SEDIMENTOLOGY OF THE WHIRLPOOL SANDSTONE (LOWER SILURIAN) IN SOUTHERN ONTARIO AND UPPER NEW YORK STATE

THE SEDIMENTOLOGY AND PETROGRAPHY OF THE WHIRLPOOL SANDSTONE (LOWER SILURIAN) IN OUTCROP AND THE SUBSURFACE IN SOUTHERN ONTARIO AND UPPER NEW YORK STATE

By

MARGARET A. RUTKA, B.Sc.

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AUTHOR: Margaret Ann Rutka, B.Sc. (Queen's University)

SUPERVISOR: Dr. Gerard V. Middleton

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ABSTRACT

The Whirlpool Sandstone (Lower Llandovery) is a thin, sheet-like sandstone, less than 9 m thick, forming the base of the Medina Group in Southern Ontario and western New York. Two very distinct units, a lower and an upper, are recognized in the Whirlpool. The lower unit lacks body and trace fossils, marine microfossils, and wave-formed structures, and is interpreted as being terrestrial in origin. The facies and facies associations, erosional facies relationships, consistent northwest paleocurrents, and lack of lateral and vertical accretion deposits all support a braided fluvial interpretation. Three facies associations, each characterized by different amounts of the trough and ripple cross-laminated and horizontal-laminated facies, are present and are indicative of downstream changes in the river's fluvial style, from a moderately braided river with relatively deep channels in the southeast to a more highly braided river with very shallow channels, in the northwest. Erosional facies relationships and abundant mud intraclasts in the Whirlpool suggest that the river experienced frequent stage fluctuations. The upper unit consists predominantly of interbedded sandstone and shale and bioturbated sandstone, and contains fossils, trace fossils (*Skolithos* and *Cruziana* ichnofacies), wave-formed

structures and shallow water indicators. The upper Whirlpool formed in a storm-influenced, low-energy nearshore zone of a shallow, low-gradient epeiric sea, where 'normal' wave energy was dissipated some distance from the shoreline. Northwest- to southeast-striking symmetrical ripples indicate that the transgression probably came from the southwest.

The Whirlpool is a moderately spherical, rounded, well-sorted subarkose. No compositional differences exist between the upper and lower Whirlpool. The porosity is secondary, comprises less than 3% of the rock, and shows no regional or vertical trends. Regionally, the Whirlpool's grain size shows an overall fining to the northwest. Vertically, the Whirlpool shows an overall fining upward trend with smaller fining-upward cycles (stacked channel-fills) superimposed on this trend. The sandstone's mineralogical and textural maturity suggests a second cycle or multicycle origin. The Oswego Sandstone may be the Whirlpool's source.

A model of lithospheric flexure is used to explain various aspects of the Whirlpool's deposition. Deposition of the fluvial Whirlpool occurred on the northwest side of a northwest-migrating peripheral bulge which formed in response to overthrust loading in the southeast. Complex lithospheric interactions of the Michigan and Appalachian Basins and loading in the south caused the depositional plain to be tilted to the southwest, initiating the transgression over the lower Whirlpool. The presence of a deeper-water facies (Cabot Head Shale) overlying the Whirlpool in the south than in the northwest (Manitoulin Dolomite) suggests that the transgression may have come from the south-southeast, as well.

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CHAPTER 1

INTRODUCTION

BACKGROUND

The Whirlpool Formation is a thin, sheet-like sandstone, less than 9 m thick, forming the base of the deltaic-shallow marine (Martini, 1966, 1971, 1974; Knight, 1969), Lower Silurian Medina Group in Southern Ontario and western New York. An aeolian (Lockwood, 1942) and a shallow marine and aeolian (Fisher, 1954) environment of deposition for the Whirlpool have been suggested previously, but most workers, both early and recent, attribute the Whirlpool's present form to a transgressive shallow marine environment (Wilson, 1903; Grabau, 1913; Williams, 1919; Martini, 1966; Seyler, 1981). But these interpretations have been challenged by the most recent workers (Salas, 1983; Middleton et al., 1983), who have shown that the Whirlpool actually consists of two parts, a lower unit and an upper unit, each, with their own set of facies and paleontological assemblages, showing convincing evidence of having been formed in two very different environments, namely nonmarine (fluvial) and marine (shallow marine) environments.

PURPOSE OF STUDY

The primary objective of this study is to examine the Whirlpool on a more regional basis than has previously been done, and, through detailed measurement and analysis of various sections, try to find evidence supporting (and further defining) or contradicting the theories that have been proposed by Salas (1983) and Middleton et al. (1983). This study involves the analysis of the facies (vertical and lateral facies relationships), paleocurrents, paleontology, ichnology, and petrography of the Whirlpool for the purpose of determining the environment(s) responsible for and the processes operating during the formation of the Whirlpool.

