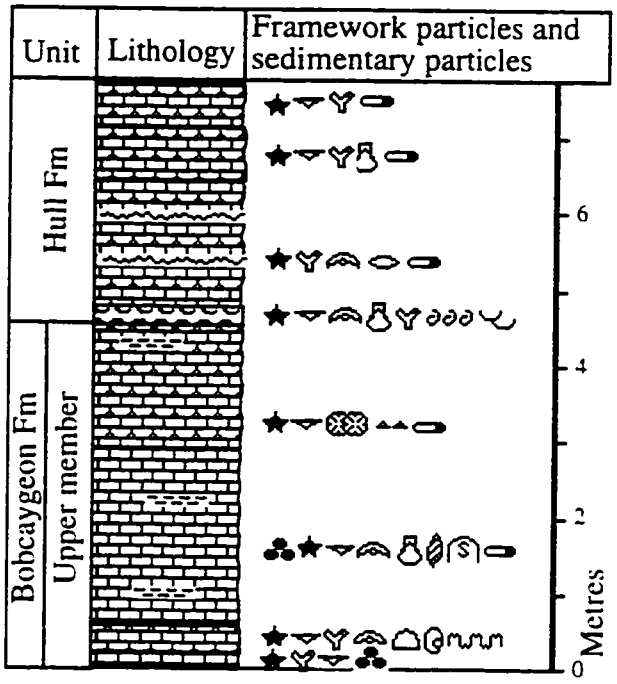
Reference:
PE-3 of Derry et al. (1991).



Loc. 3

Name and location of the section:
Abandoned (Pakenham) quarry at about 1 km northeast of the Pakenham village, Pakenham Township.

Reference:
AQ AR-1 of Williams (1991), see also Barnes (1967), p. 238.

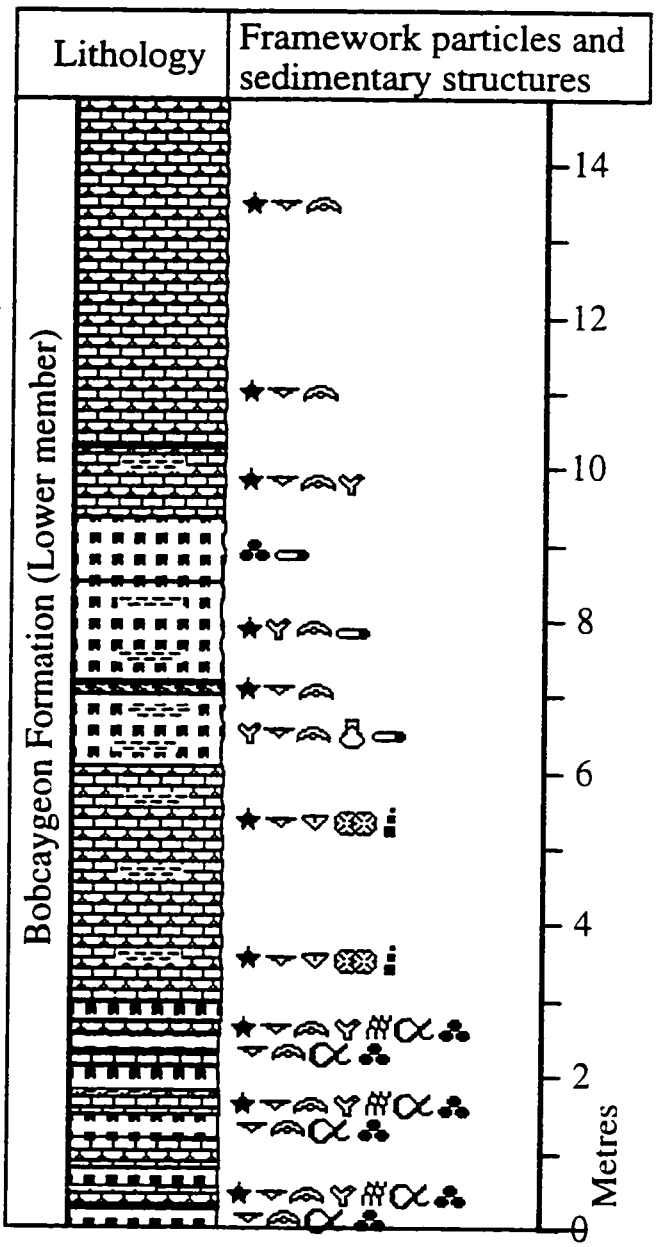


Loc. 4

Name and location of the section:

Kinburn quarry at ~ 4 km south of the Kinburn village, West Carleton Township.
Company: Thomas Cavanagh Construction Ltd.

Reference:
CP-2 of the Limestone Industries of Ontario (1991).

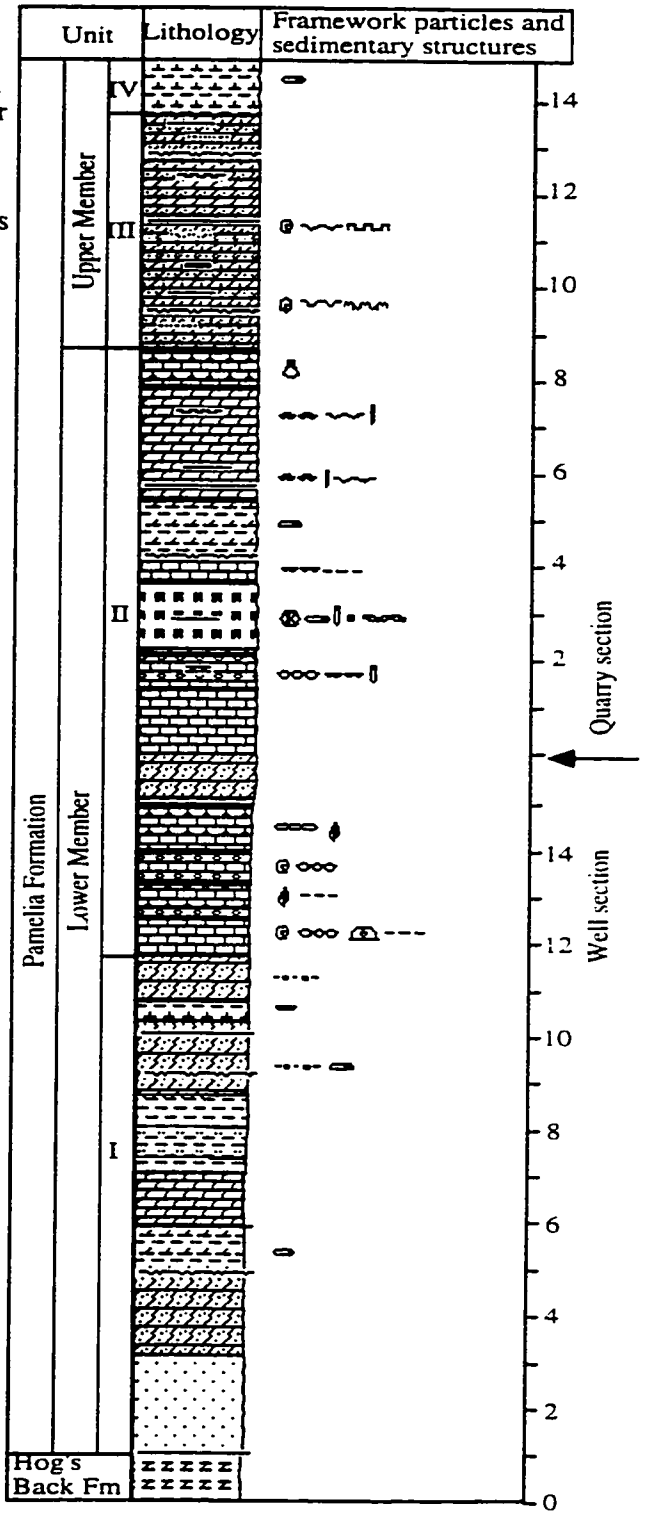


Loc. 5

Name and location of the section:
The section consists a lower part from an OGS well at Westport and an upper part from a quarry at about 2 km west of Town of Westport, North Crosby Township. The well was drilled at the base of the quarry and the two sections are continuous.

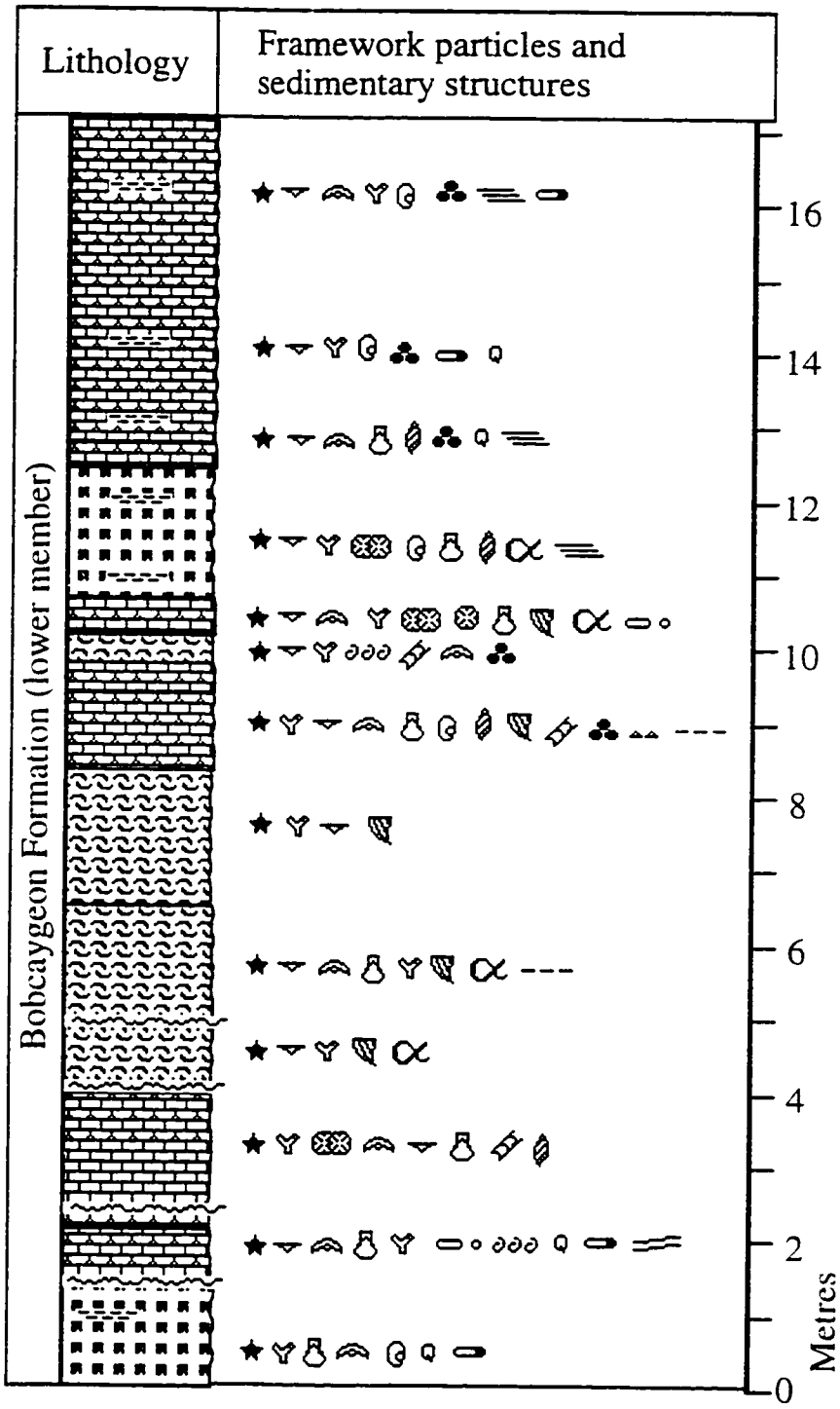
Company owning the quarry:
Griffin Brothers Gananoque Ltd.

Reference:
Quarry: LQ WE-6, Well: GDH WE-4 of Williams (1991)



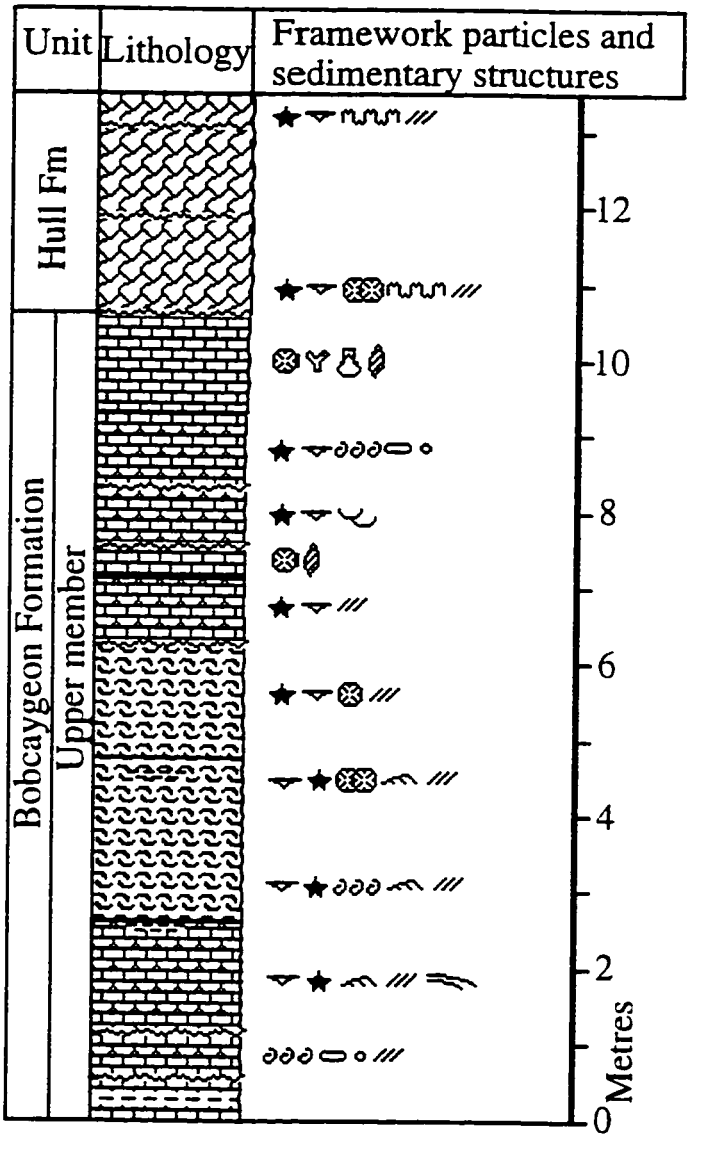
Loc. 6

Name and location of the section: West Carleton Quarry, 6 km NE Almonte. **Company:** Thomas Cavanagh Construction Ltd. **Reference**: PE-2 of Derry et al. (1991)



Loc. 7

Location of the section:
Road-cut at Highway 7, about 1.5 km south of where Highway 417 splits into Highway 7 and Highway 17, near Stittsville., Ontario.

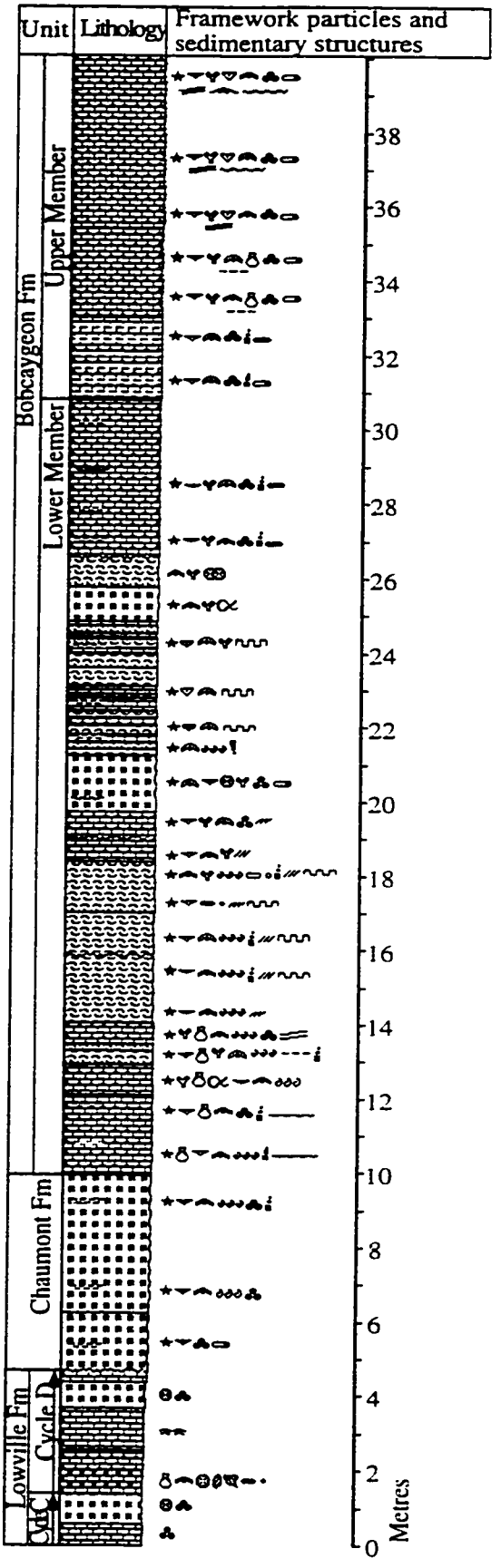


Loc. 8

Name and location of the section:
Clarke quarry at about 3 km west of Stittsville, West Carleton Township, Ottawa - Carleton Regional Municipality.

Company:
West Carleton Sand and Gravel Inc.

Reference:
CP-10 of Derry et al. (1989), LQ Ot-2 of Williams (1991)

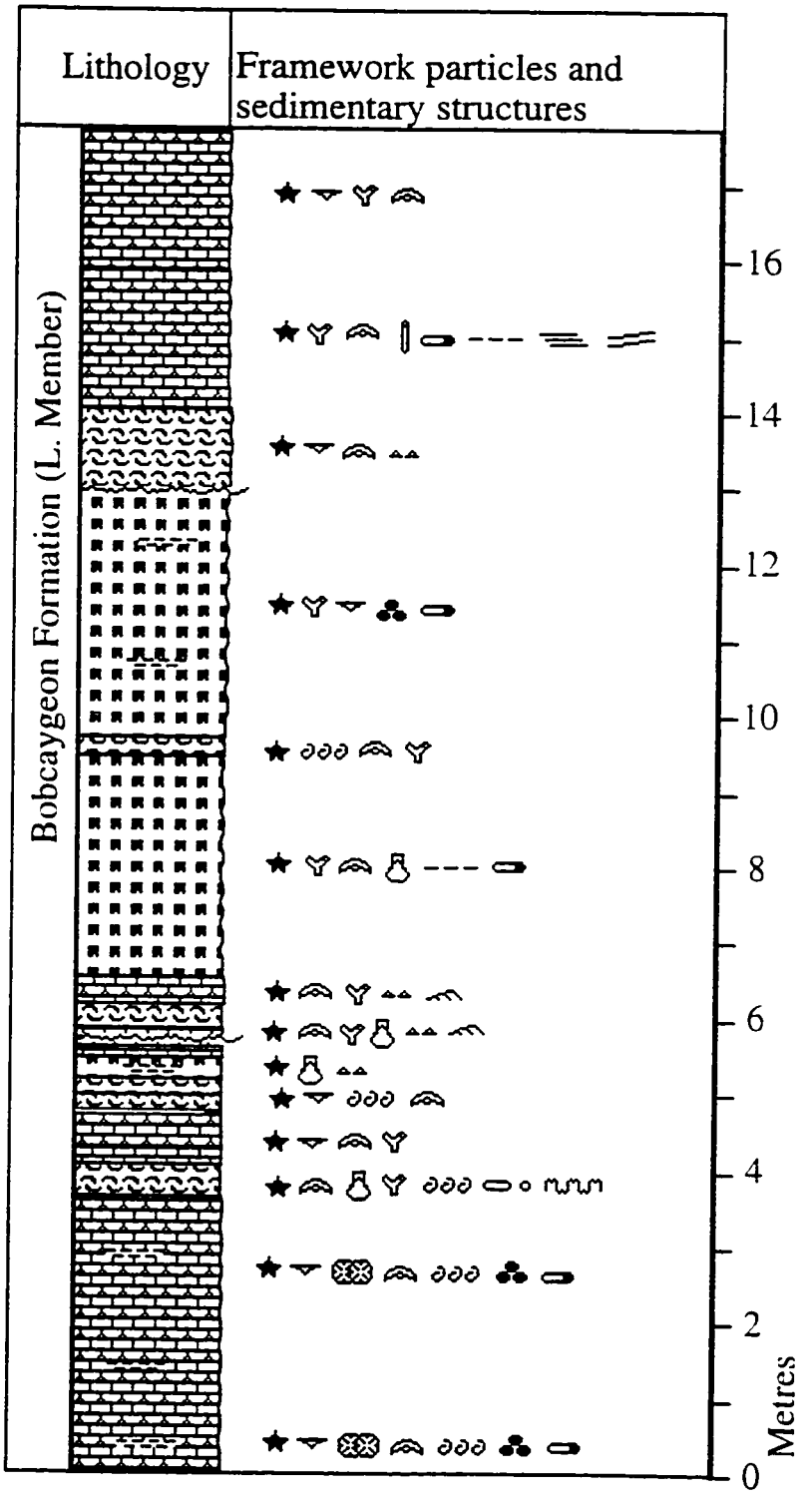


Loc. 9

Name and location of the section:
Spratt Quarry:
Ltd. 5 km NW Stittsville

Company:
Spratt Sand and Gravel Ltd.