Although a petrographic analysis of the Whirlpool would contribute least to the environmental interpretation of the Whirlpool, its inclusion in this study is considered necessary to complement the data base and provide additional support to the ideas and conclusions presented. The intention is to look at certain aspects of the Whirlpool not previously examined in detail by earlier workers, namely the type of porosity present and the regional and vertical variability of the Whirlpool's composition, feldspar content, grain size, and percentage of porosity.

It is also proposed to examine, if possible, the Whirlpool's relationship with its lateral equivalents, the Manitoulin and Cabot Head Formations. The limited areal extent of the outcrop belt and the lack of outcrops in key areas has made it necessary to turn to the subsurface for possible clues. Apart from providing information on lateral relationships, the cores (which are located in Lake Erie) will also extend and add more dimension to the regional analysis of the Whirlpool, provide fresh samples for petrographic analysis, and provide unweathered sections which can be compared to outcrop sections nearby or to those located near the pinch out areas, further to the north.

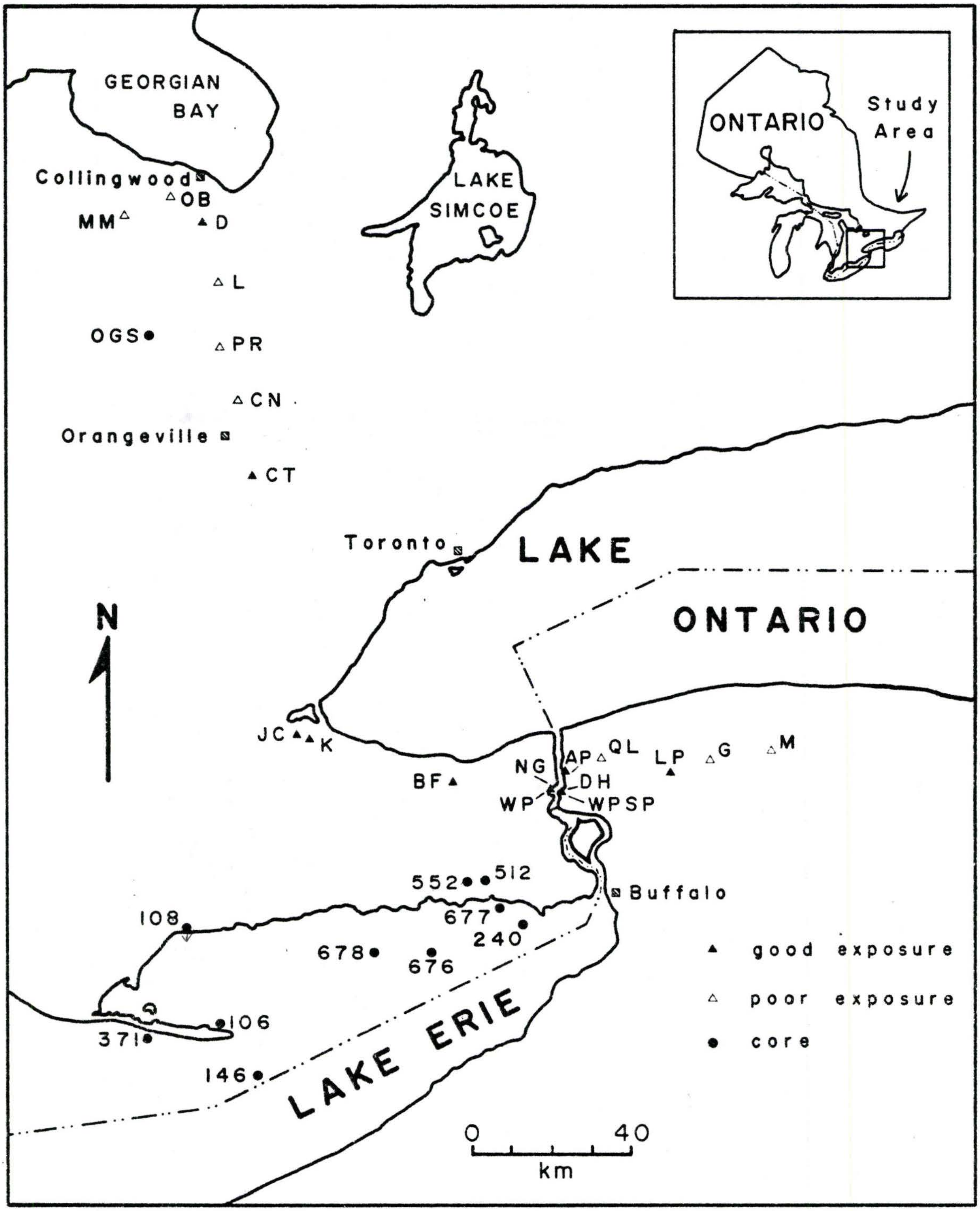
The Whirlpool is an interesting unit to study from both a sedimentological and tectonic standpoint. From a sedimentological point of view, it is hoped that this study can contribute to our present state of knowledge of the processes acting in and the deposits preserved in fluvial and transgressive shallow marine environments. From a tectonic point of view, it is hoped that a mechanism can be found that would explain the Whirlpool's deposition and that would account for the transgression that occurred sometime during the Whirlpool's formation. This mechanism should also explain the nature of some of the other Medina Group formations.