Reference:
CP-9 of Derry et al. (1991).

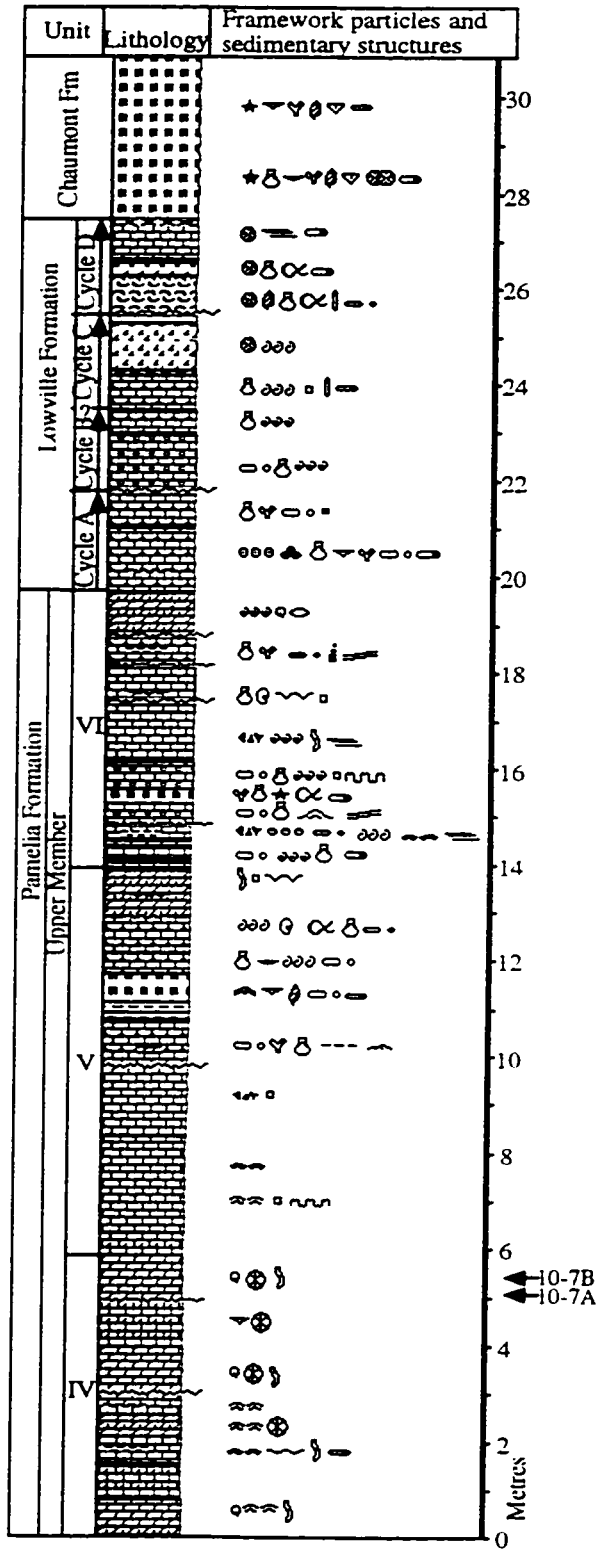


Loc. 10

Name and location of the section:
Moodie Dr (Fallowfield) quarry, at about 1.5 km northeast of Fallowfield, Nepean City, Ottawa - Carleton Regional Municipality.

Company:
George Wimpey Canada Ltd.

Reference:
CP-15 of Derry et al. (1989), LQ OT-3 of Williams (1991).

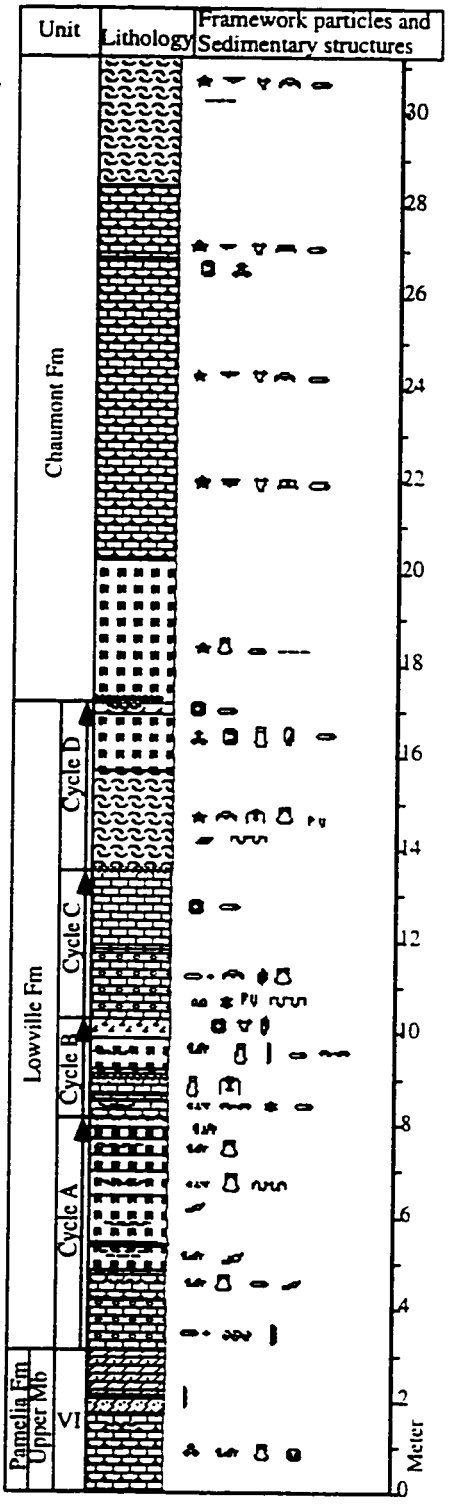


Loc. 11

Name and location of the section:
Fallowfield quarry at Fallowfield Rd, Nepean City, Ottawa-Carleton Regional Municipality.

Company:
R.W. Tomlinson Ltd.

Reference:
CP-14 of Derry et al. (1989), LQ OT-4 of Williams (1991)

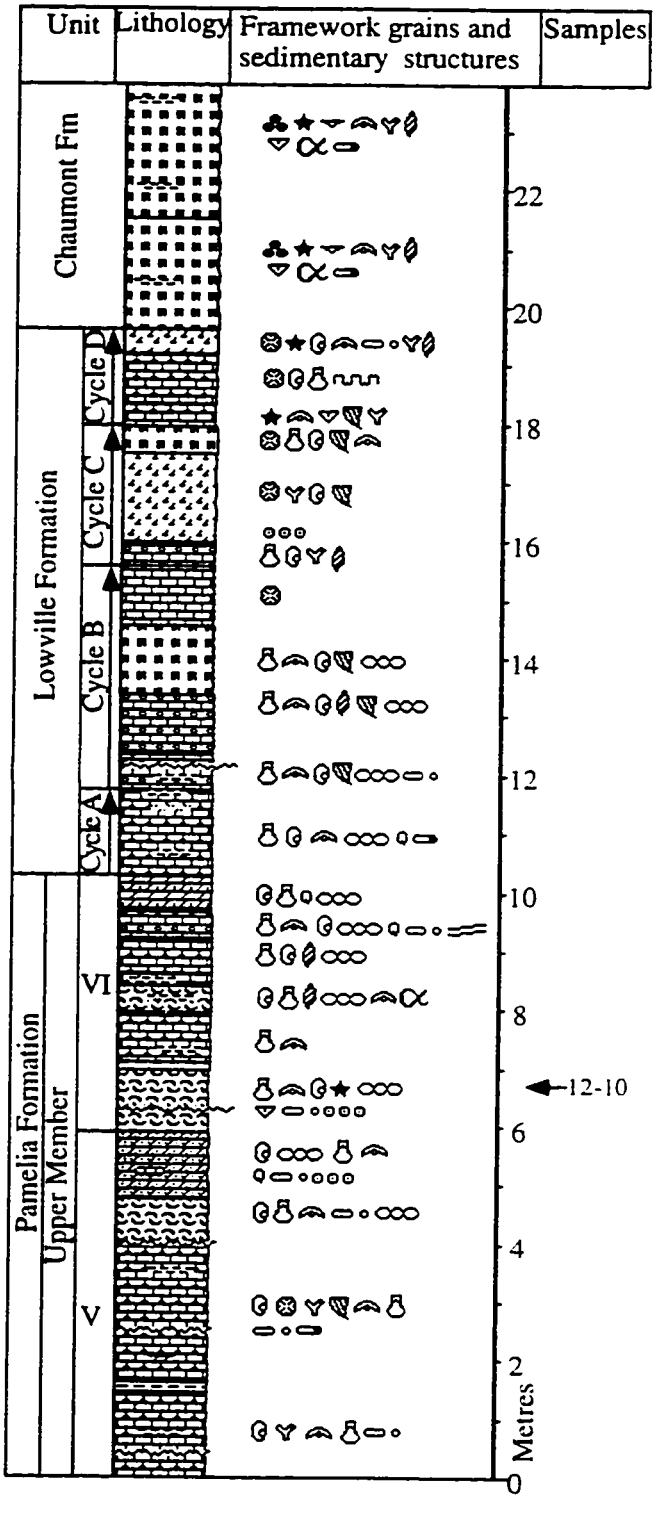


Loc. 12

Name and section location:
Houlahan (Fallowfield) quarry at about 2.5 km east of Fallowfield, Nepean City, Ottawa - Carleton Regional Municipality.

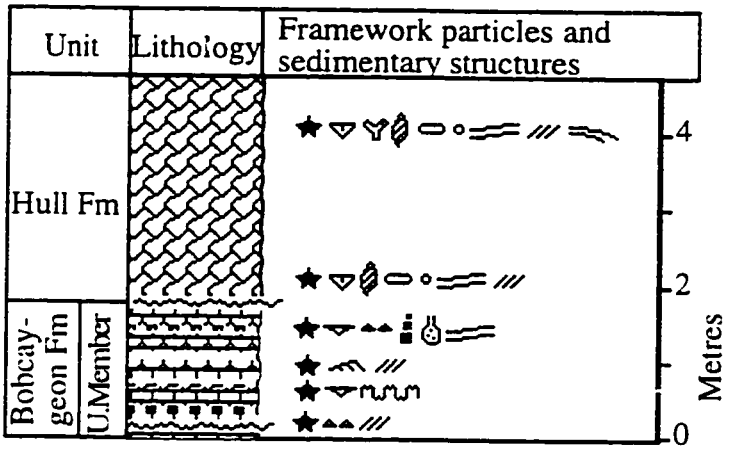
Company:
Warren Paving and Materials Group Ltd.

Reference:
CP-16 of Derry et al. (1989), LQ OT-5 of Williams (1991)



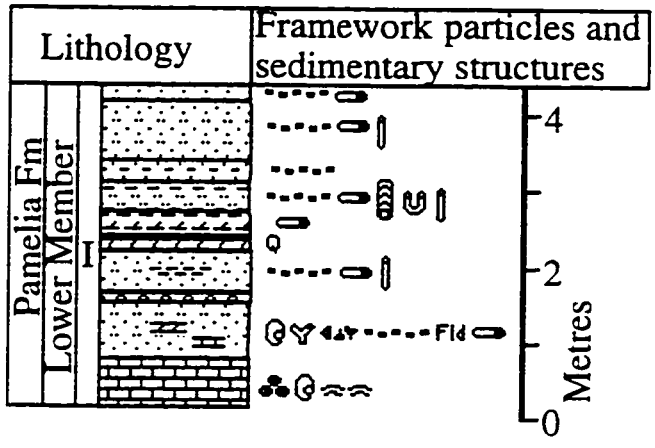
Loc. 13

Location of the section
Road-cut at Lac des Fees at St. Jean-Bosco, Hull, Quebec



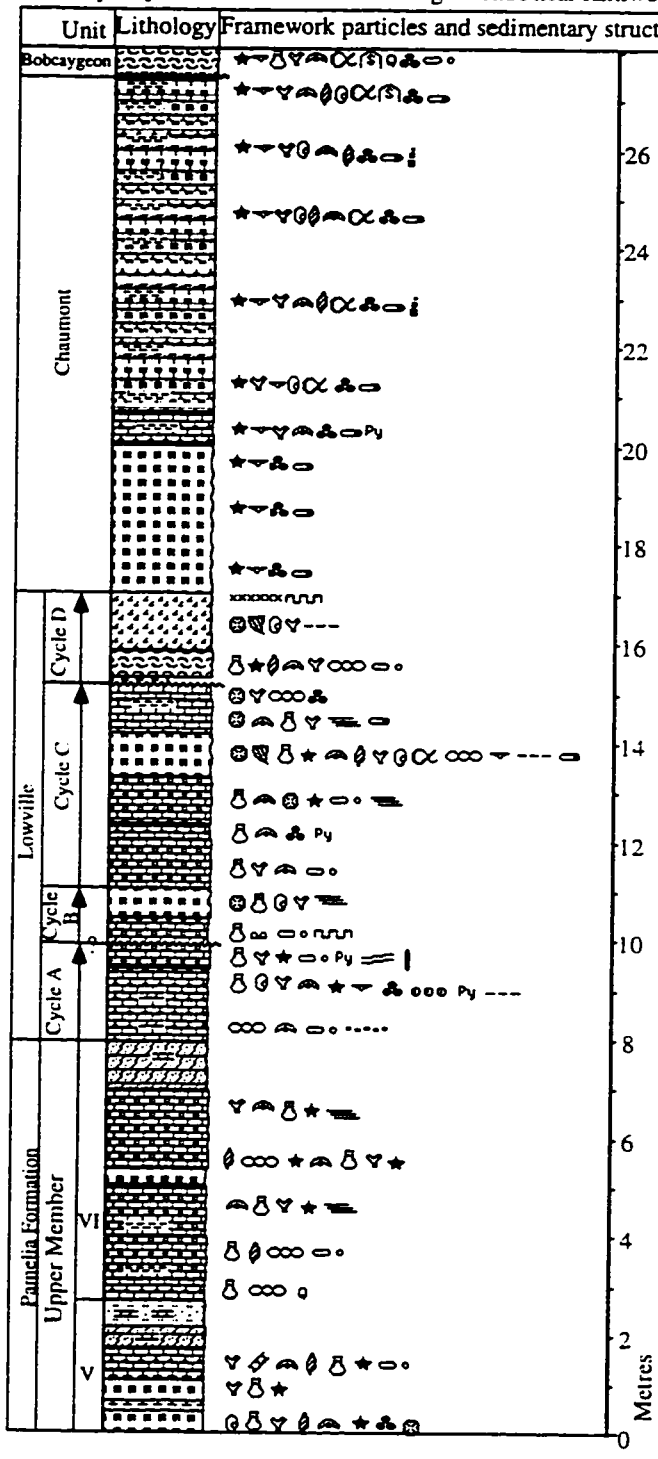
Loc. 14

Transitway at Iris road and Queensway, Ottawa



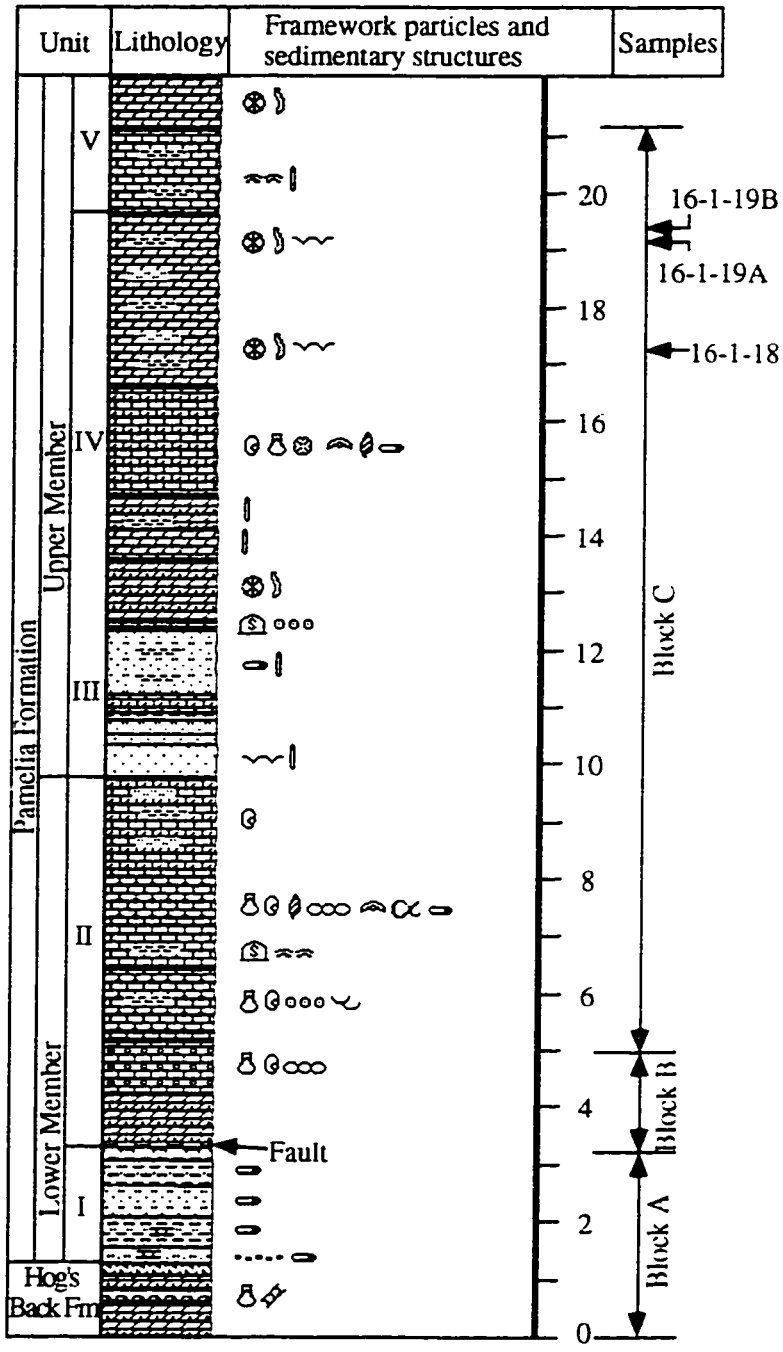
Loc. 15

Abondonded quarry of Frazer Duntile at Carling Avenue near Kirkwood Dr., Ottawa

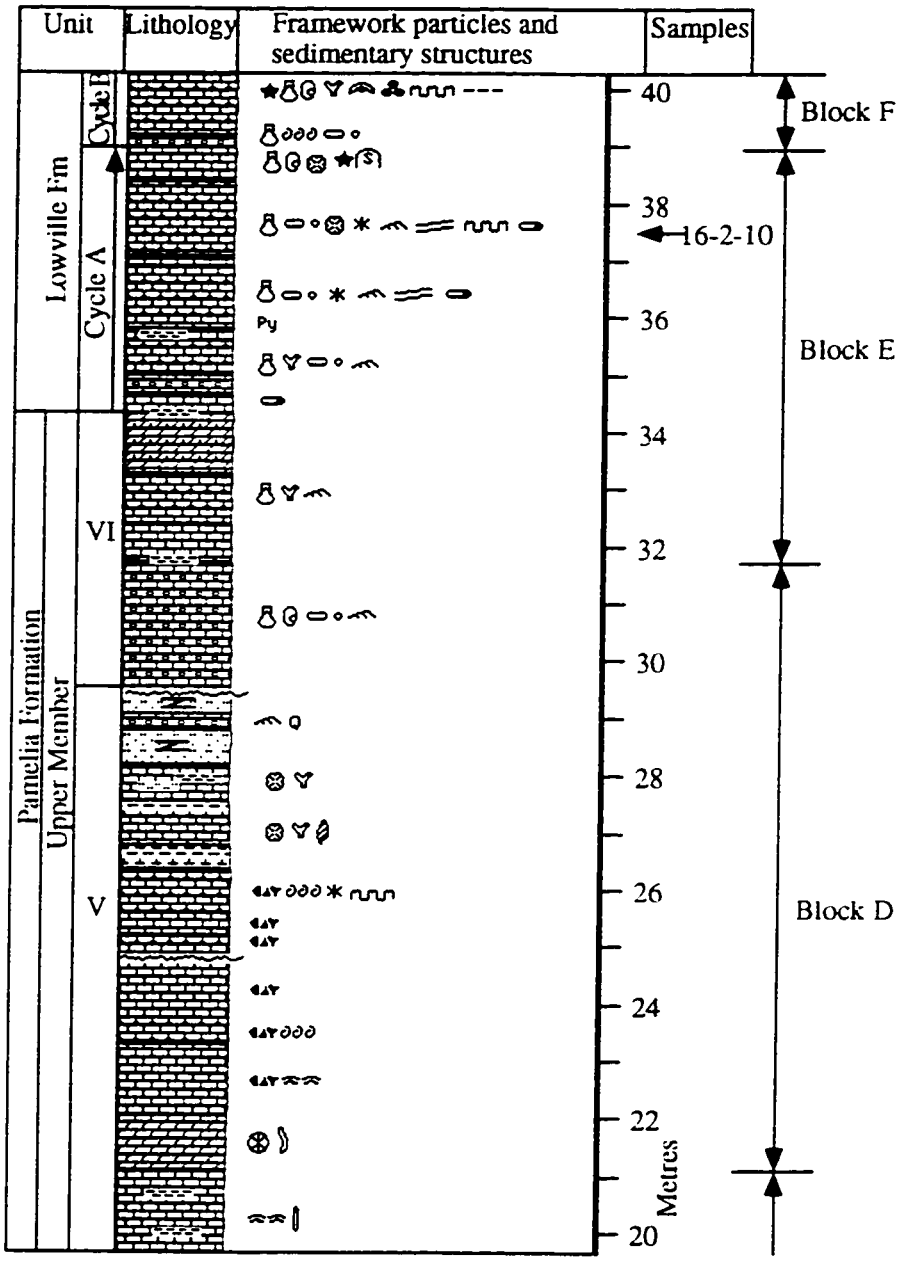


Loc. 16

Section location: Riverside Drive (Road-cut), about 2 km south of Walkley Rd - Riverside Dr junction, Ottawa. The section is composite from 6 fault blocks (A-F). Blocks A, D, & E are from east side of the road, south of the bridge, Blocks B & C are fron west of the road, south of the bridge, and Block F is from west of the road, north of the bridge.

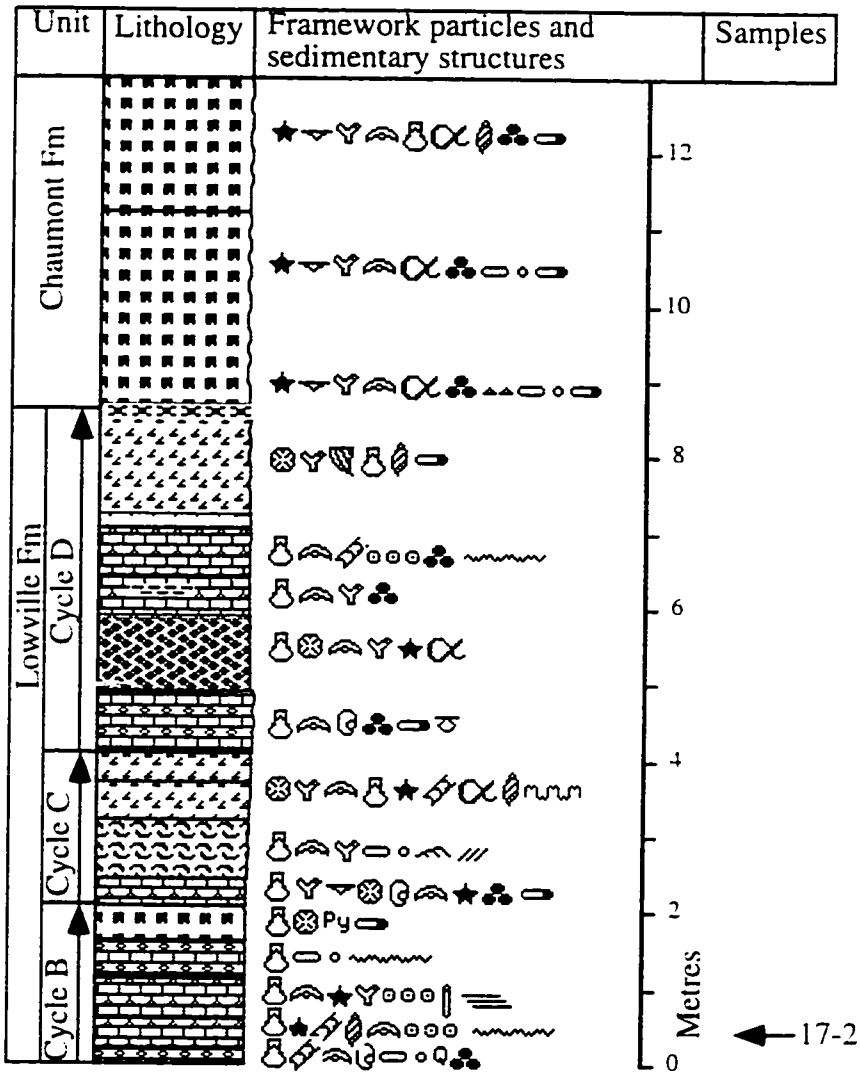


Section 16 continues



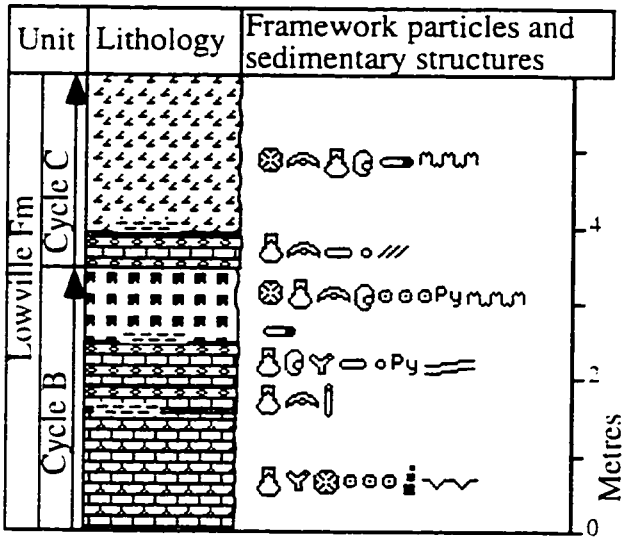
Loc. 17

Redevloped quarry (Western Community) between Bourbon St. and Owl Dr., Ottawa. Reference: Section 14 of Sawford (1972).



Loc. 18

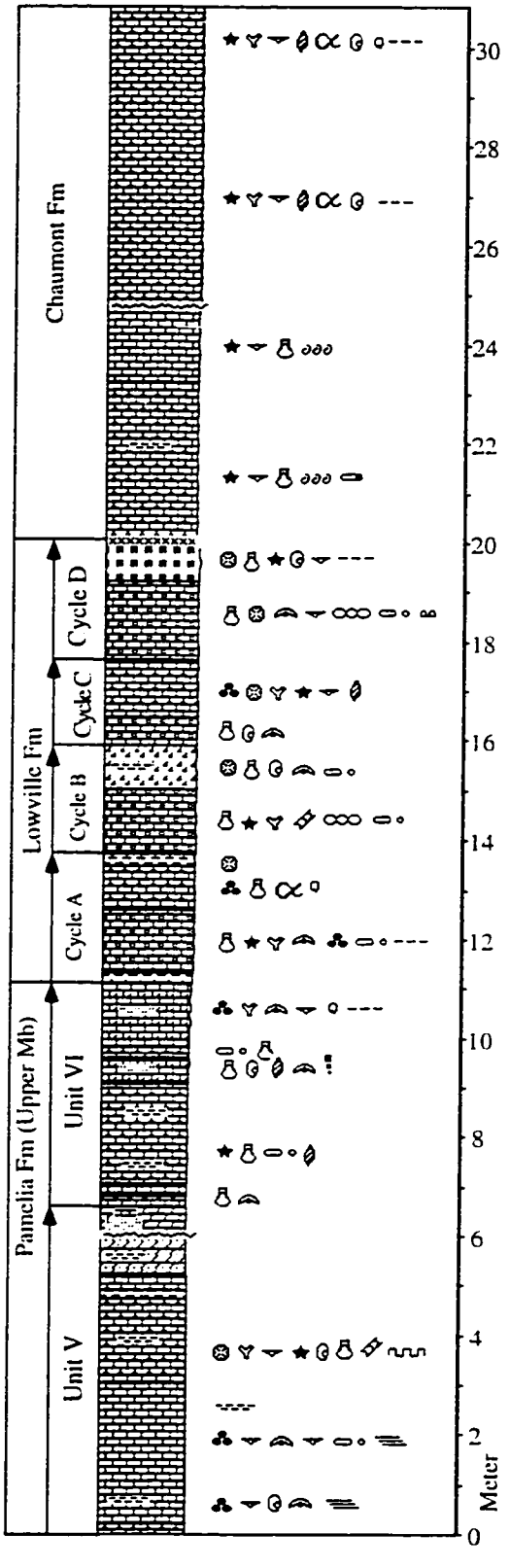
Road-cut section at Plante Dr., Ottawa



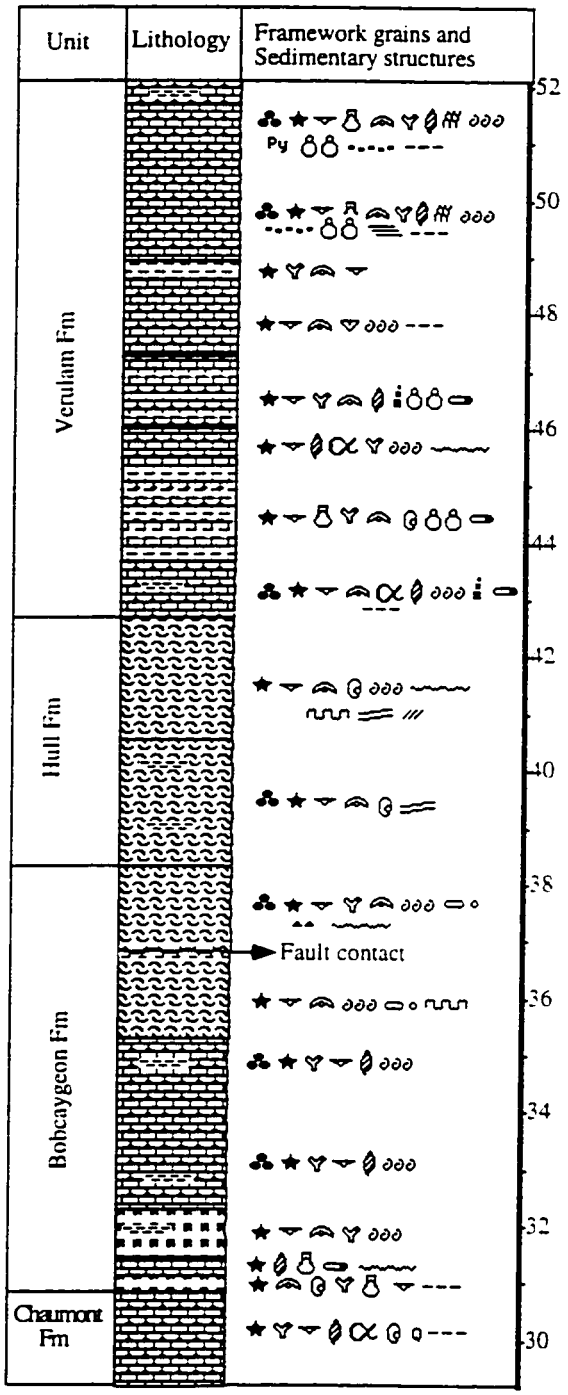
Loc. 19

Section location:
McCarthy Road at
Walkley Rd. Ottawa

Reference: Section 15 of
Sawford (1972)



Loc. 19 Cont.


Unit
Lithology
Framework grains and Sedimentary structures
Verulam Fm
Hull Fm
Bobcaygeon Fm
Chaumont Fm
Py
Fault contact
52
50
48
46
44
42
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38
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32
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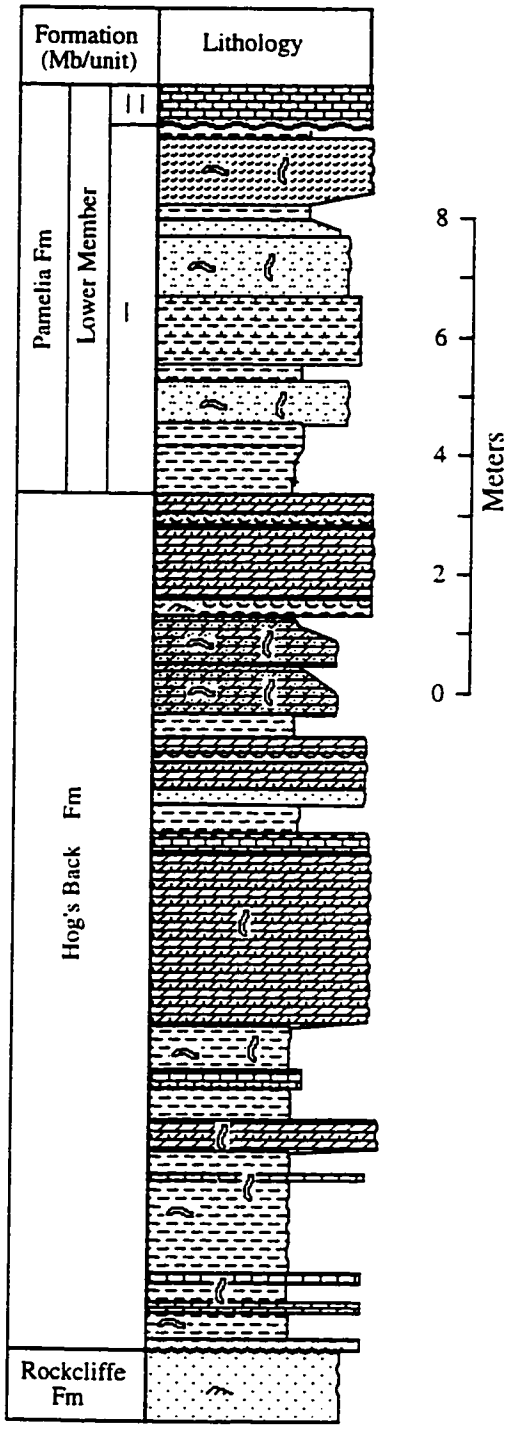
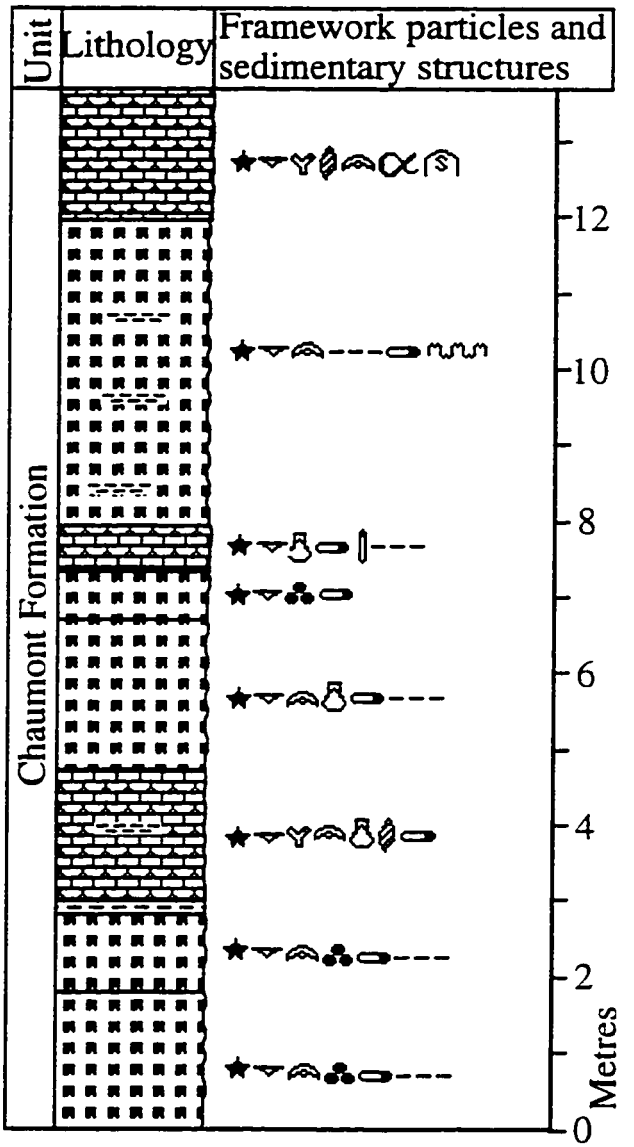
Loc. 20

Section location:
Prince of Wales Falls,
Rideau River at Hog's
Back Park, Ottawa.



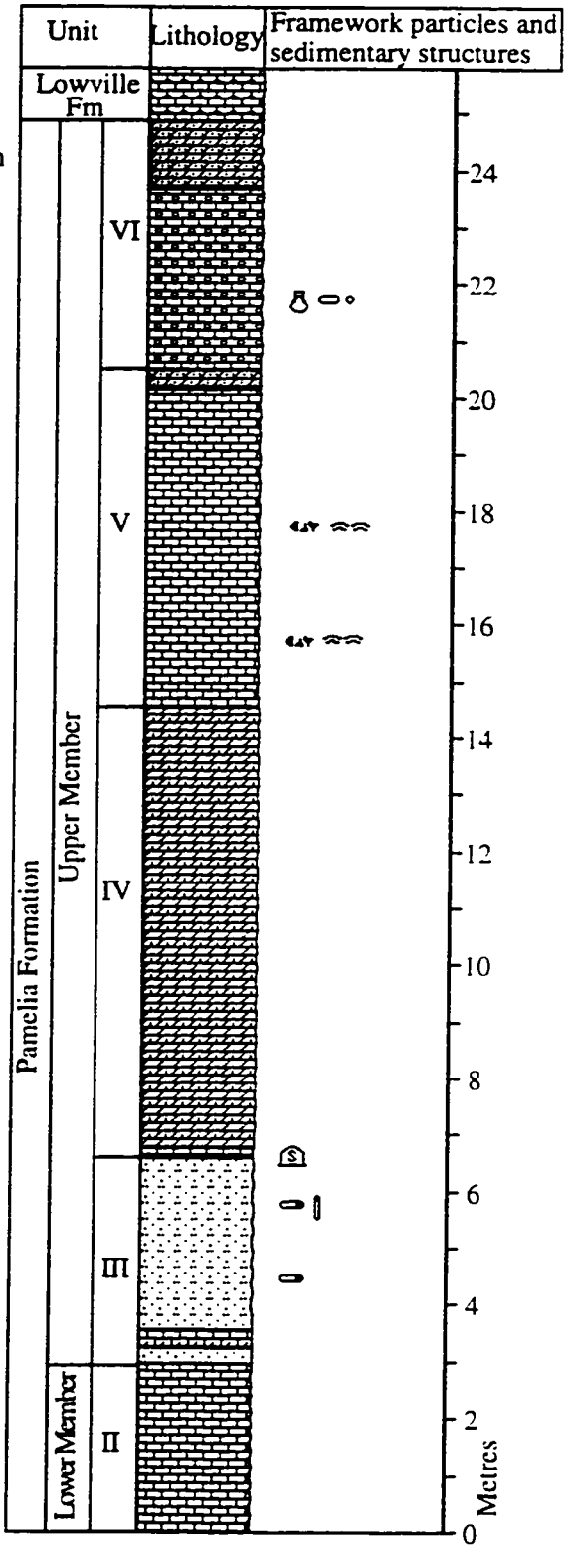
Loc. 21

Abondaned Hog's Back quarry at about 300 m northwest of the Hog's Back Road - Riverside Drive intersection, Ottawa



Loc. 22

GSC Observetory well at Observetory Crescent. Ottawa. The core is poorly preserved and various core pieces appear to have been misplaced. Only this portion which seemed to have relatively better conservation has been logged.