STUDY AREA

The study area, which is shown in Figure 1-1 along with the locations of all the sections (19 outcrops and 11

Figure 1-1. Map of Southern Ontario showing the study area and the locations of the 19 sections and 11 cores measured for this study. From northwest to southeast, the names of the sections are:

MM -	Mitchell's Mills	NG -	Niagara Glen
OB -	Osler Bluff	WP -	The Whirlpool
D -	Duntroon	WPSP -	Whirlpool State Park
L -	Lavender		
PR -	Primrose	DH -	Devil's Hole
CN -	Canning Falls	AP -	Artpark
CT -	Cataract	QL -	Quarry Lake
JC -	The Jolley Cut	LP -	Lockport
K -	Kenilworth Ave.	G -	Gasport
BF -	Balls Falls	M -	Medina


GEORGIAN BAY
Collingwood
OB
MM
D
L
OGS
PR
CN
Orangeville
CT
LAKE SIMCOE
ONTARIO
Study Area
Toronto
LAKE ONTARIO
N
JC
K
BF
NG
AP
QL
LP
G
M
DH
WP
WPSP
552
512
Buffalo
108
677
240
678
676
106
371
146
LAKE ERIE
good exposure
poor exposure
core
0
40
km

cores) measured, is located in Southern Ontario and western New York State (see Appendix 1 for detailed directions to each section). All Whirlpool outcrops, both natural and man-made, are situated along the Niagara Escarpment, covering a distance of approximately 275 km from Medina, New York, to Mitchell's Mills (near Duncan), Ontario. South of Lake Ontario, the Niagara Escarpment runs roughly parallel to the depositional strike of the Whirlpool, while in the north, the outcrop trend is roughly perpendicular to this. The sections outcrop at waterfalls, river cuts, road cuts, and quarries, and all are easily accessible and close to main or gravel roads. The nature of the exposures is quite variable: about 56% of the sections show 100% completeness of exposure, and, based on the state of preservation, only about 50% of the sections fall within the categories of good to excellent (see Fig. 1-1).

The cores are all located, with the exception of one further north, in or near Lake Erie. They are variably spaced within a 120 km by 40 km area located in the northeastern portion of Lake Erie.

METHODS

No formal procedures were followed for the selecting of the outcrops and cores to be measured for this study. All the best outcrops (minus those measured by Salas, 1983;

and Martini and Salas, 1983) were chosen, and the rest were selected (from a limited number of exposures) to provide as good a coverage of the Whirlpool's distribution as possible. All sections were measured in detail (see Chapter 4), paying particular attention to the sedimentary structures present so that the various facies (see Chapter 3) could be identified. At localities showing considerable lateral variability of the facies, more than one section was measured, and if the outcrop was long enough (greater than about 30 m), a cross-section, or sketch, of the outcrop face was drawn. Also, bedding plane maps were drawn wherever bedding plane surfaces were extensive (as in the Niagara Gorge).

Directional features are abundant in the Whirlpool, and play a major role in the environmental analysis. Paleocurrent readings were obtained from channel-like features (large troughs or scours), trough cross-laminations, planar tabular cross-laminations, parting lineations, rib-and-furrow structures, symmetrical ripples, current crescents, and the inclination direction of the fold axes of convolute laminations. The procedures for obtaining these readings (using a brunton compass) are fairly straight forward and are outlined in Potter and Pettijohn (1963) and Collinson and Thompson (1982). At each locality, readings collected from each of the various sedimentary structures were tabulated and statistically treated separately so as to avoid any misinterpretations of the data, which can easily occur when planar tabular cross-laminations and ripple cross-laminations are involved. The amount of directional information available varied from outcrop to outcrop, but in general, the procedure was to obtain as many readings as possible from all features at each locality. Because the Whirlpool's regional dip is less than 1 degree (to the south or southwest; see Chapter 2), no additional treatment (restoration to original horizontal positions) of the data was considered necessary.