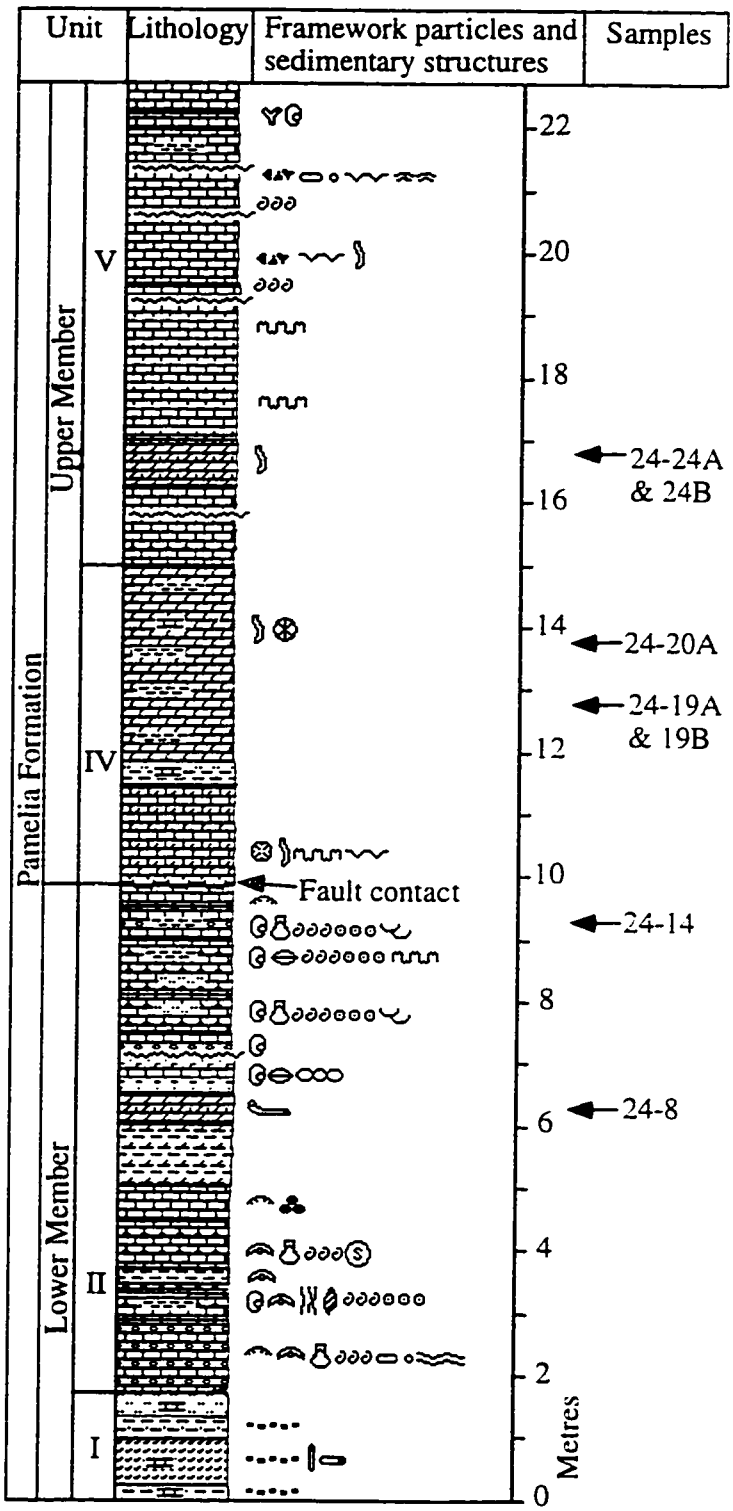


Loc. 24

Section location: Transitway along Scott street, Ottawa.

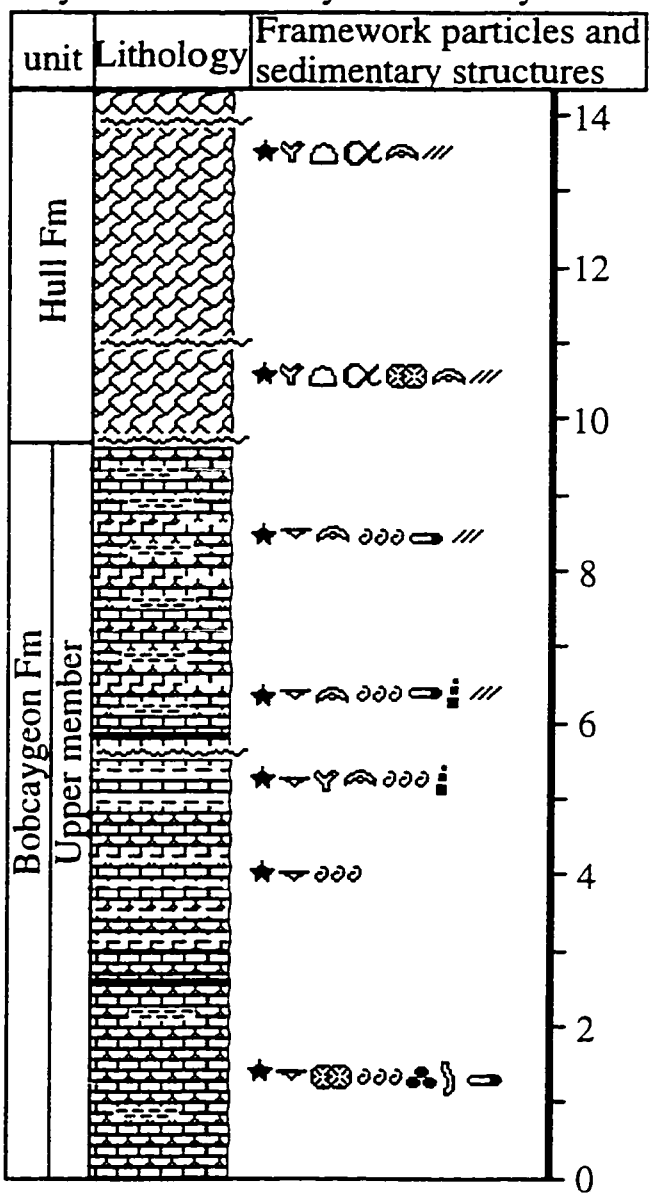
The Transitway is owned by the OCTranspo.

The section begins at the base of the fault block at Churchill bridge and proceeds eastward upto the fault-block just east of Tunny's Pasture bus station.



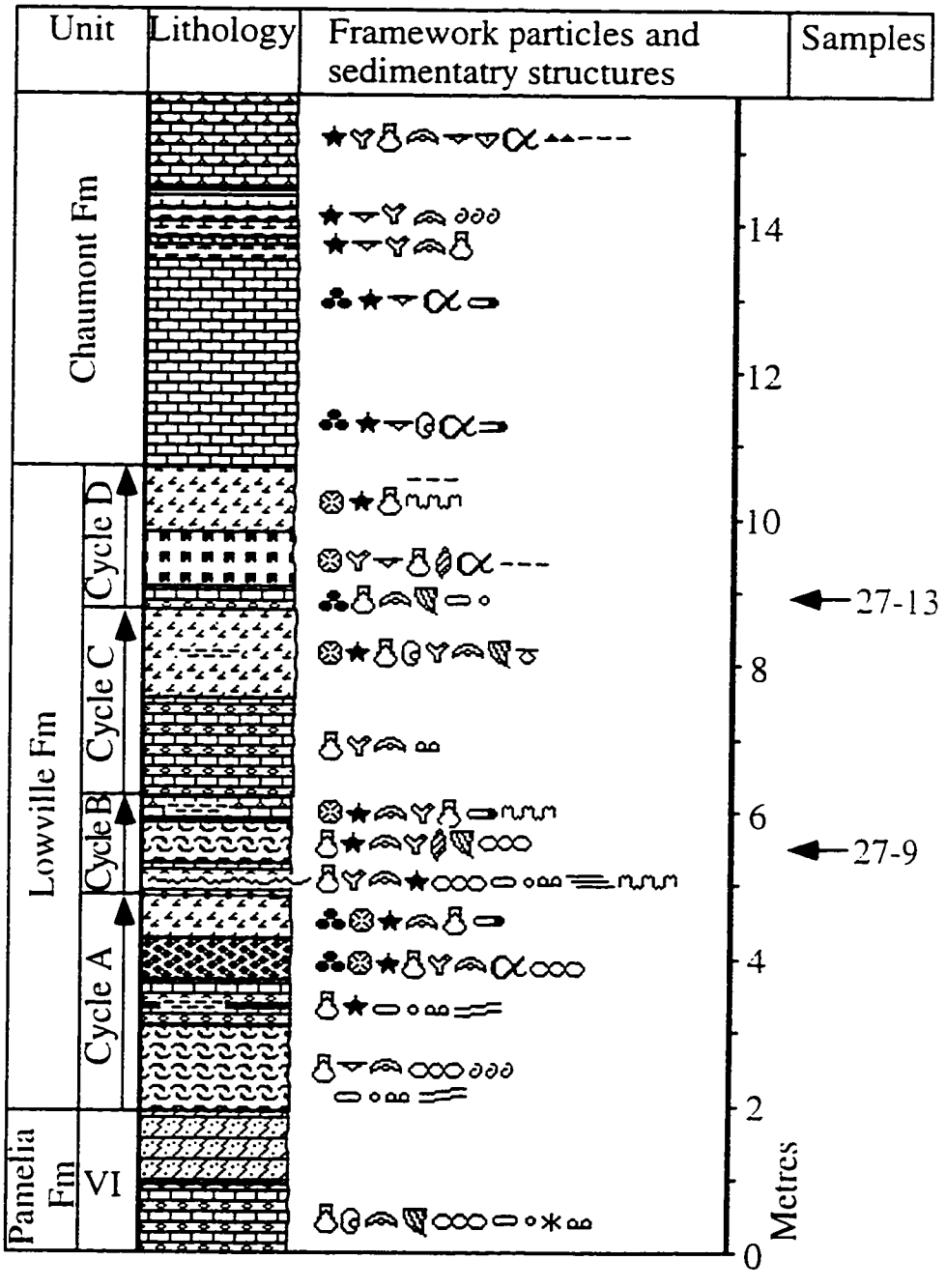
Loc. 25

Location of the section:
Eastern part of the Transitway at Scott street, Ottawa. The sections is along the southern wall of the Transitway and begins at the eastern entrance of the Transitway. The Transitway is owned by OCTranspo.



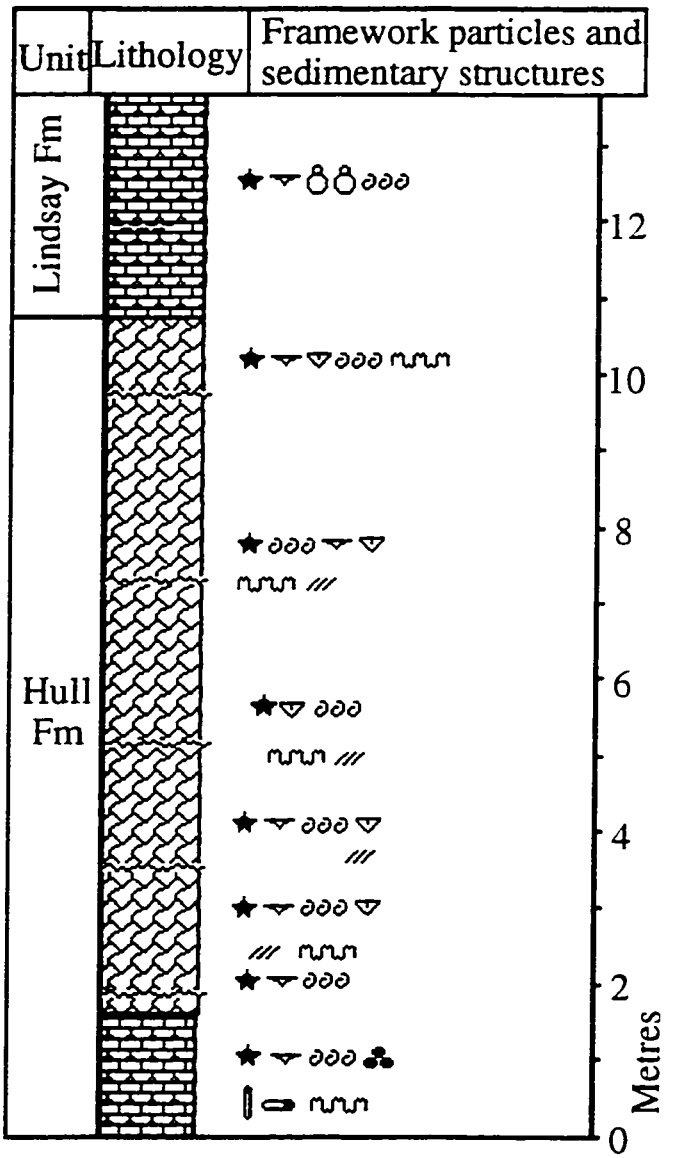
Loc. 27

Section location: Beechwood Road-cut at the Beechwood Cemetry, Ottawa.



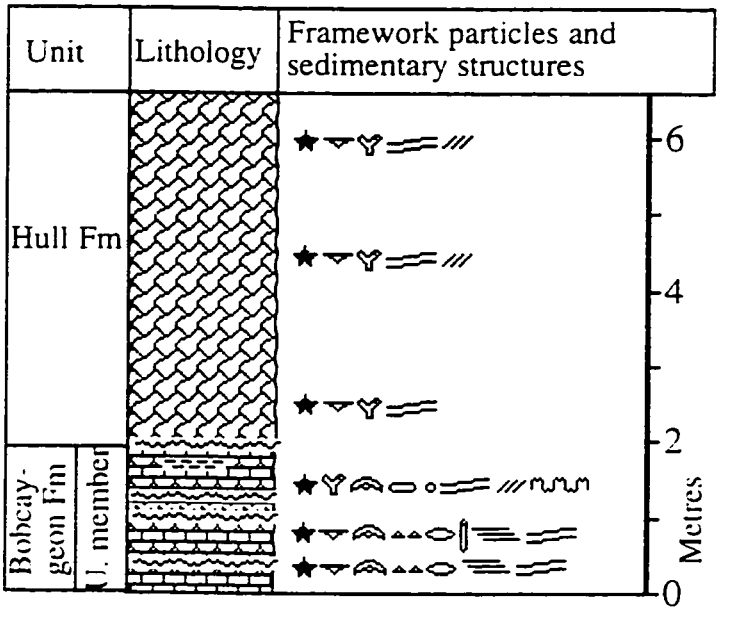
Loc. 28

Abondoned quarry in the Beechwood Cemetry, Beechwood Rd, Ottawa.



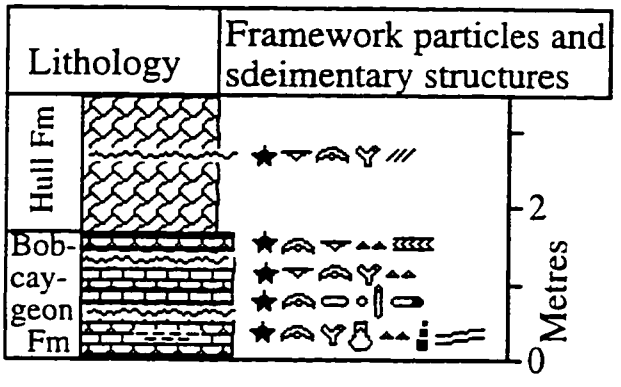
Loc. 29

Location of the section:
Redevloped old quarry at Quarry Rd. Ottawa



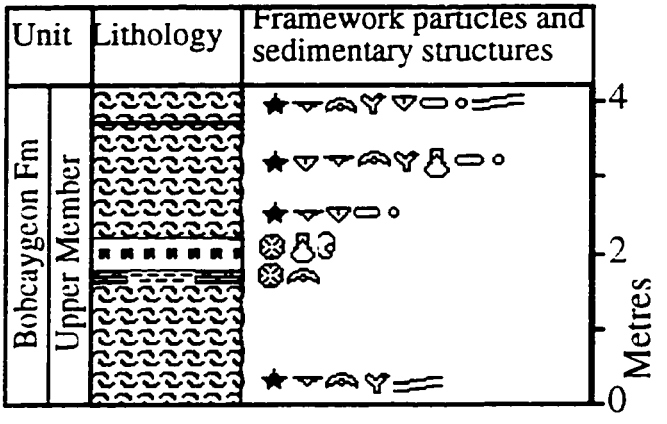
Loc. 30

Redeveloped quarry at Brittany Rd and St. Laurent Blvrd junction, Ottawa



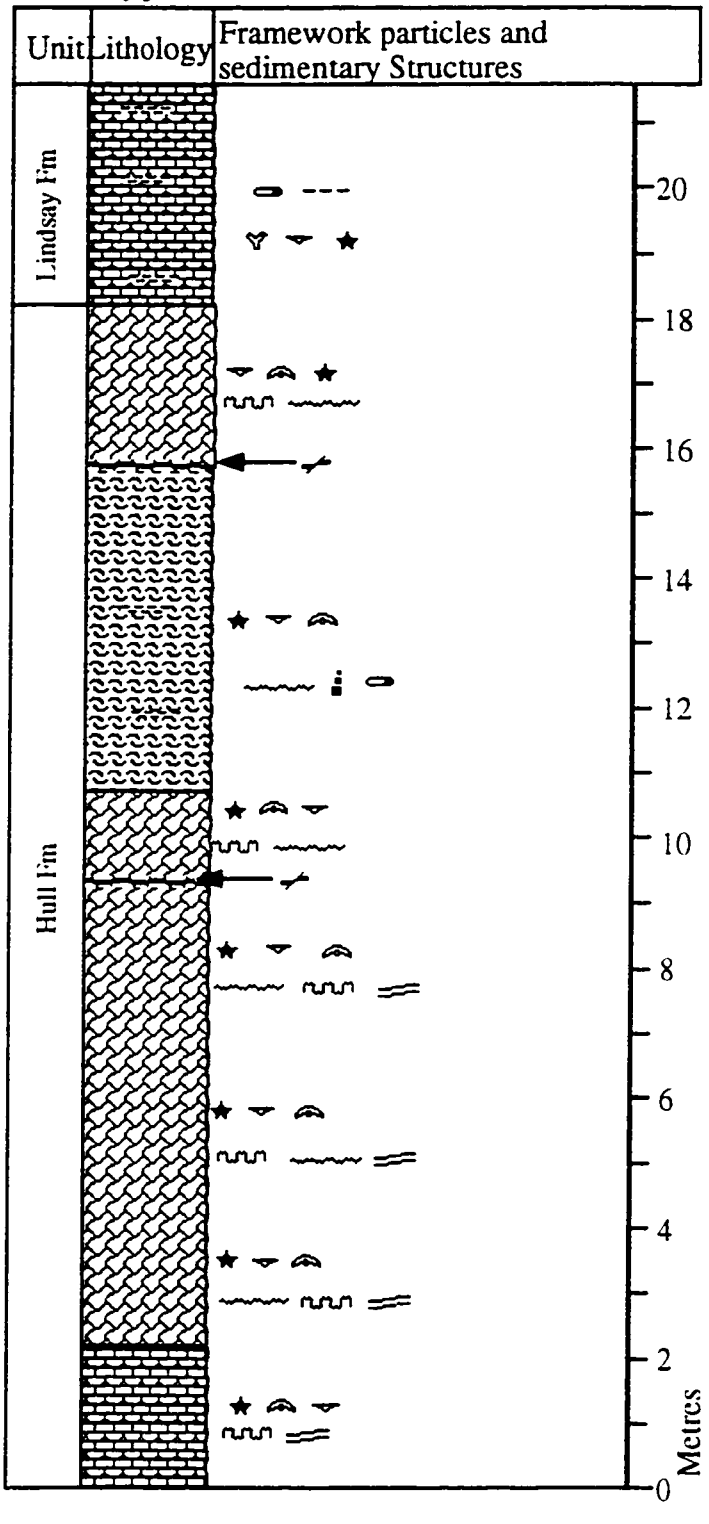
Loc. 31

Location of the section:
Road-cut at Brittany Rd, about 400 m east of the Brittany Rd - St. Laurent Blvrdjunction, in the residential area south of the Brittany Rd, Ottawa.



Loc. 32

Section location: Road-cut at Aviation Parkway, about 600 m north of the Montreal Rd - Aviation Parkway junction (northern section), Ottawa.

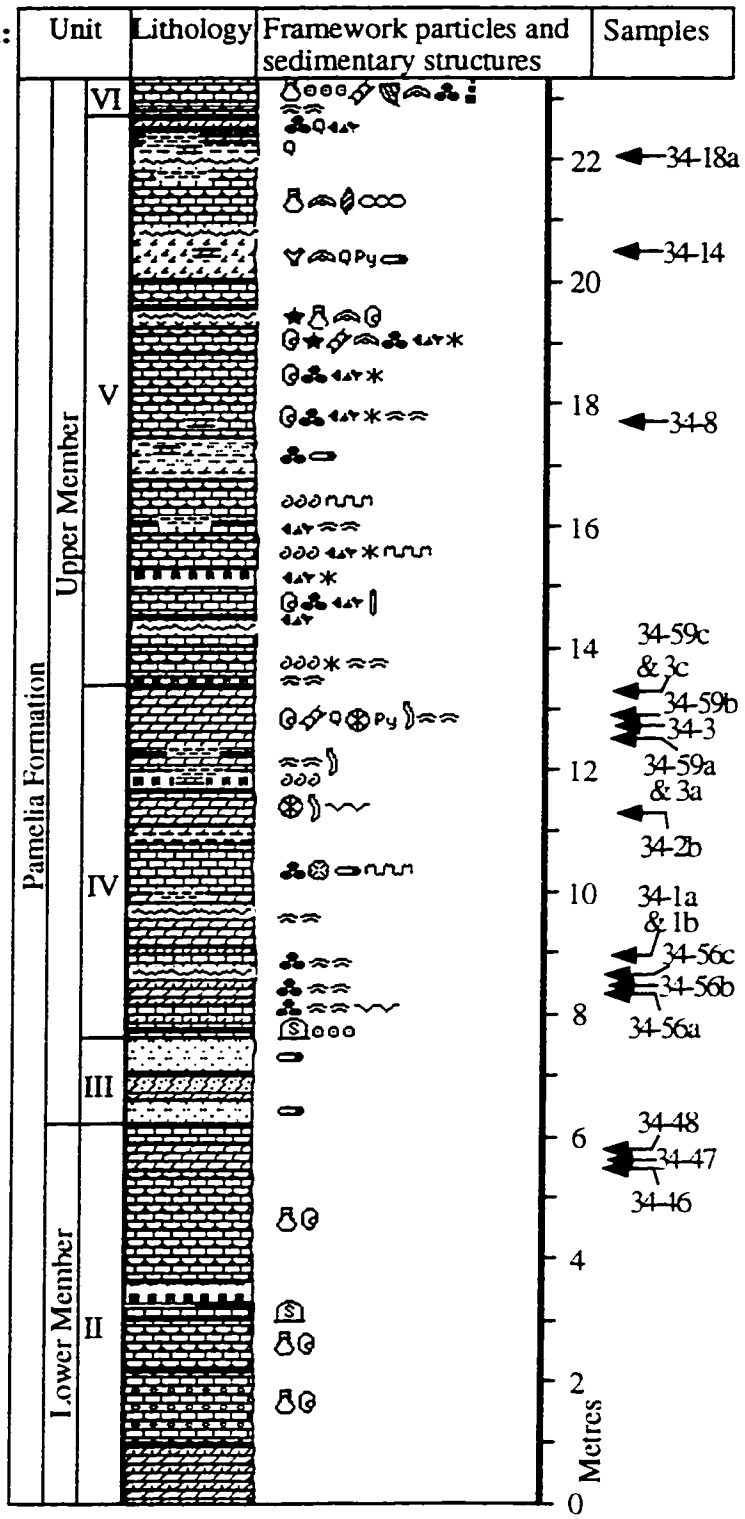


Loc. 34

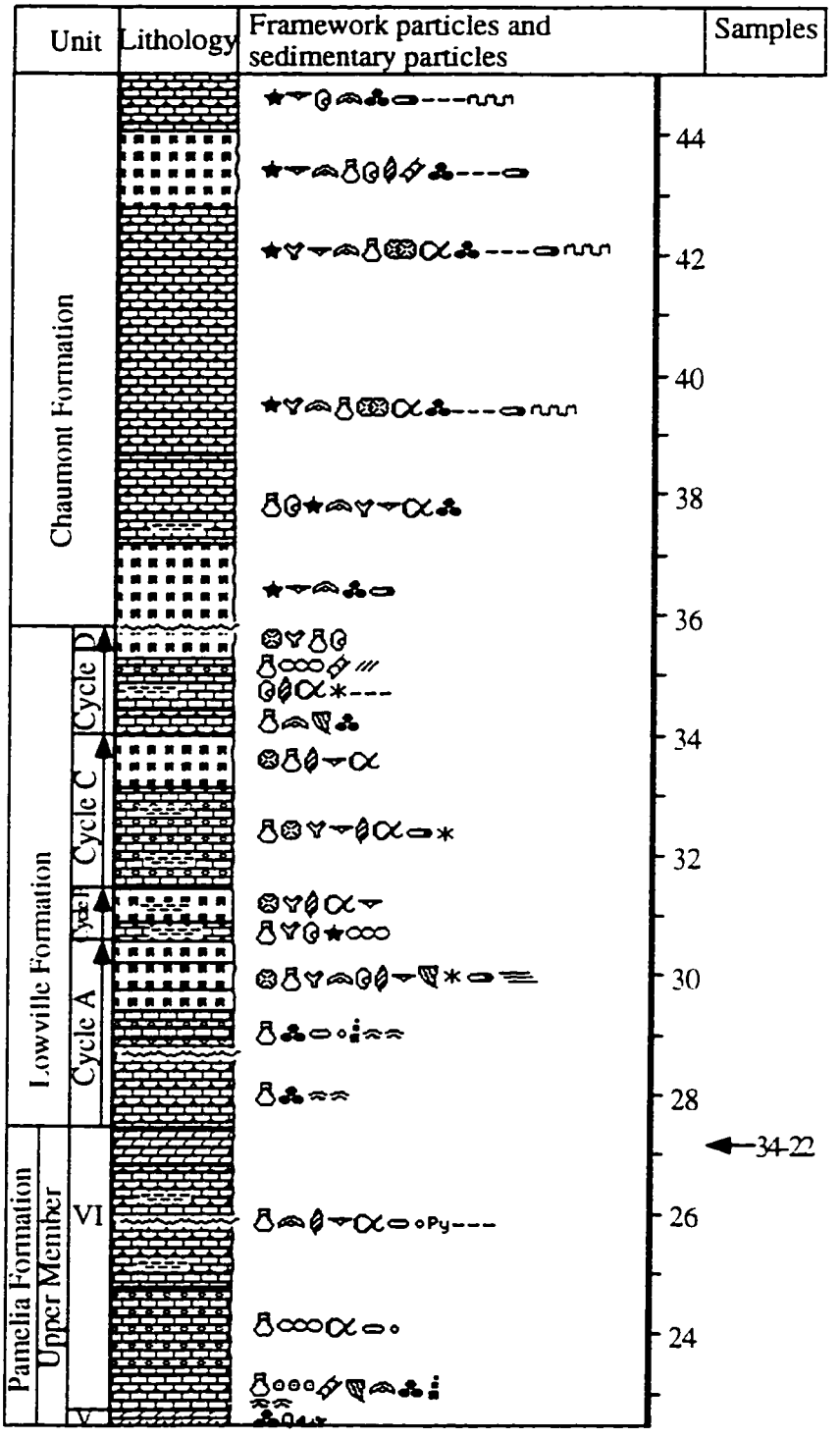
Name and location of the section:
Francon (northern) quarry at Blackburn Hamlet, Gloucester Township, Regional Municipality of Ottawa - Carleton

Company:
Francon division of Canfarge Ltd.

Reference:
Cp-22 of Limestone Industries of Ontario (1989),
LQ OT-11a of Williams (1991)



Loc. 34 Continues

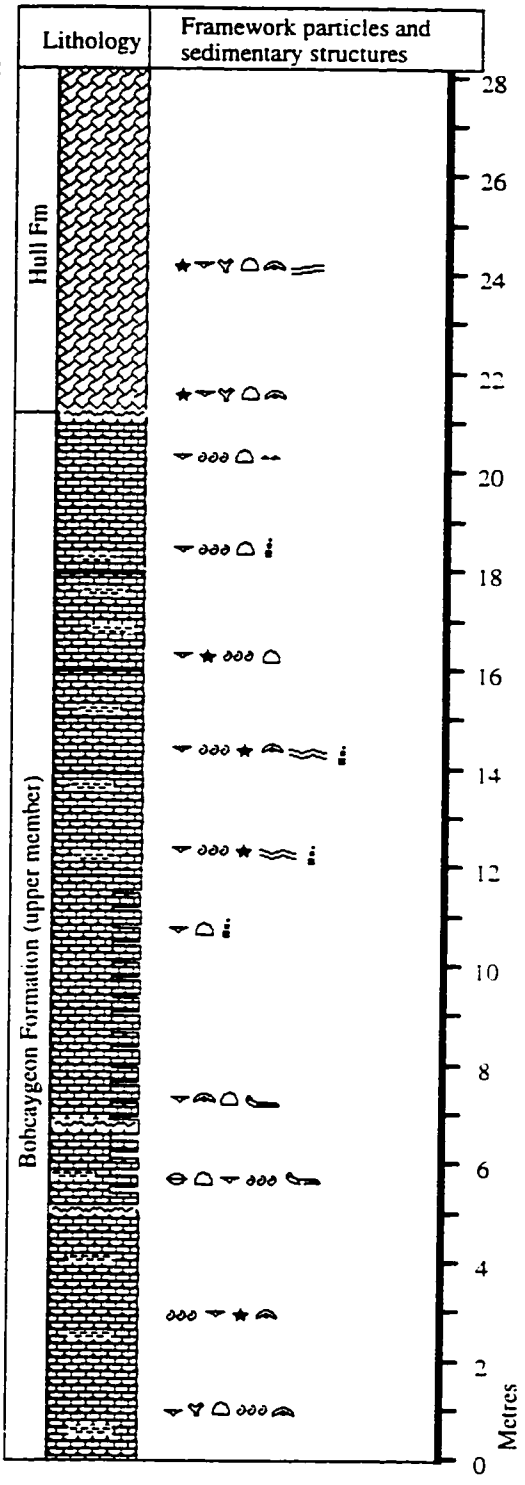


Loc. 35

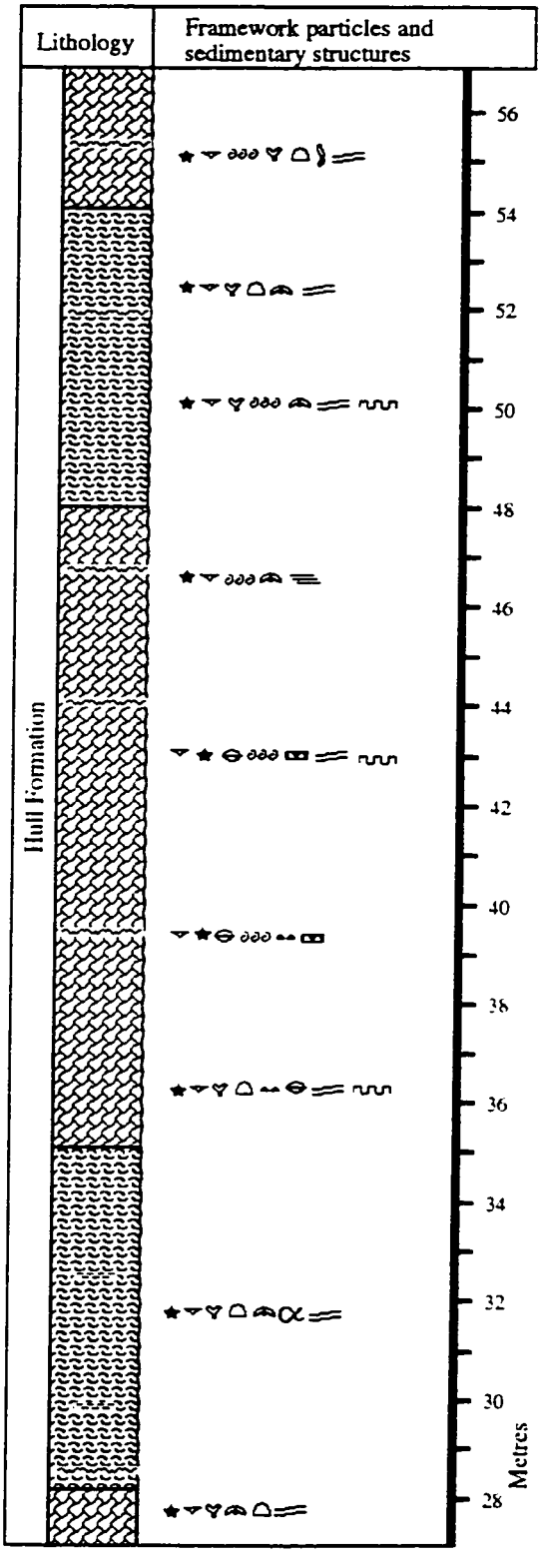
Name and location of the section:
Francon (southern) quarry at Blackburn Hamlet, Gloucester Township, Regional Municipality of Ottawa - Carleton

Company:
Francon division of Canfarge Ltd.

Reference:
Cp-22 of Derry et al. (1989).
LQ OT-11a of Williams (1991)

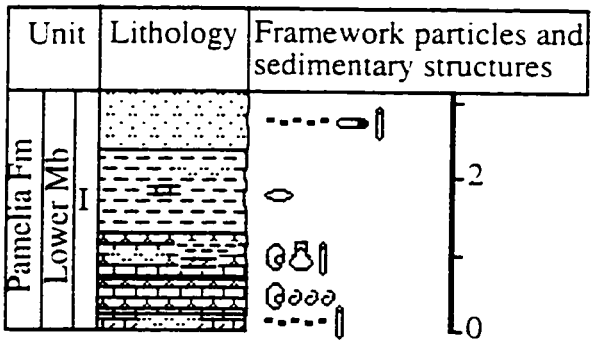


Loc. 35 cont.

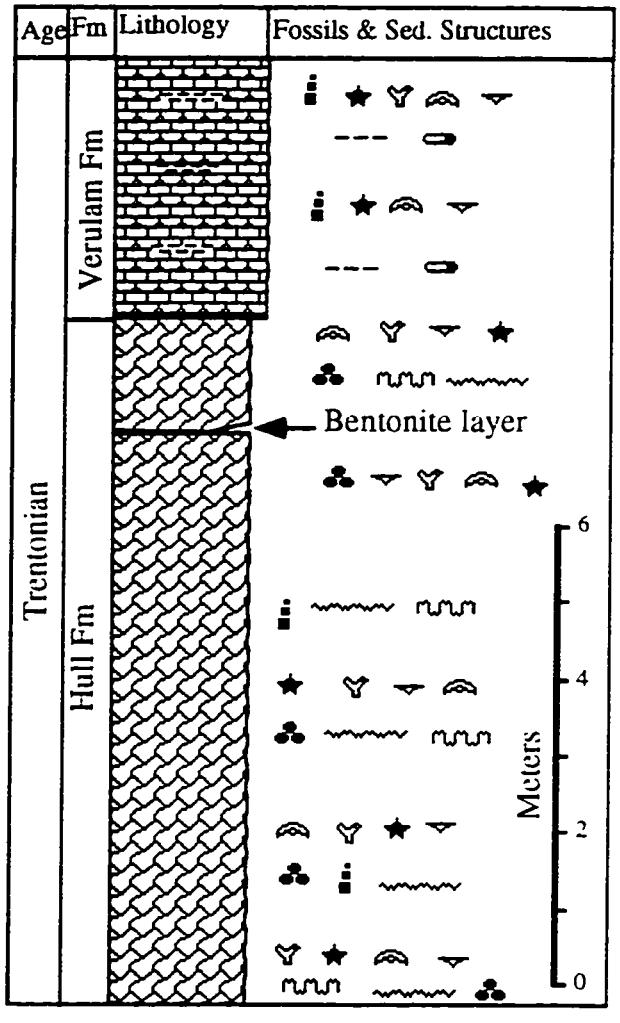

Lithology
Framework particles and sedimentary structures
Hull Formation
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
Metres

Loc. 36

Road-cut at St. Joseph Blvrd near Hart Rd, at about 3 km east of the bridge at highway 17 and Montreal road, Gloucester.

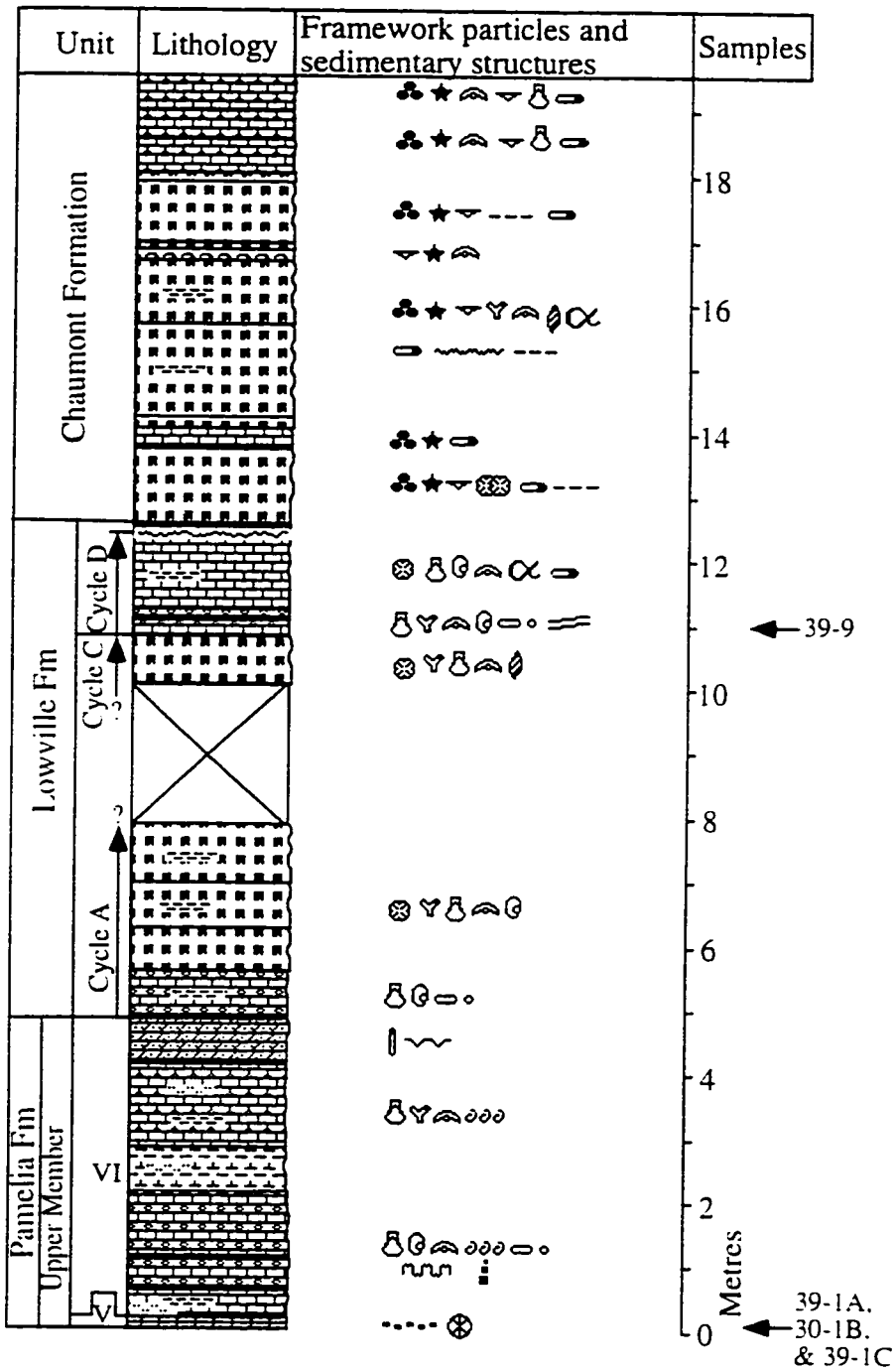


Loc. 38
Road-cut at St. Joseph/Tenth
Line intersection (Orleans)



Loc. 39

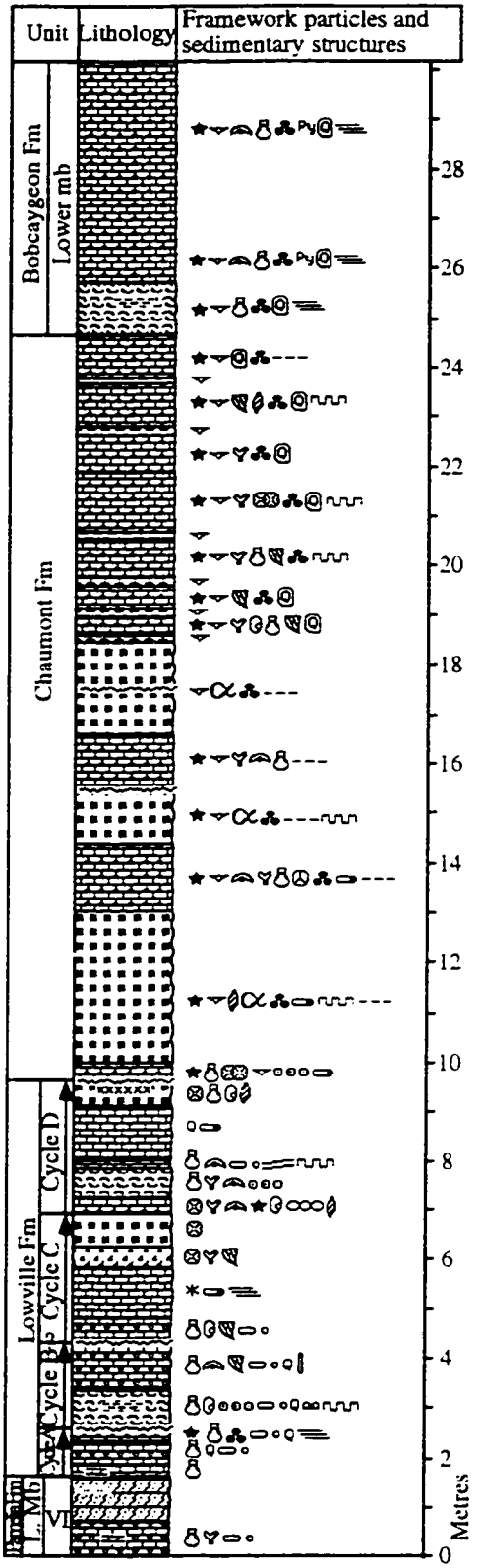
Road-cut outcrop along St. Joseph Blvd. at about 300 m east of the intersection with Tenth Line, Orleans.



Loc. 40

Name and location of the section:
Abandoned Stewart (Rockland) quarry at about 2.5 km south of Rockland town, Clarence Township, Russell County.