Obtaining accurate paleocurrent information from the trough cross-laminations posed the greatest problem in the paleocurrent analysis. Because of the paucity of bedding plane exposures (bedding planes provide the most accurate indication of paleocurrent flow), it was necessary to obtain magnitude and direction of dip measurements from the foresets exposed on the randomly oriented outcrop faces. Readings obtained from a single trough would be paired, that is, tabulated as left and right readings, but in the end, during the statistical manipulation of the data, all readings, whether right or left, were treated as individual readings. It was assumed that the vector mean obtained in this way would give a good indication of the true paleocurrent direction.

All the paleocurrent readings obtained in this study are listed in Appendix 2. The rose diagrams and the values for vector mean (theta), vector magnitude (R), consistency (L), Chi-square, and Rayleigh test, which are shown in Appendix 3, on the section diagrams, and on the regional paleocurrent maps (Chapter 4), were obtained using a program written by Dr. G. V. Middleton. The equations used in this program are summarized in Potter and Pettijohn (1963).

Details concerning the methods used for point counting, thin section staining, and microfossil extraction will not be discussed here, but can be found in the appropriate chapters (Chapters 5 and 6).

FORMAT OF THE THESIS

Chapters one and two, which serve as the introductory chapters to this thesis, cover the background and purpose of the study and the geologic setting. Chapters three to six are largely descriptive, containing the data collected during this study, and describe the facies, sections, paleontology, ichnology, and petrography of the Whirlpool. The seventh chapter discusses the defined facies and suggests possible environmental interpretations for the facies assemblages observed at each locality. Chapter eight utilizes and summarizes all the data (and trends) presented in the previous chapters to reconstruct the Whirlpool's depositional environments, paleoclimate, and paleogeography. Chapter nine takes a brief look at how the lithosphere's natural response to crustal loading may have been responsible for and affected the formation of not only the Whirlpool but also some of the other formations of the Medina Group. Chapter ten lists the major conclusions of this study. And finally, information concerning the outcrop locations, paleocurrent data, and microfossil extraction technique are included in the appendices.

CHAPTER 2

GEOLOGIC SETTING AND STRATIGRAPHY

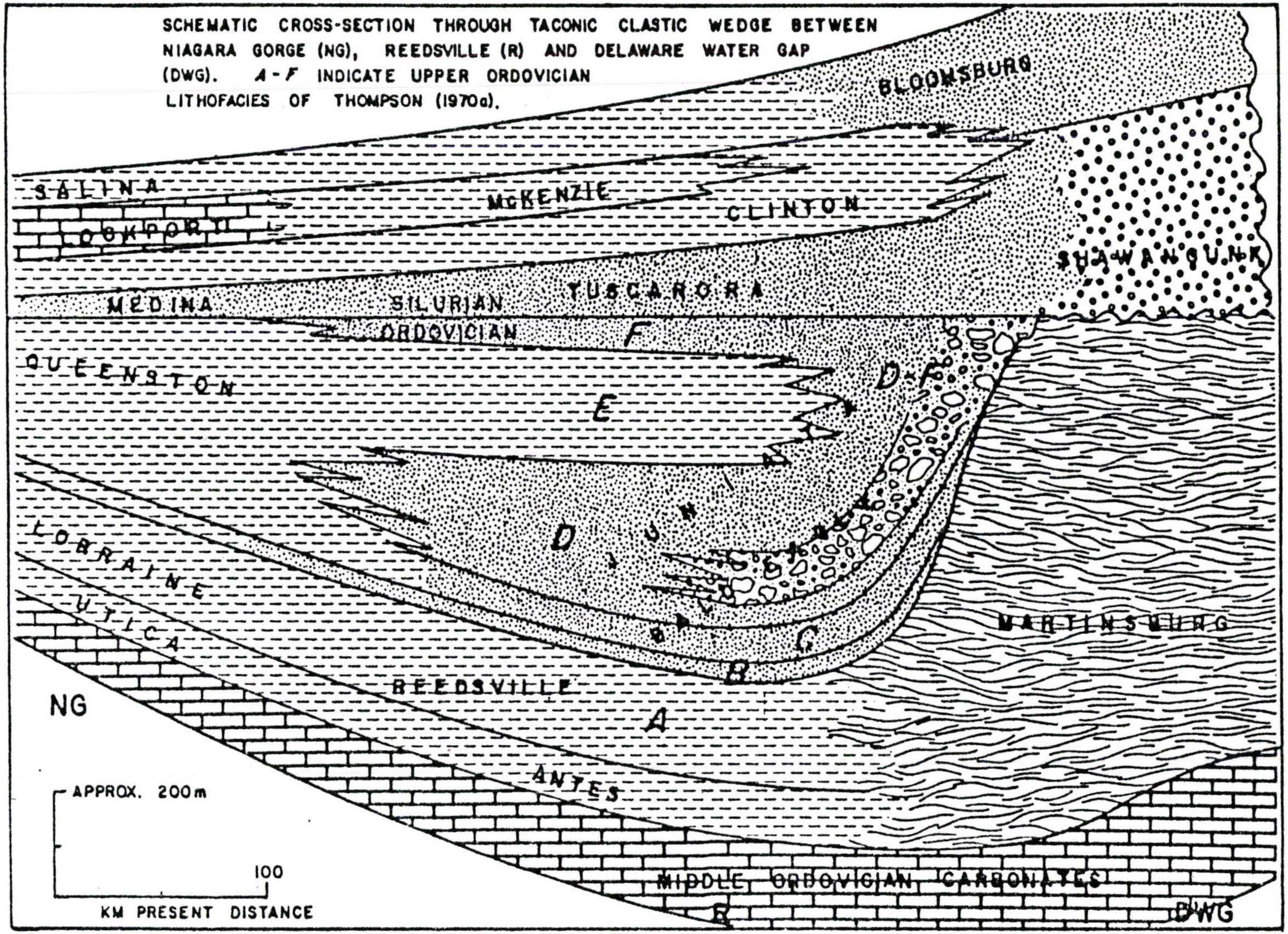
GEOLOGIC HISTORY

The Whirlpool Sandstone (Lower Llandovery) forms a very small part of a thick succession of terrigenous clastic rocks known as the Taconic clastic wedge (Fig. 2-1), which is preserved today in the Appalachian Basin of the Eastern Interior of North America. The Taconic clastic wedge consists of Middle Ordovician to Upper Silurian flysch and molasse sequences that were derived from the highlands produced during the Taconic orogeny (Thompson and Sevon, 1982).

Southern Ontario and western New York State during this time were situated approximately 20 to 25 degrees south of the equator (Scotese et al., 1979; Ziegler et al., 1977).

With the closing of the Proto-Atlantic and the initiation of a west-dipping or east-dipping subduction zone in the Middle Ordovician (Robinson and Hall, 1980; cited in Thompson and Sevon, 1982), the passive carbonate platform occupying northeastern United States was converted into a foreland basin; this event marked the onset of the Taconic orogeny. The Taconic orogeny, which ended at the close of