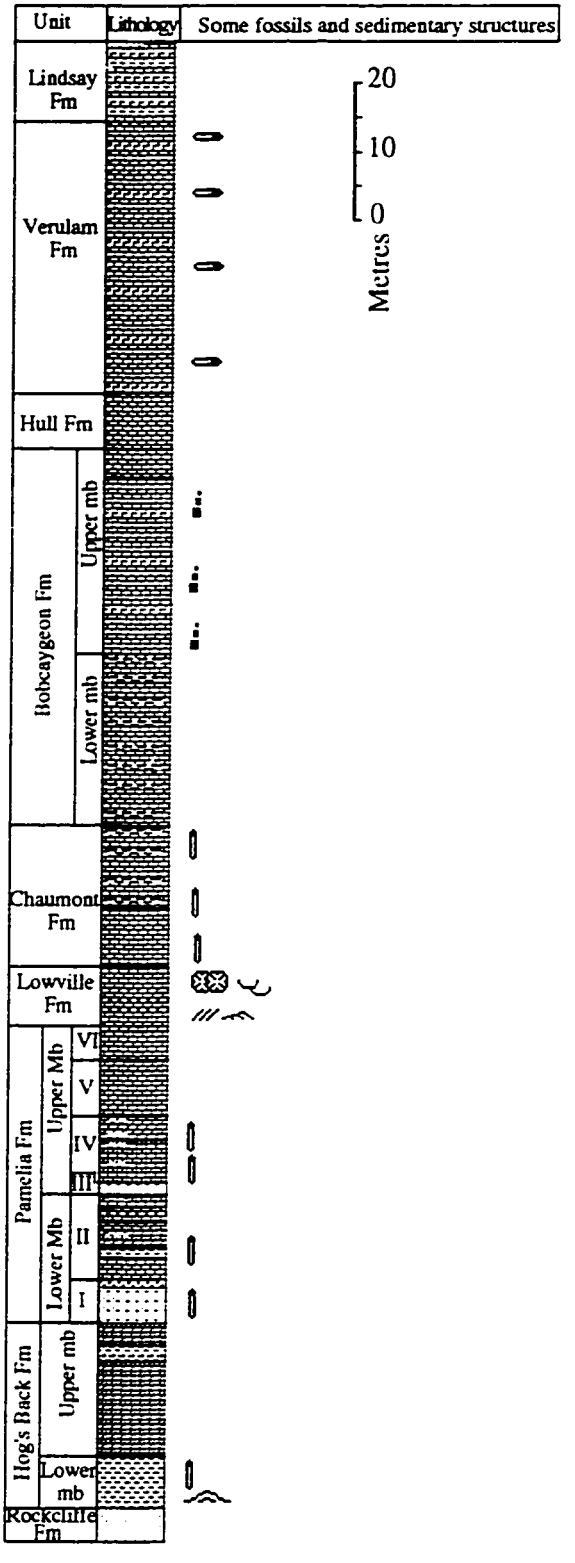
Reference:
CW-8 of Derry et al. (1989), AQ TH-1 of Williams (1991).



Loc. 41

Name and location of the section:
Russell well at the Russell County
Owned by the GSC.

Reference:
DH Ru-24 of Williams (1991)

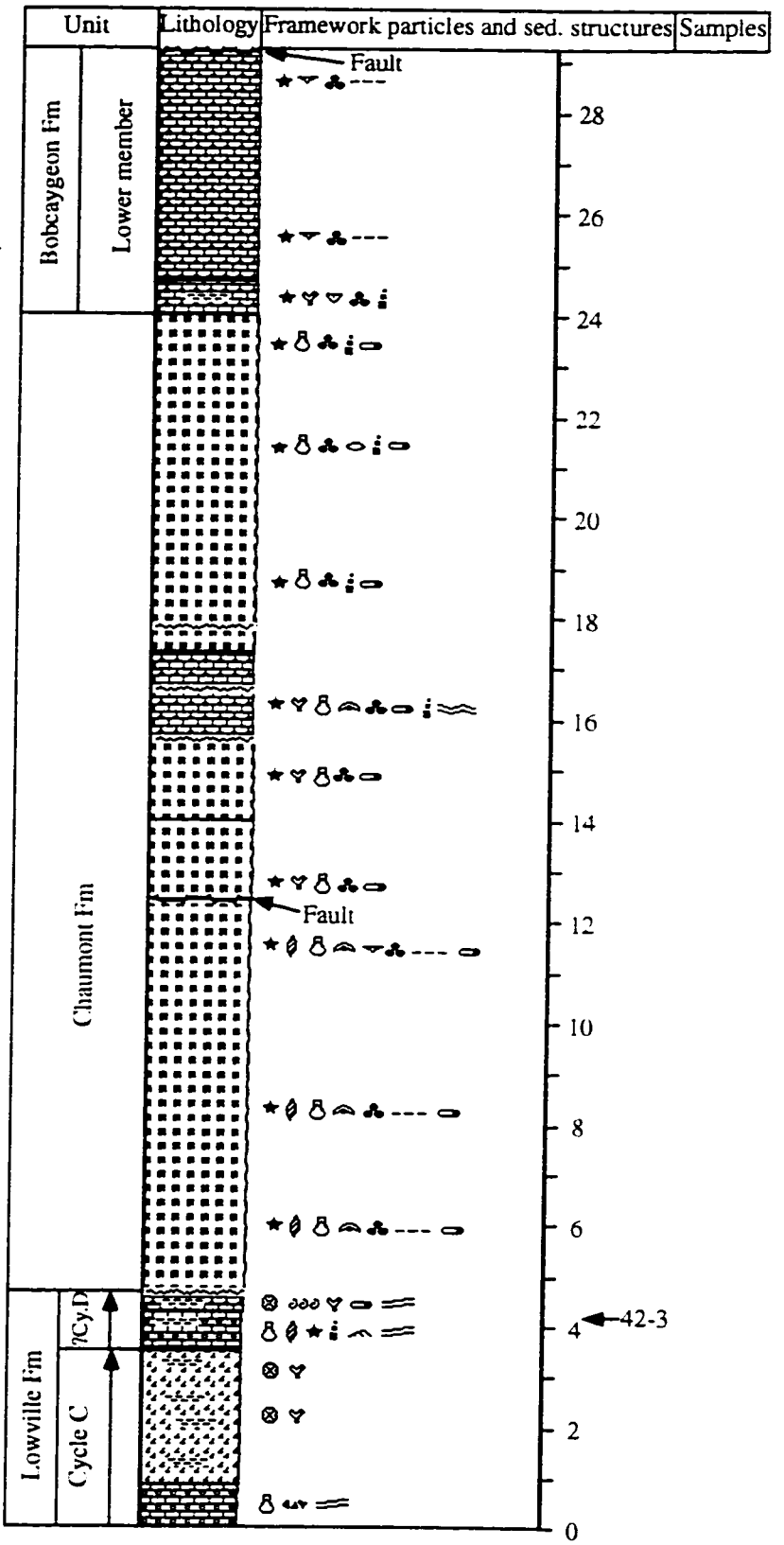


Loc. 42

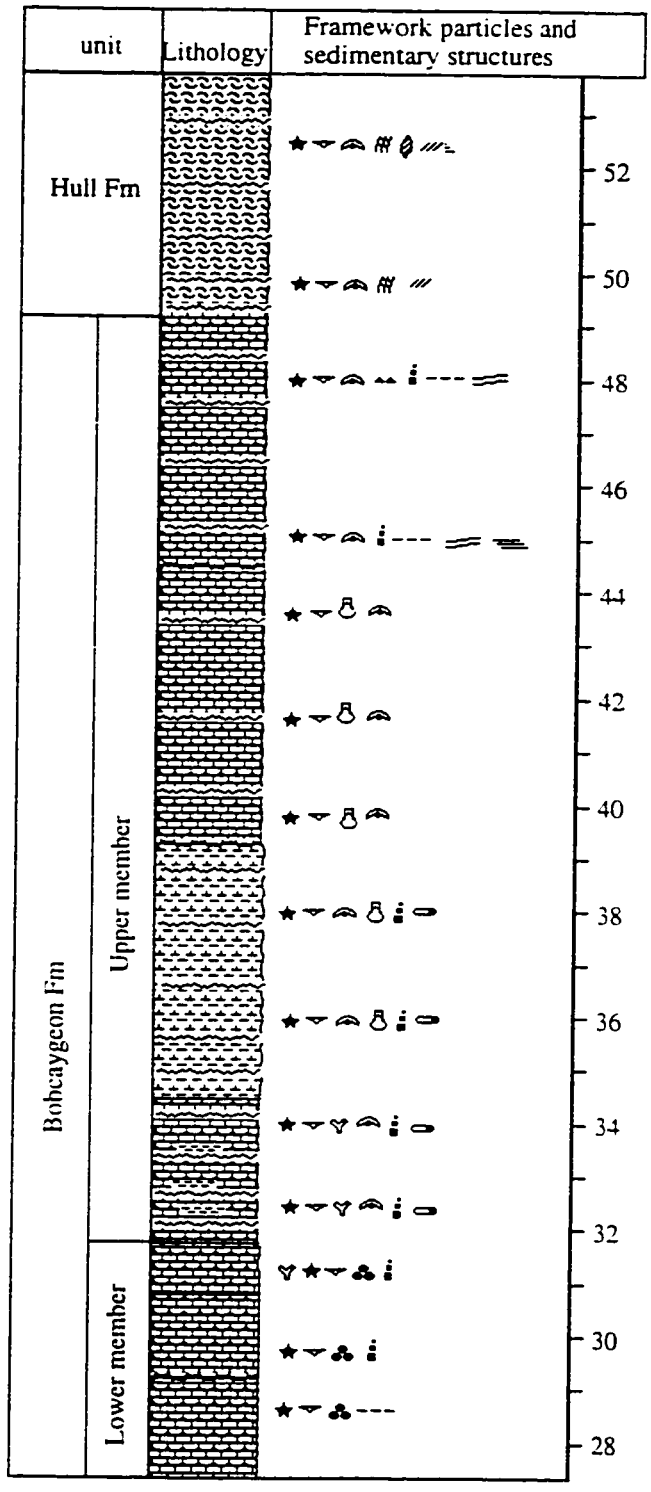
Name and location of the section:
Embrun quarry at the Embrun village, Russell Township, Russell County.

Company: A.L. Blair Construction Co. Ltd.

Reference: LQ RU-5 of Williams (1991), CW-5 of Derry et al 1989



Loc. 42 (cont.)


unit
Lithology
Framework particles and sedimentary structures
Hull Fm
Bobcaygeon Fm
Upper member
Lower member
52
50
48
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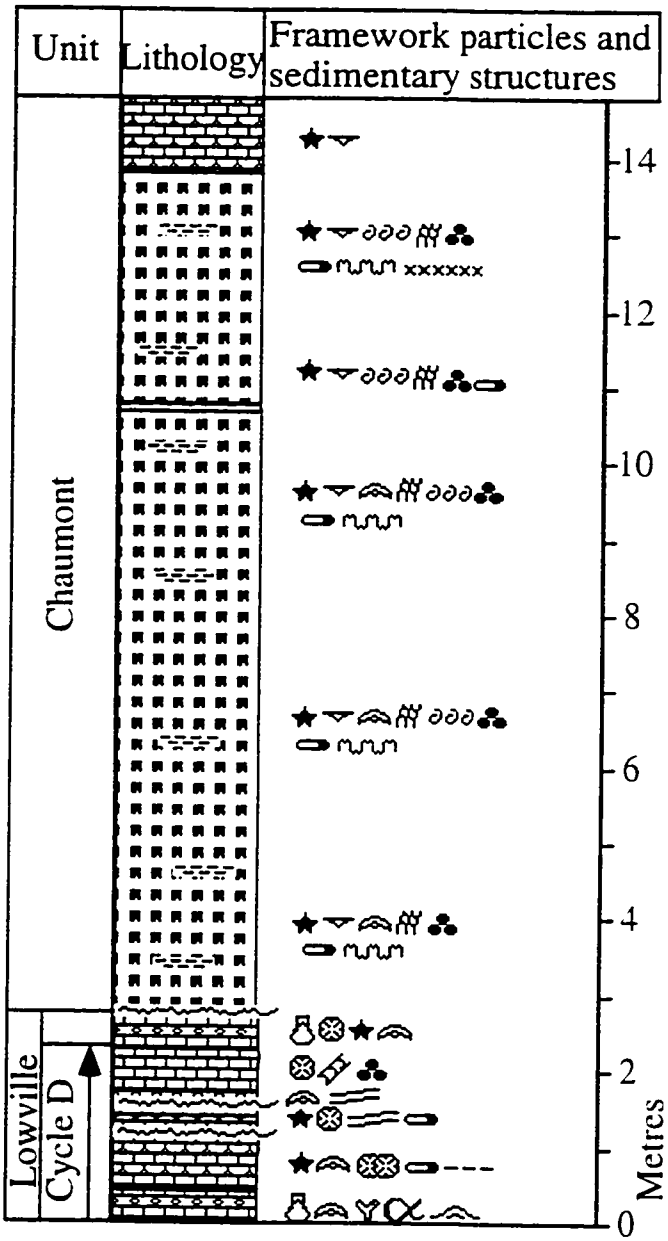
Loc. 43

Name and location of the section:
St. Albert Station quarry at about 1.5 km west of St. Albert station, Finch Township, Stormont County.

Company:
A.L. Blair Construction Co. Ltd.

Reference:
CW-4 of Derry (1989), LQ WI-3 of Williams (1991).

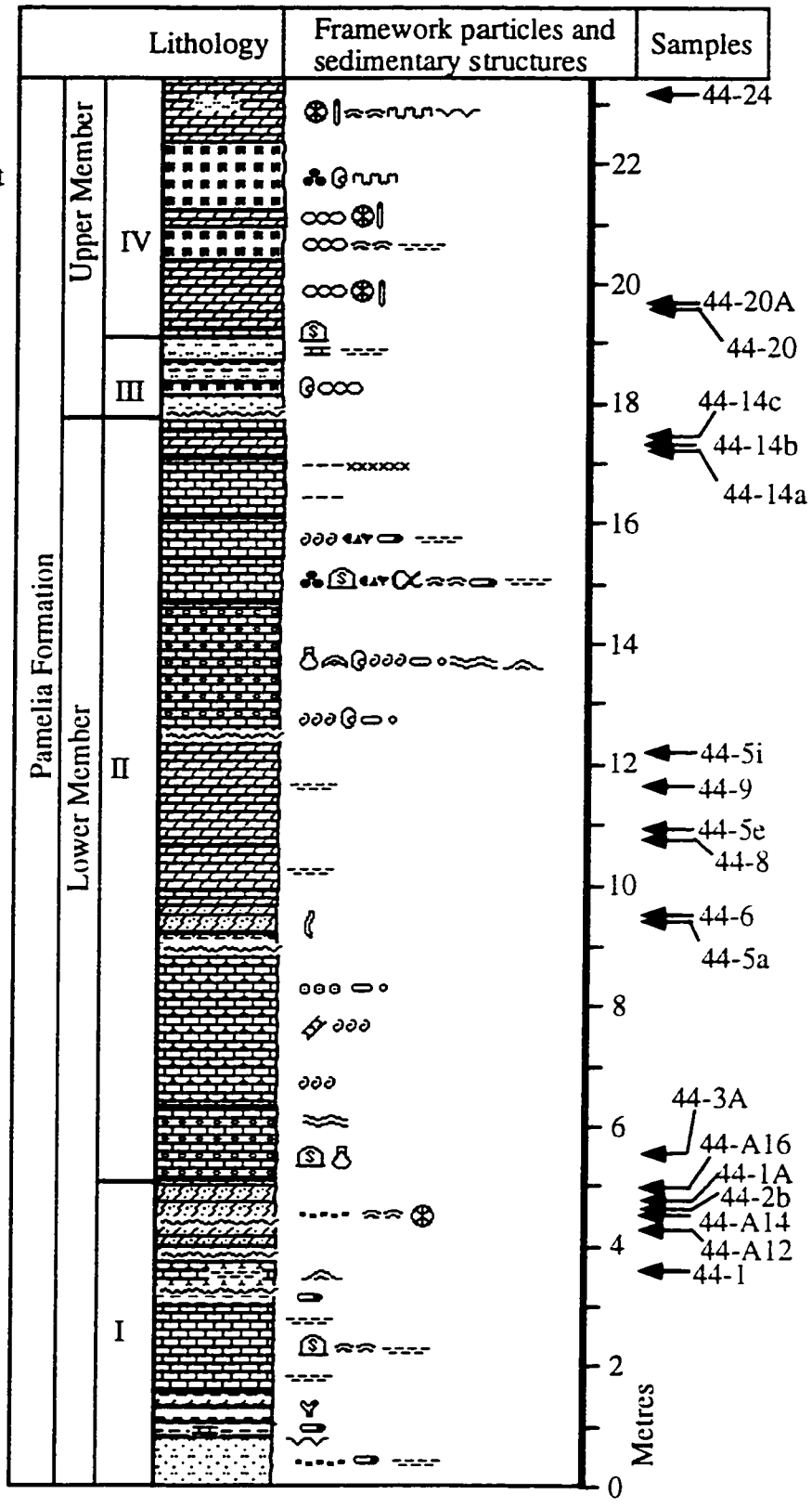


Loc. 44

Name and location of the section:
Cruickshank quarry at Winchester Springs, Williamsbourgh Township.

Company:
Cruickshank Construction Ltd.

Reference:
LQ WI-1 of Williams 1991, CW-3 of Derry et al. 1989

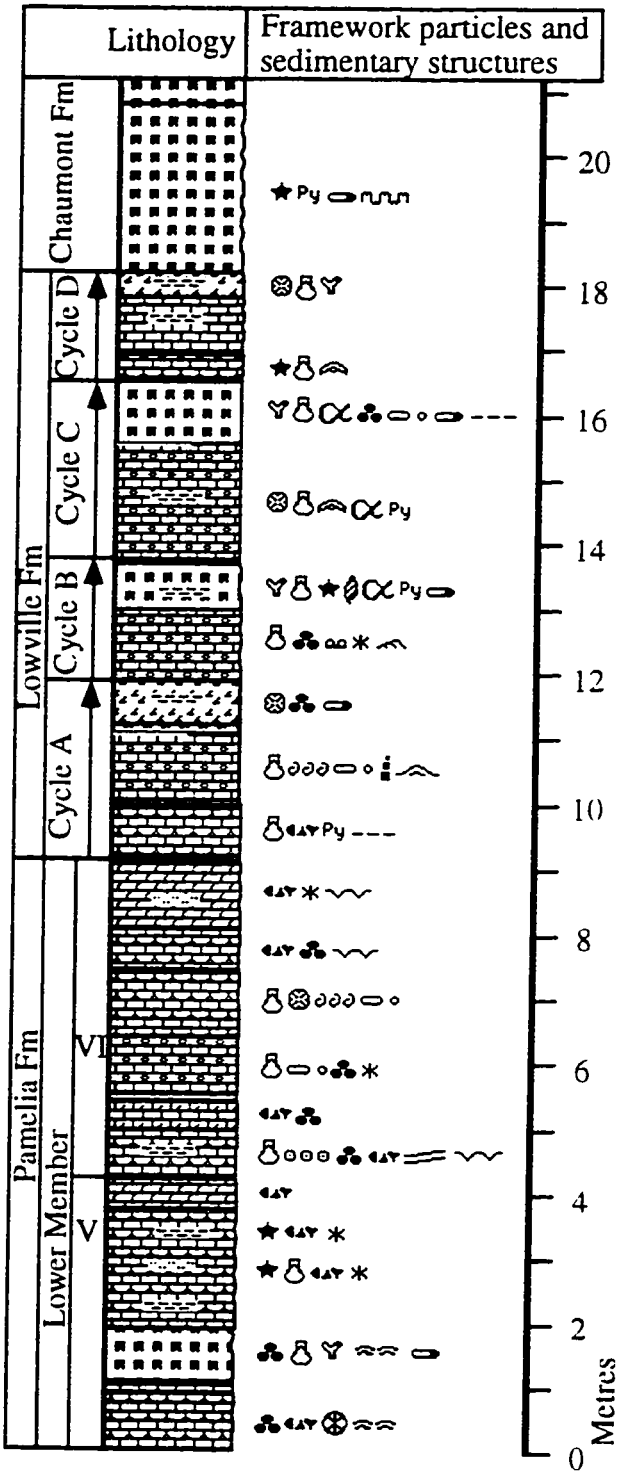


Loc. 45

Name and location:
Cornwall Quarry
near Cornwall

Company:
Permanent Concrete

Refernce:
CW-12 of Derry
et al. 1989



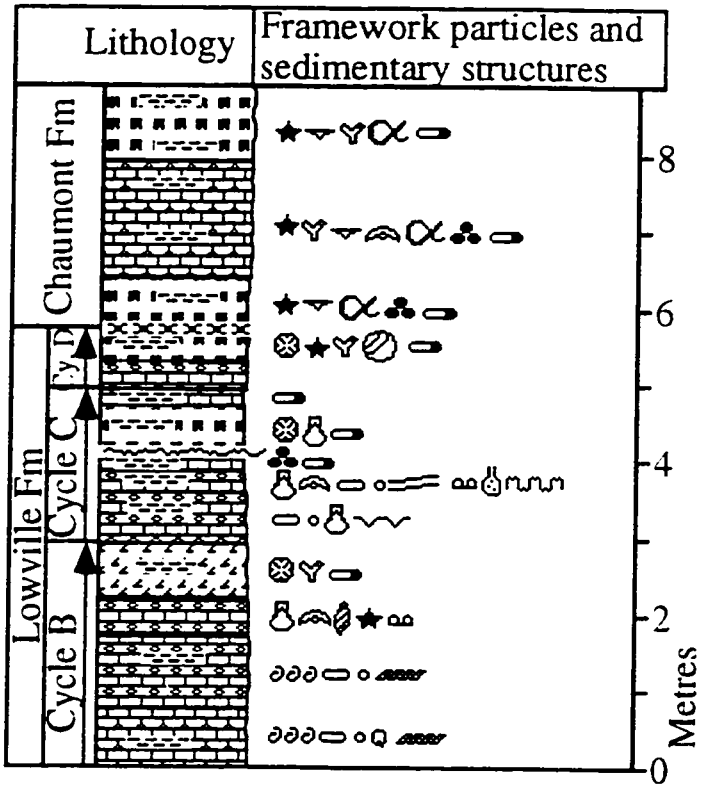
Loc. 46

Name and location of the section:

Cornwall quarry at about 6 km NW of Cornwall Township.