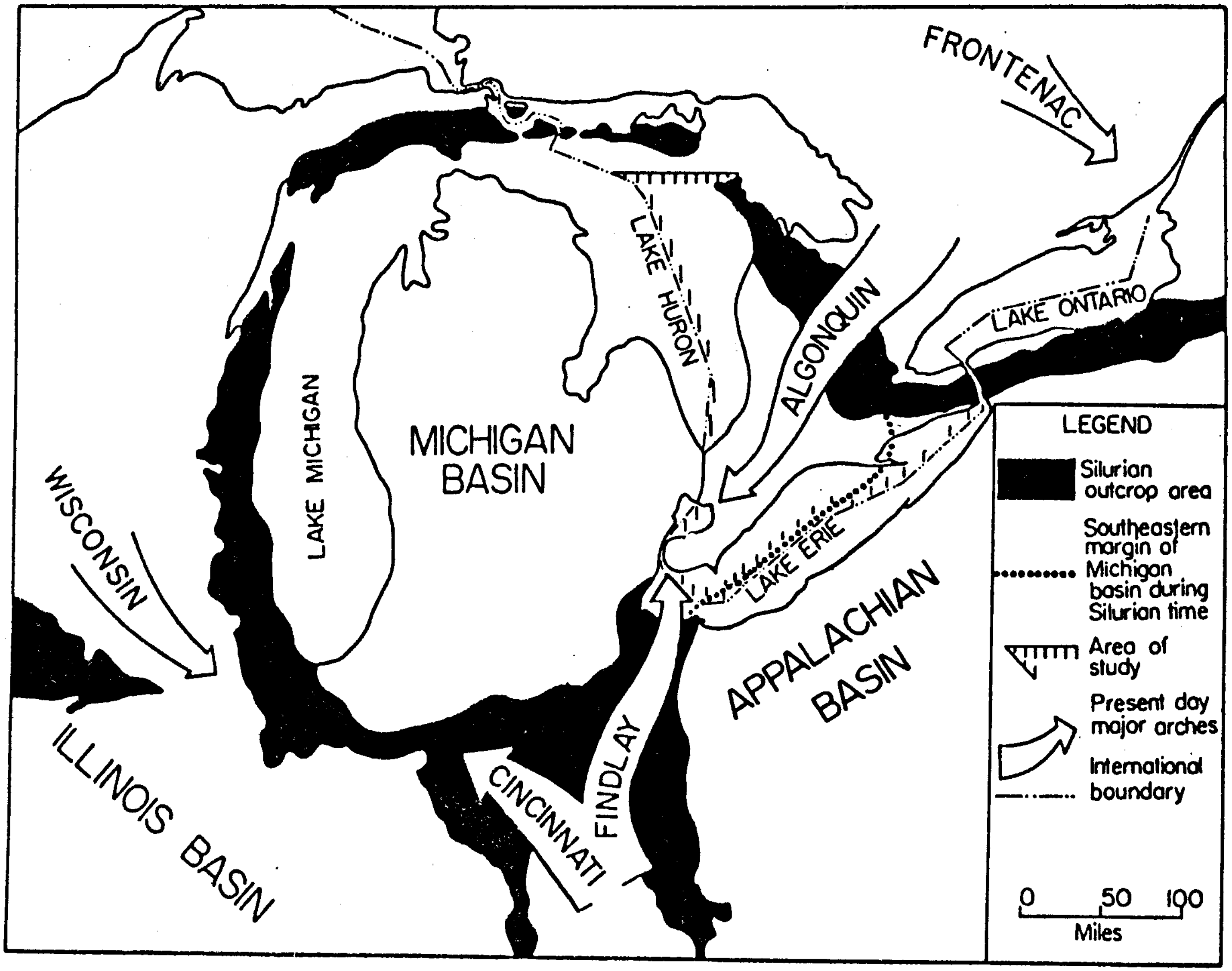
Figure 2-1. Cross-section of the Taconic clastic wedge between the Niagara Gorge and Delaware Water Gap. The sequence of rocks from the Middle Ordovician carbonates to the Queenston Shale constitute the Taconic clastic sequence. The Tuscarora to Bloomsburg sequence constitute the post-Taconian (Silurian) sequence. The Whirlpool Sandstone forms the base of the Medina Group. From Thompson and Sevon, 1982.



SCHEMATIC CROSS-SECTION THROUGH TACONIC CLASTIC WEDGE BETWEEN NIAGARA GORGE (NG), REEDSVILLE (R) AND DELAWARE WATER GAP (DWG). A-F INDICATE UPPER ORDOVICIAN LITHOFACIES OF THOMPSON (1970a).
BLOOMSBURG
SALINA
McKENZIE
CLINTON
LOCKPORT
SHAWANGUNK
MEDINA
SILURIAN
TUSCARORA
ORDOVICIAN
F
QUEENSTON
D-F
E
D
LORRAINE
UTICA
MARTINSBURG
C
B
REEDSVILLE
NG
A
ANTES
APPROX. 200m
100
KM PRESENT DISTANCE
MIDDLE ORDOVICIAN CARBONATES
R
DWG

the Ordovician, actually consisted of a series of pulses, or climaxes, with the strongest pulse occurring in the early part of the Late Ordovician (Rodgers, 1967, 1971). The deformation was expressed as folding, thrust faulting, uplift and gravity sliding, low grade metamorphism, and granodiorite and ultramafic intrusions (Friedman et al., 1982), and produced a linear landmass or a chain of mountains commonly referred to as 'Appalachia', but perhaps more appropriately called 'Taconica' or the Taconic Highlands (Rodgers, 1971). The highlands were situated over an area which is now northern Maine, western New England, northern New Jersey, and southeastern Pennsylvania, and they became the primary source for the sediments comprising the Taconic clastic wedge (the Shield area possibly had a minor influence; Sanford, 1972). Sediments were also shed to the east into the Iapetus Ocean (Ziegler et al., 1977), but most of the sedimentation took place in the Appalachian Basin (Fig. 2-2), to the southwest, west, and northwest of the Taconic Highlands. The Appalachian Basin was a northeast-trending, elliptical-shaped basin extending from Alabama to New York (Berry and Boucot, 1970; Dennison and Head, 1975). Its width fluctuated with time, reflecting the irregular nature of the Taconic orogeny, and reached a maximum northwestward extension somewhere near the present day Findlay-Algonquin Arch. Maximum subsidence, generally coinciding with the areas of maximum wedge thickness, was

Figure 2-2. Basins and arches of the Eastern Interior. After Sanford, 1969.