Company: Dibblee Construction Co Ltd.

Reference: LQ-CO-3 of Williams (1991), CW-13 of Derry et al. (1989)

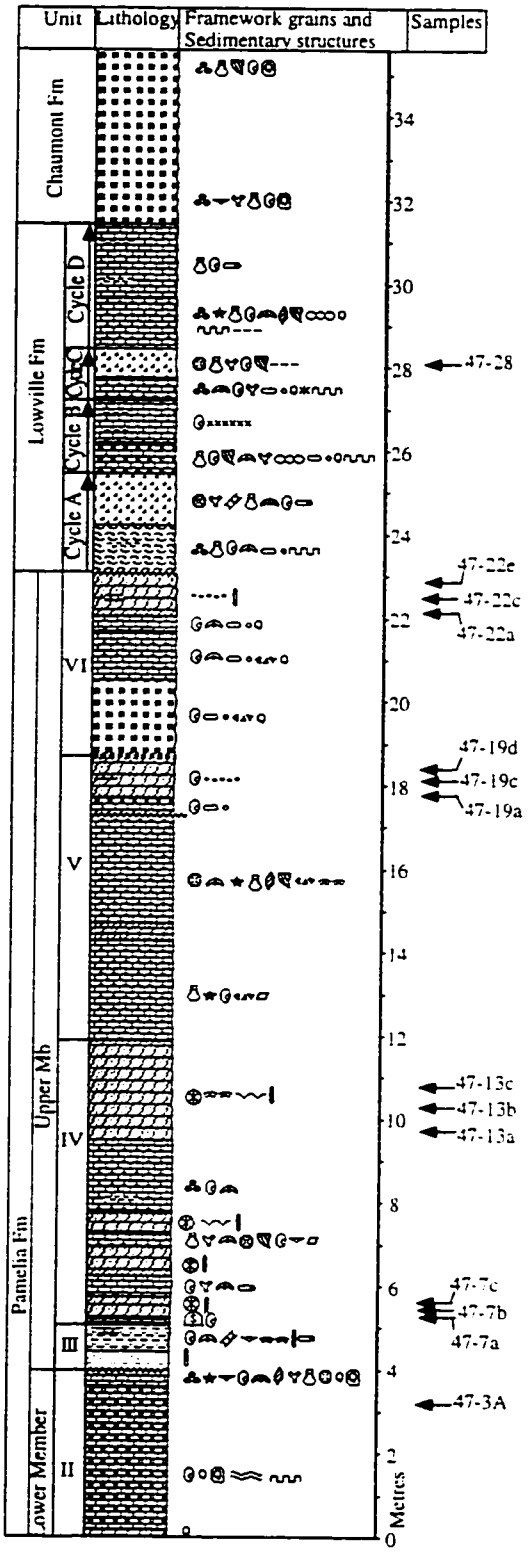


Loc. 47

Name and location of the section:
Macleod quarry at about 5 km north of Cornwall, Cornwall Township, Stormont County.

Company:
Cornwall Gravel Company Ltd.

Reference:
CW-14 of Derry et al. (1989).
LQ CO-1 of Williams (1991)

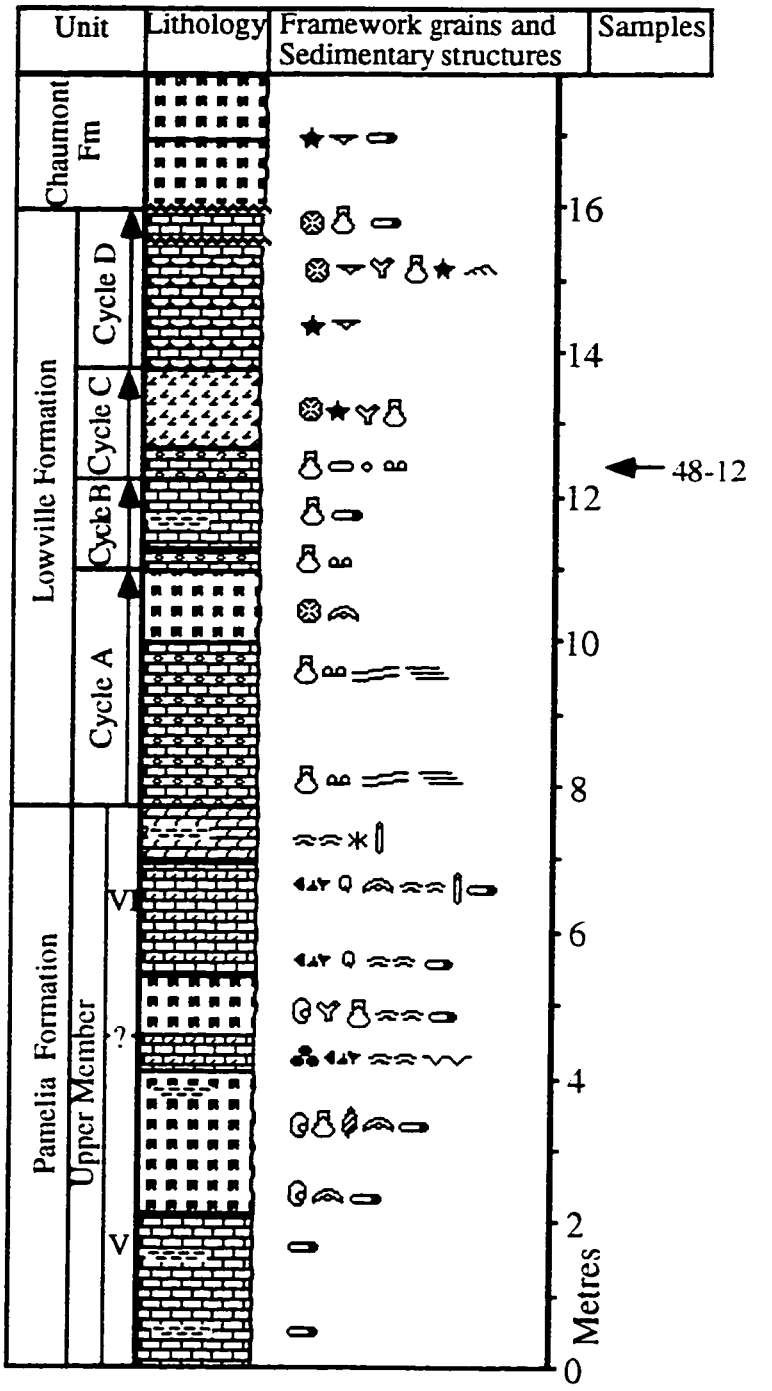


Loc. 48

Name and section location:
Green Valley quarry at about one km north of Pine Hill, Lancaster Township Glengarry County.

Company:
Cruickshank Construction Ltd.

Reference:
CW-27 of Derry et al. (1989), LQ CO-6 of Williams (1991).

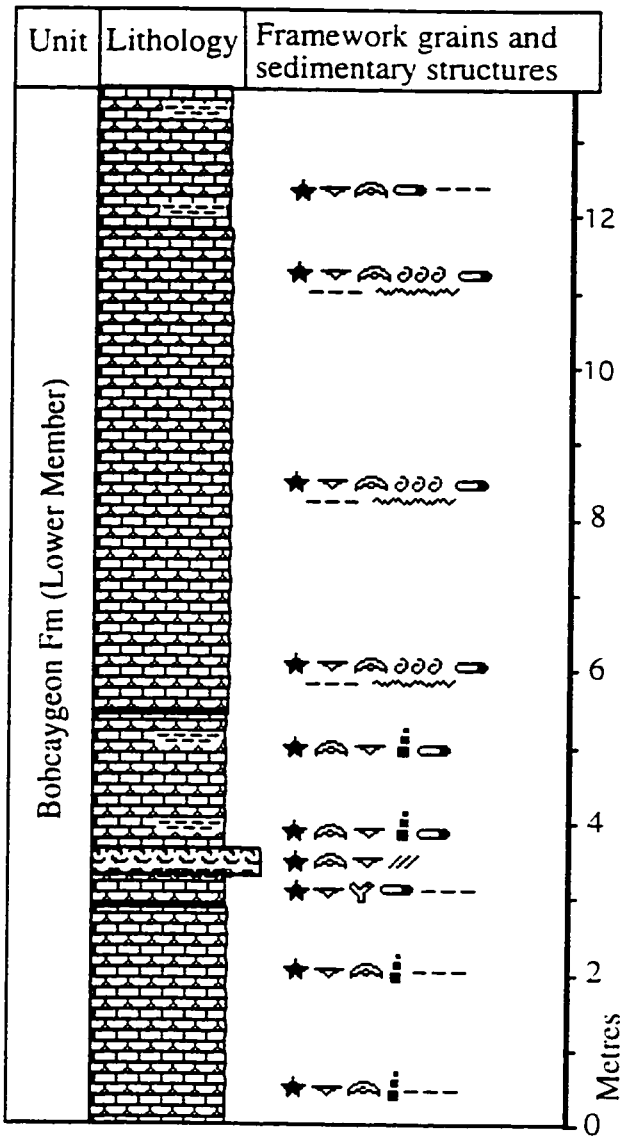


Loc. 49

Name and location:
Duval Quarry at about 6 km east of the village of Dunvegan

Company:
A.L. Blair Construction Company Ltd.

Reference:
CW-26 of Derry et al. 1989

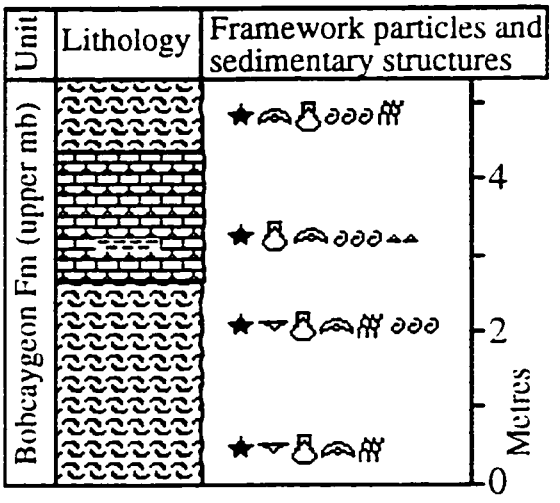


Loc. 50

Name and location of the section:
Gauther quarry at about 8 km east of St. Isidore de Prescott, Caledonia Township, Prescott County

Company: Cruickshank Construction Ltd.

Reference: CW-25 of Derry et al. (1989).

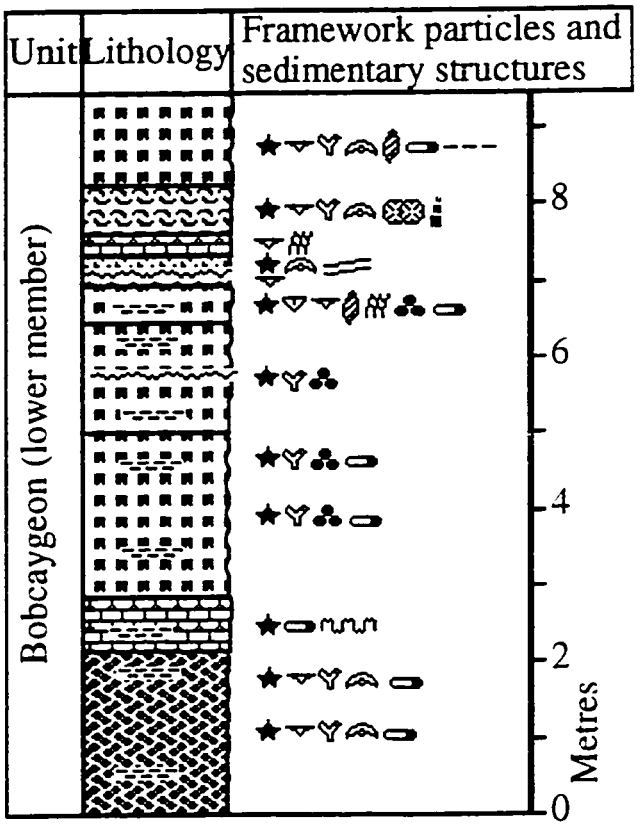


Loc. 51

Name and location of the section:
Leroux (Skye) quarry at 6 km soth of the Bernardin village, Caledonia Township, Prescott County.

Company: Sintra Inc.

Reference: CW-24 of Derry et al. (1989)

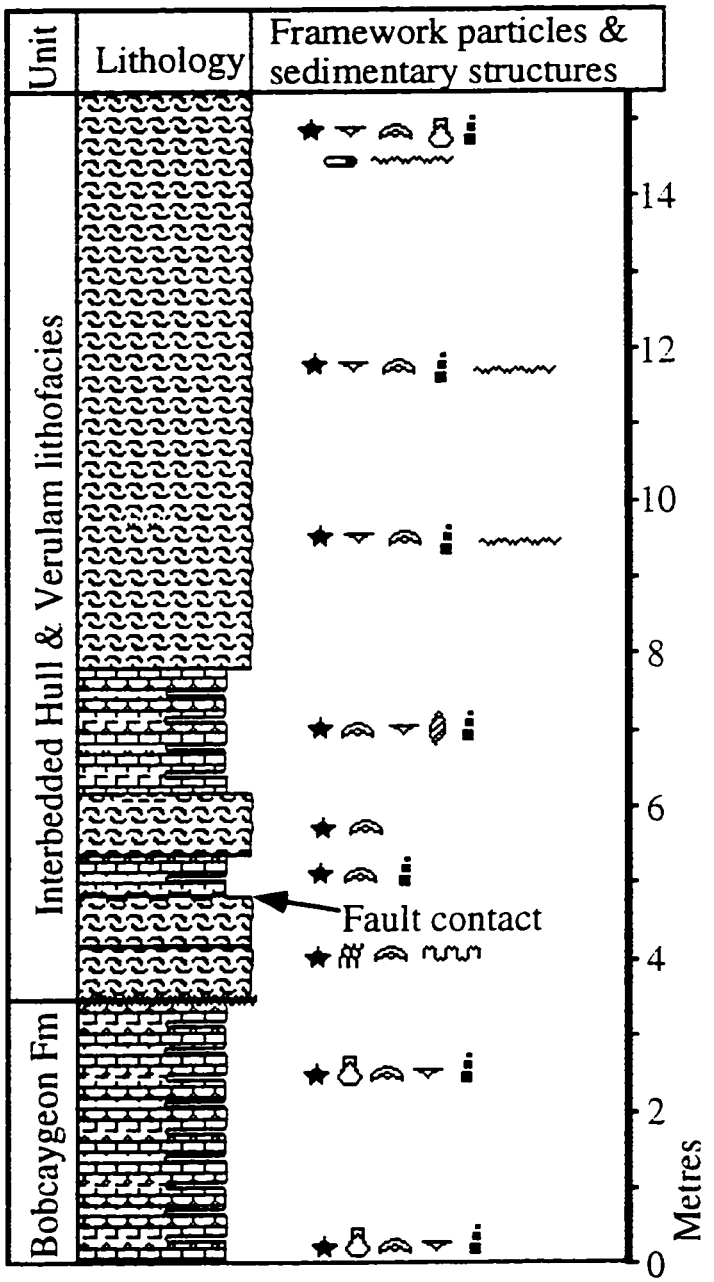


Loc. 52

Name and location of the section:

Cliftondale (McAlpine) quarry at about 7 km west of the Vankleek Hill town, Caledonia Township, owned by Dale and Clare.

Reference: CW-23 of Derry et al. (1989).

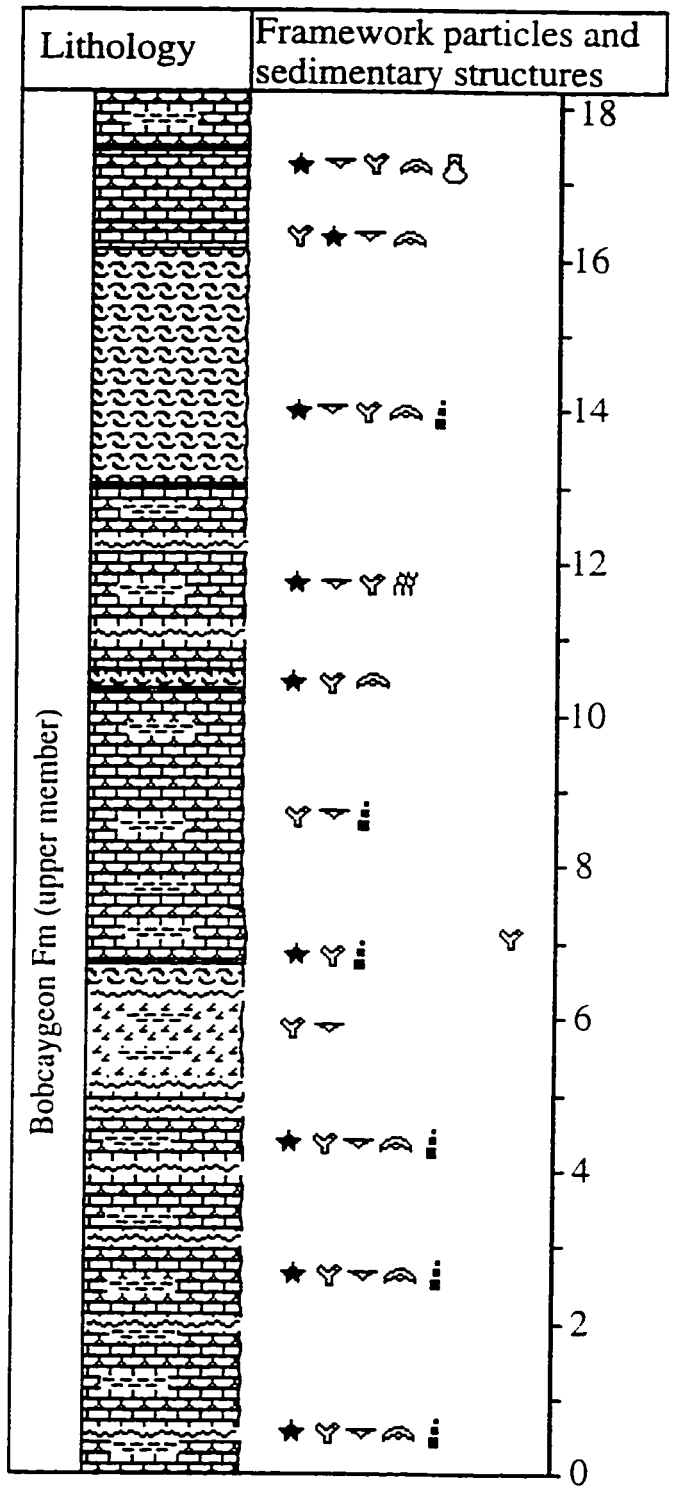


Loc. 53

Name and location of the section:
L'Original quarry at about 5 km west of the L'Original Village, Longueuil Township.

Company: Bertrand & Freres Construction Co. Ltd.