FRONTENAC
LAKE ONTARIO
LAKE HURON
ALGONQUIN
LAKE MICHIGAN
MICHIGAN BASIN
WISCONSIN
LAKE ERIE
APPALACHIAN BASIN
ILLINOIS BASIN
CINCINNATI
FINDLAY
LEGEND
Silurian outcrop area
Southeastern margin of Michigan basin during Silurian time
Area of study
Present day major arches
International boundary
0 50 100
Miles

localized near southwestern Pennsylvania (Dennison and Head, 1975).

To the west and northwest, beyond the limits of Taconic influence, a limit which most workers attribute to the presence of an arch or platform (Bolton, 1957), and some, to an energy barrier (Sanford, 1972), carbonate sedimentation was prevalent in a broad shallow sea that covered much of the Continental Interior of North America from the Middle Ordovician through to Middle Silurian times (Berry and Boucot, 1970; Scotese et al., 1979; Johnson, 1980).

The Taconic clastic wedge (Fig. 2-1) consists of two parts, or sequences (Diecchio, 1985). The lower, the Taconian clastic sequence (Middle to Upper Ordovician), is a coarsening- and shallowing-upward progradational sequence that contains mineralogically immature sediments. The post-Taconian (Silurian) sequence, on the other hand, is recognized by its mineralogical maturity.

The initial clastic phase of the Taconic orogeny is represented by the Martinsburg (thousands of meters thick) and Reedsville (less than 300 m) Formations. Both are shales with minor amounts of siltstone and sandstone beds (Thompson and Sevon, 1982). Paleocurrents are consistently to the northwest (Thompson and Sevon, 1982). The Martinsburg and Reedsville form the lower part of a progradational sequence and encompass a variety of environments that include basin center (McBride, 1962), distal and medial to more proximal portions of submarine fans, proximal offshore, and tide-dominated sand-flat complexes (Thompson and Sevon, 1982).

A glacio-eustatic lowering of sea level in the Late Ordovician coincided with the culmination of the Taconic orogeny (Dennison and Head, 1975; Ziegler et al., 1977; Thompson and Sevon, 1982). The mountain front shifted further westward, and sediments were shed northwestward (Yeakel, 1962), forming the 400 m of medium-to coarse-grained sandstones and conglomerates of the Bald Eagle, Oswego, and the red Juniata Formations (a braided, proximal alluvial-plain to coalescing-fan complex (Thompson and Sevon, 1982)). Further to the northwest and west, the red shales with minor siltstones (maximum thickness 340 m) of the Queenston Formation were deposited on a lower to mid delta plain (Smosna and Patchen, 1978).

Renewed uplift just prior to the Silurian deformed the Martinsburg Shale (Bird and Dewey, 1970; Dennison and Head, 1975) and shifted the mountain front further southeastward (Yeakel, 1962). Sediments were carried northwestward (Yeakel, 1962) and were deposited by braided streams in a proximal alluvial fan environment in the east (Shawangunk Conglomerate; Smith, 1970), and to the west, by braided rivers on an alluvial plain forming the Clinch and Tuscarora Sandstones (Yeakel, 1962). Other interpretations for the Tuscarora and Clinch include fluvial and beach (Folk, 1960; Dennison, 1976; Miller, 1976) and shallow-marine shelf, coastal and fluvial environments (Cotter, 1983). Towards the basin edge, in New York and Southern Ontario, the Medina Group--the Whirlpool forms the basal unit of this group--represents a paralic facies of the Tuscarora (Knight, 1969; Martini, 1966). The base of the Tuscarora and Medina is generally assumed to mark the Ordovician-Silurian boundary (Dennison and Head, 1975) and to overlie the Queenston Shale with a disconformable contact; however, the absence of body fossils makes it difficult to determine the significance of this contact.

A marine transgression began in the Early Silurian, affecting the deposits of the Medina and Tuscarora, but it did not reach its fullest extent until the Middle Silurian, when the Clinton marine shales were deposited. A final regressive phase deposited the red Bloomsburg (Upper Silurian) deltaic sediments (Thompson and Sevon, 1982).