Reference:
CW-21 of Derry et al. 1989



Appendix 2

This appendix shows the results of the microprobe analysis on various calcite cements. Analyzed elements include Fe, Mg, Mn, Na, and Sr. Detection limits of these elements are: 400 ppm for Fe, 100 ppm for Mg, 300 ppm for Mn, 100 ppm for Na, and 150 ppm for Sr. The value 0 means below detection limit. Samples are assigned with three numbers (e.g., 48-12-20, sometimes the middle number is accompanied by a letter, like 47-3A-15). The first number represents section (or location) number, the second number (with letter) is the sample number and the last number represents the analyzed point number. For major elements, analyses are accurate to ± 1-2%. For minor or trace elements, relative error increases to ± 50% as the minimum detection limit is approached

Appendix 2a

Results of microprobe point analysis for the prismatic calcite cement

Sample	Fe(ppm)	Mg(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
27-13-1	0	2955	0	0	0
27-13-2	0	1568	0	0	0
27-13-5	0	3739	0	0	0
27-13-6	0	181	0	0	846
27-13-11	0	3859	0	0	169
27-9-4	1166	2834	310	223	254
27-9-8	1243	3377	0	148	0
27-9-9	699	1749	0	0	254
27-9-10	1010	2653	387	0	0
17-2-1	0	5427	0	0	0
17-2-10	0	2291	0	0	0
17-2-11	0	482	0	0	0
17-2-12	0	1447	0	0	1353
16-10-7	855	3739	0	0	169
16-10-8	0	784	0	0	169
16-10-11	855	3377	0	0	0
12.-10-1	0	5005	0	0	0
12.-10-2	0	3437	0	0	254
12.10-3	0	4402	0	0	0
12.-10-12	0	2291	0	0	169
12.-10-13	0	1809	0	0	2537
42--3-14	777	2171	0	0	1522
42-3-15	0	302	0	0	2621
48-12-5	0	1688	0	0	2283
48-12-6	0	965	0	0	0
48-12-7	0	844	0	0	1099
48-12-14	0	2774	0	0	592
48-12-20	0	2472	0	0	761
24-14-9	699	2231	0	0	0
24-14-15	0	1628	0	0	254

Appendix 2b

Results of microprobe point analysis for the fibrous calcite cement

Sample	Fe(ppm)	Mg(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
27-13-7	0	5005	0	0	254
27-13-8	0	4583	0	0	0
16-10-1	0	3437	0	0	254
16-10-2	622	2653	0	0	592
16-10-5	544	4884	0	0	169
16-10-6	544	4161	0	0	0
16-10-13	932	5186	0	0	0
16-10-14	0	5487	0	0	0
12.-10-4	544	3799	0	148	169
12.-10-5	0	3437	0	148	507
12.-10-6	0	1085	0	148	1776
12.-10-8	0	3618	0	0	423
12.-10-9	0	2834	0	0	1015
42-3-1	0	5548	0	0	423
42-3-2	0	1025	0	0	761
42-3-9	0	3678	0	0	169
42-3-10	0	1025	0	0	507
24-14-1	0	2593	464	148	169
24-14-2	0	3377	0	0	0
47-3A-11	0	3196	0	148	0
47-3A-12	1166	4161	0	223	3636
47-3A-16	1166	2533	310	148	338

Appendix 2c

Results of microprobe point analysis for the blocky calcite cement

Sample	Fe(ppm)	Mg(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
42-3-3	1399	724	0	0	0
42-3-4	0	2834	0	0	0
42-3-5	0	3015	310	445	0
42-3-6	0	2894	0	0	254
42-3-7	0	2774	0	0	254
42-3-8	0	3497	0	0	592
42-3-11	0	724	0	0	761
42-3-12	0	1749	0	0	0
42-3-13	0	3558	0	0	0
42-12-3	0	2533	0	0	169
48-12-4	0	2714	0	0	0
48-12-8	0	1387	0	0	2537
48-12-9	0	905	0	0	0
48-12-10	0	603	0	0	0
48-12-11	0	482	0	0	1691
48-12-12	0	1266	0	0	507
48-12-13	0	1628	0	0	2283
48-12-18	544	4402	0	0	254
48-12-19	0	4764	0	0	507
48-12-24	0	1628	0	0	423
48-12-21	0	1387	0	0	3636
48-12-22	0	1447	0	0	3890
48-12-23	0	482	0	0	3636
27-13-3	0	3799	0	0	0
27-13-4	0	3437	0	0	338
27-13-9	0	3377	0	0	338
27-13-10	0	2171	0	0	0
27-13-12	0	1327	0	0	338
27-13-13	0	2834	0	bdl	0
27-9-1	622	4824	0	223	423
27-9-2	0	663	0	148	423
27-9-3	932	1990	0	0	0
27-9-5	622	1809	0	148	423

Appendix 2c cont.

Sample	Fe(ppm)	Mg(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
27-9-6	0	1628	0	0	254
27-9-7	0	3497	0	0	0
17-2-2	0	3739	0	0	0
17-2-3	0	422	0	0	1776
17-2-6	0	3256	0	0	0
17-2-7	0	3497	0	0	0
17-2-8	0	3920	0	0	0
17-2-9	0	3317	0	0	0
16-10-3	0	3075	0	0	254
16-10-4	0	5608	0	0	0
16-10-9	0	3377	0	0	0
16-10-10	0	3015	0	0	0
16-10-12	3807	3799	387	0	0
12-10-7	0	2231	0	4007	1353
12-10-10	0	1930	0	148	1015
12-10-11	0	2593	0	0	761
12-10-14	0	2894	0	0	0
12-10-15	0	2955	0	0	0
12-10-16	0	2412	0	0	0
12-10-17	0	1749	0	0	0
12-10-18	0	2352	0	0	0
12-10-19	0	3075	0	0	0
44-1-14	0	9708	0	0	761
44-1-17	0	6211	0	0	592
24-14-3	3730	4281	1316	0	0
24-14-4	2720	3317	1006	0	0
24-14-5	2953	3739	1393	148	0
24-14-6	1010	2352	310	0	338
24-14-7	1399	3136	0	0	169
24-14-8	1943	3256	542	0	0
24-14-14	0	1628	929	0	507
47-3A-13	932	3015	310	223	1860
47-3A-14	1321	2894	0	0	930
47-3A-15	2953	4945	542	0	0
47-3A-17	1399	1508	0	148	1691

Appendix 2c cont.

Sample	Fe(ppm)	Mg(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
44-1-15	2875	3678	310	0	0
44-1-16	466	7115	0	0	507
44-1-18	2564	2834	619	0	0
44-1-19	2564	2111	310	0	761
44-1-23	2486	3739	387	0	0
44-1-24	2331	3317	464	0	0
44-1-25	3497	3317	542	0	0

Appendix 3

This appendix shows results of the geochemical (major and trace elements, as well as $\delta^{18}O$ and $\delta^{13}C$ analyses of the thick dolomite beds in the Pamelia Formation. Relative Standard Deviation for the major and trace elements is 2%. However, contamination of sodium is noticed. Standard deviation for the $\delta^{18}O$ and $\delta^{13}C$ is ± 0.10 ‰.The samples are numbered with two numbers.. A letter usually accompanies the second number (e.g., 47-13c). The first number represents section or location number whereas the second number with (or without) a letter is the sample number. If two or more samples carry the same number but different letters (e.g., 34-56a, 34-56b, and 34-56c), it means that these samples are collected from the same unit but from different points (e.g., bottom, middle, and top) within that unit. There are three samples from locality 44 (44-A12, 44-A14, & 44-A16). These samples are from the lower part of the quarry which has been developed after my first mapping of the quarry. I denoted 44-A for this lower part of the section and the numbers following the letter are the sample numbers.

Appendix 3a

Results of the geochemical analysis of the dolostone samples from the Pam

Sample No.	CaCO3(%)	MgCO3(%)	Fe(ppm)	Mn(ppm)	Na(ppm)	Sr(ppm)
47-22e	73.5	26.5	21274	490	531	648
47-22c	68.2	31.8	17611	499	599	418
47-22a	76.2	23.8	30124	472	1070	585
47-19d	91.4	8.6	11940	375	592	536
47-19c	77.5	22.5	23243	467	649	506
47-19a	90.4	9.6	14478	324	1584	717
47-13c	77.1	22.9	16849	387	1125	474
47-13b	64.8	35.2	12811	450	862	315
47-13a	71.3	28.7	18128	517	1194	446
47-7c	62.0	38.0	16748	575	1200	307
47-7b	59.9	40.1	14085	616	766	268
47-7a	59.4	40.6	14531	625	2140	311
44-24	76.2	20.7	30900	954	450	575
44-20	67.6	25.0	74000	1625	618	4120
44-14c	80.2	19.8	14593	1111	579	468
44-14b	59.5	40.5	32461	1253	1119	280
44-14a	61.9	38.1	19513	1232	433	448
44-5i	61.6	38.4	9364	583	976	317
44-9	68.2	31.8	19772	1577	1234	801
44-5e	60.5	39.5	10067	587	478	269
44-5a	60.4	39.6	11754	667	1293	239
44-8	65.7	34.3	25539	1896	1000	749
44-6	71.8	26.5	17600	1644	660	692
44-A16	62.7	37.3	14835	927	1574	262
44-A14	60.9	39.1	17220	1025	2871	354
44-2b	68.9	27.2	39600	2699	911	657
44-A12	70.7	29.3	11581	855	972	324
34-22	70.6	29.4	19945	648	2361	345
34-18a	74.0	26.0	49241	807	2151	486
34-18	48.6	51.4	146464	1156	1093	1457
34-14	66.8	33.2	19460	595	1353	369
34-59c	59.6	40.4	26995	640	926	865
34-59b	60.2	39.8	21624	650	624	1829
34-3	70.0	25.3	46800	1489	916	680

Appendix 3a continues

Sample No.	CaCO3(%)	MgCO3(%)	Fe(ppm)	Mn(ppm	Na(ppm)	Sr(ppm)
34-59a	62.2	37.8	17342	642	592	13972
34-1b	77.5	17.5	49800	1849	805	9116
34-1a	78.8	17.6	35900	1289	791	74725
34-56c	64.5	35.5	14105	835	554	383
34-56b	62.3	37.7	14561	817	677	402
34-56a	60.5	39.5	17349	846	1403	374
34-48	60.9	39.1	22181	1818	518	193
34-47	59.1	40.9	30084	1727	623	235
34-46	58.9	41.1	30306	1893	812	208
34-8	74.6	25.4	13207	1834	504	183

Appendix 3b

$\delta^{18}O$ and $\delta^{13}C$ values of samples from the dolostones of the Pamelia Fm

Sample No	$\delta^{18}O$(SMOW)	$\delta^{18}O$(PDB)	$\delta^{13}C$(PDB)
34-46	27.52	-3.29	-6.34
34-47	27.06	-3.74	-6.15
34-48	27.1	-3.7	-6.18
34-18a	22.63	-8.04	-2.06
34-56a	27.4	-3.4	-2.37
34-56b	26.97	-3.82	-2.2
34-56c	26.1	-4.67	-1.97
34-59a	27.2	-3.6	-1.82
34-59b	27.28	-3.52	-1.11
34-59c	27.03	-3.77	-1.48
34-22	26.08	-4.69	-0.07
34-14	24.28	-6.23	-1.03
44-A12	26.07	-4.7	-2.89
44-A14	27.78	-3.04	-2.92
44-A16	27.27	-3.53	-3.26
44-5a	26.37	-4.4	-2.28
44-5e	26.18	-4.59	-2.06
44-5i	26.36	-4.42	-2.48
44-14a	26.99	-3.8	-3.79
44-14b	26.94	-3.85	-3.76
44-14c	24.26	-6.45	-4.19
47-7a	27.66	-3.15	-1.62
47-7b	27.52	-3.28	-1.65
47-7c	27.05	-3.74	-1.56
47-13a	25.49	-5.26	-1
47-13b	26.74	-4.04	-0.49
47-13c	24.82	-5.91	-0.78
47-19a	25.13	-5.61	-3.99
47-19c	26.06	-4.7	0.2
47-19d	25.35	-5.39	-0.2
47-22a	26.44	-4.33	0.8
47-22c	27.76	-3.06	0.51
47-22e	26.87	-3.92	0.46
24-8	23.31	-7.38	-3.85

Appendix 4

Trace elements (Fe, Mn, Na, and Sr) concentration and $\delta^{18}O$ (presented as in PDB and Standard Mean Oceanic Water; SMOW) and $\delta^{13}C$ (in PDB) values of the calcite nodules. Standard deviation for both $\delta^{18}O$ and $\delta^{13}C$ is ± 0.10 ‰. Samples are numbered with two numbers and a letter. The first number is the location or section number, the second number and letter represent the sample number of the calcite nodule. Since the calcite nodules are concentrated in the dolostone lithofacies, the sample number preceding the letter is the same number as the sample number taken from the dolostone layer hosting the calcite nodule.

Appendix 4

Trace elements (Fe, Mn, Na, & Sr) contents and $\delta^{18}O$ and $\delta^{13}C$ values of the calcite nodules

Sample No	Fe ppm	Mn ppm	Na ppm	Sr ppm	$\delta^{18}O$ SMOW	$\delta^{18}O$ PDB	$\delta^{13}C$ PDB
24-20A	5980	1218	222	2478	22.03	-8.61	-2.15
24-19A	5380	2286	201	1176			
24-19B	11775	4575	250	776	21.44	-9.19	-2.87
24-24A	3431	549	288	1422	22.36	-8.29	-1.7
24-24B	4079	666	558	2485			
16-1-18	10558	2799	151	643	20.04	-10.55	-2.2
16-1-19A	5830	1270	459	2182	21.49	-9.14	-2.22
16-1-19B.	5421	1143	280	1856			
10-7A	8008	2332	612	774	22.21	-8.44	-1.97
34-2B	7595	3758	543	925	22.86	-7.81	-3.34
34-3A	5426	2395	634	1429	23.16	-7.52	-3.07
34-3C	5495	2375	267	1168			
10-7B	7234	713	479	2613	21.84	-8.8	-2.64
39-1A	5070	960	243	1454	22.69	-7.98	-2.14
39-1B	5807	891	151	1835			
39-1C	8680	1113	678	1291			
44-1A	9617	2367	1723	3	22.67	-7.99	-3.99
44-20A	7922	1465	144	4228	22.61	-8.05	-2.56
47-11B	6783	813	556	4321	21.65	-8.99	-2.85

Appendix 5

This appendix shows the results of the microprobe analysis on Dolomite II. Analyzed elements include Fe, Mg, Mn, Na, and Sr. Detection limits of these elements are: 400 ppm for Fe, 100 ppm for Mg, 300 ppm for Mn, 100 ppm for Na, and 150 ppm for Sr. The value 0 means below detection limit. Samples are assigned with three numbers (e.g., 48-12-20, sometimes the middle number is accompanied by a letter, like 47-3A-15). The first number represents section (or location) number, the second number (with letter) is the sample number and the last number represents the analyzed point number. Some analyzed points have a number (the last number) accompanied by a letter (e.g., 27-13-3a, 27-13-3b). This means that these points are from the same crystal but different points. For major elements, analyses are accurate to ± 1-2%. For minor or trace elements, relative error increases to ± 50% as the minimum detection limit is approached.

Appendix 5

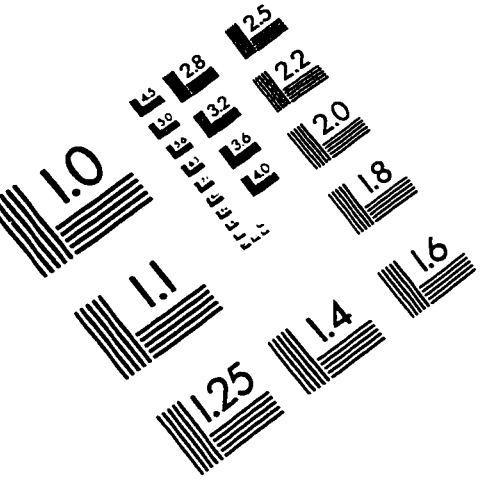
Results of microprobe point analysis for the dolomite cyrstals of Dolomite II

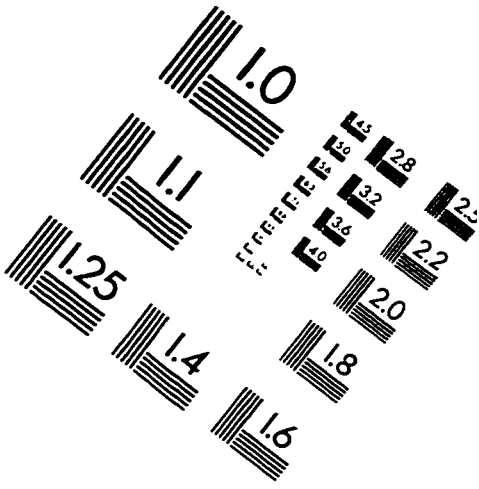
Sample	Fe(ppm)	Mg(%)	Mn(ppm)	Na(ppm)	Sr(ppm)
44-1-20	3263	11.1	1625	371	254
44-1-21	5828	11.4	1238	445	0
44-1-22	4040	11.5	1006	668	254
44-3A-18	2720	12.1	697	445	169
44-3A-19	2642	11.5	464	519	254
24-14-10	14608	11.9	3251	0	0
24-14-11	12199	12.0	3096	0	0
24-14-12	17949	11.5	3793	0	0
44-14-13	12199	12.0	3019	0	0
17-2-4	0	0.5	0	223	592
17-2-5	1709	11.9	0	148	0
17-2-13	16861	6.7	774	223	676
17-2-14	0	11.9	310	0	846
48-12-1	13753	10.8	310	223	676
48-12-2	13442	10.9	464	223	676
48-12-15	14297	10.4	0	148	2452
48-12-16	14297	10.8	542	0	1015
48-12-17	14141	11.0	0	148	846
39-9-1	466	11.8	0	297	676
39-9-2	466	11.5	0	297	1099
39-9-3	855	11.5	387	223	1015
39-9-4	0	12.0	0	371	846
39-9-5	699	11.9	0	519	338
39-9-6	0	12.0	542	297	169
39-9-7	0	12.6	0	297	0
39-9-8	0	12.4	0	223	592
39-9-9	0	0.4	0	0	676
47-28-1	699	0.4	0	0	1438
47-28-2	1243	0.3	0	148	2960
47-28-3	0	0.3	0	0	1438
47-28-4	1632	0.3	0	0	1607

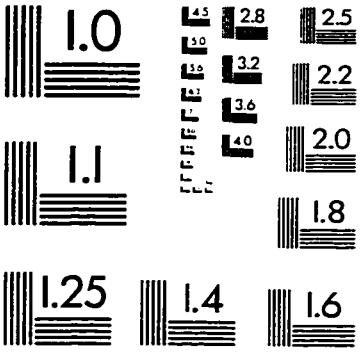
Appendix 5 cont.

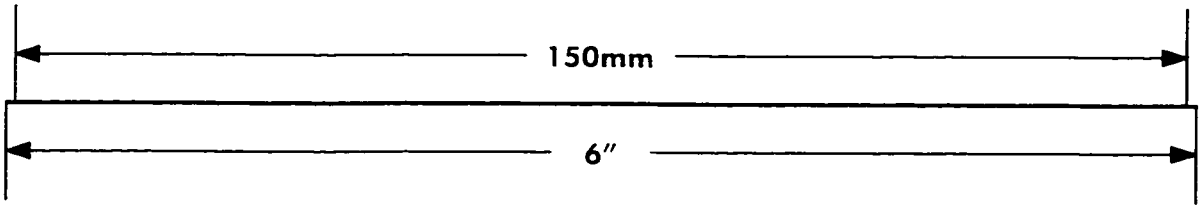
Sample	Fe(ppm)	Mg(%)	Mn(ppm)	Na(ppm)	Sr(ppm)
47-28-5	0	11.5	310	0	761
47-28-6	1709	0.4	0	0	1099
27-9-1	1943	12.5	464	0	676
27-9-1b	2409	12.2	310	519	930
27-9-2	0	0.3	0	148	338
27-9-3	0	0.3	0	0	761
27-9-4	0	0.3	0	0	846
27-9-4b	1088	12.2	0	0	1015
27-9-5	0	0.3	0	0	0
27-9-6	1709	0.3	0	0	0
27-9-7	1166	0.3	0	0	0
27-13-3a	2176	11.0	0	0	423
27-13-3b	9946	11.6	464	297	592
27-13-2a	1243	11.4	0	223	930
27-13-2b	27040	11.4	1161	0	592
27-13-2c	25019	6.8	1858	0	254
27-13-4	12354	4.2	1316	148	846
27-13-5	6216	8.1	929	148	338
27-13-6	5828	3.7	2012	0	169

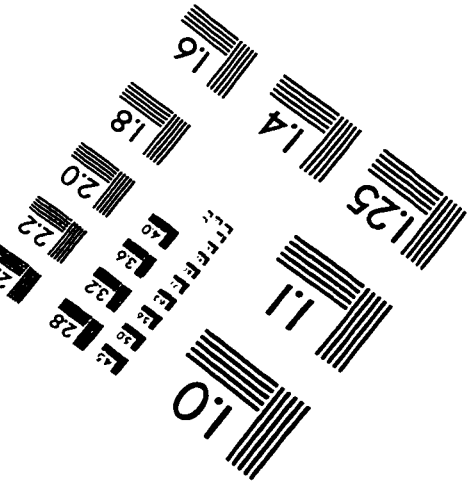
IMAGE EVALUATION TEST TARGET (QA-3)











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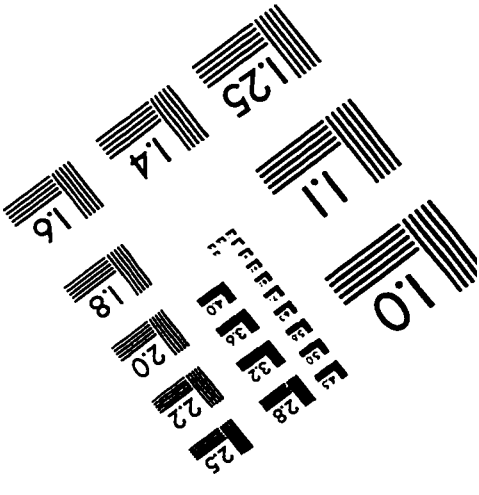
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