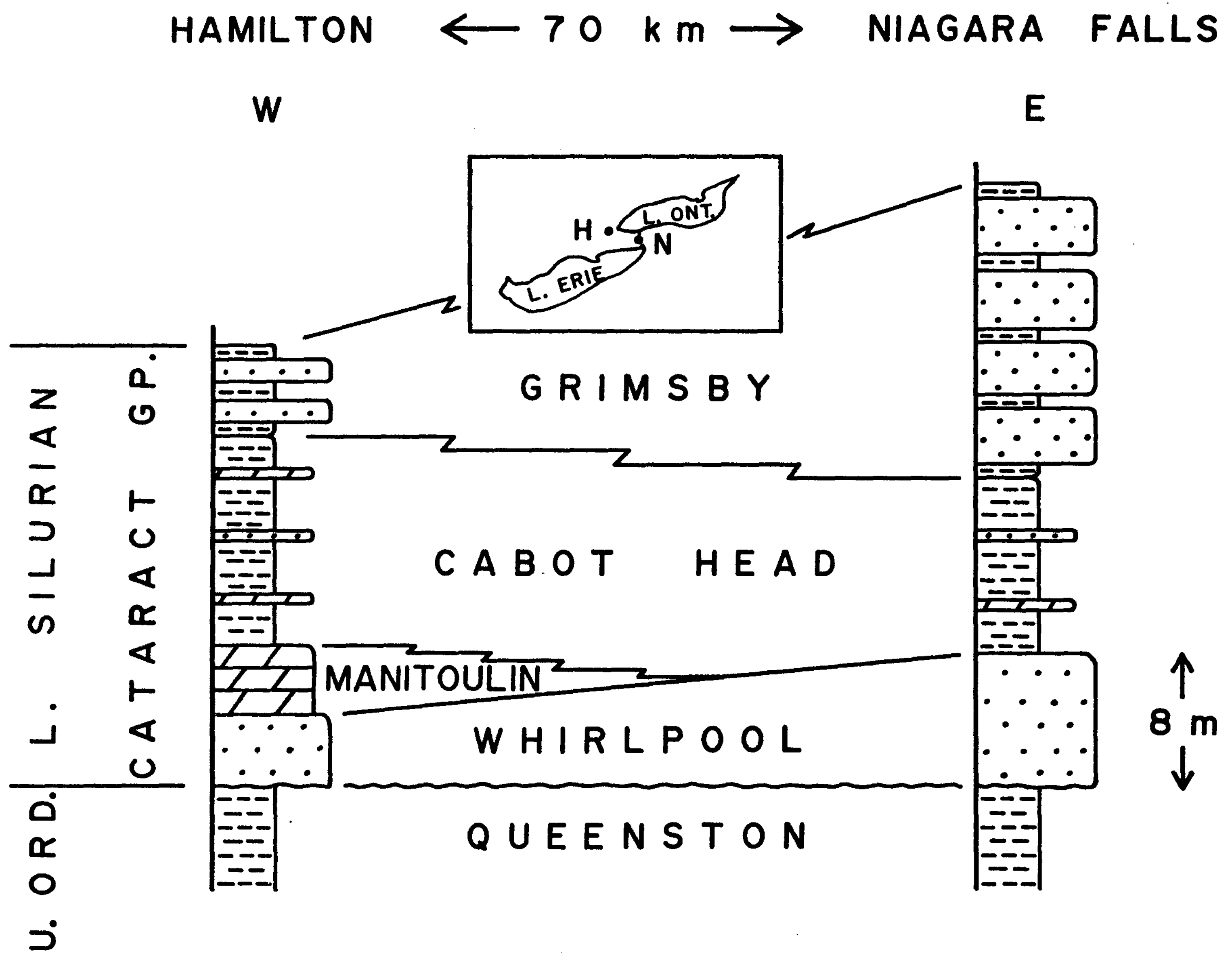
Two other orogenies of the Appalachian orogenic cycle, the Acadian (Devonian) and the Alleghanian (Pennsylvanian) orogenies, produced similar clastic wedges and placed a final mark on the Appalachian orogenic belt (Rodgers, 1967).

MEDINAN STRATIGRAPHY

The Medina Group (Lower Silurian) is possibly the paralic (basin-edge) facies equivalent to the Tuscarora Sandstone and is present in Ohio (there known as the Albion; Knight, 1969), Pennsylvania, New York, and Southern Ontario. Knight (1969) considered all Medinan, or Albion, sandstones to be tongues of the Tuscarora. At the type section of the Whirlpool Sandstone, in the Niagara Gorge (Fig. 2-3), the Medina Group includes (in ascending order) the Whirlpool Sandstone, the Power Glen Shale, the Grimsby Sandstone and Shale, and the Thorold Sandstone (Caley, 1940; Fisher, 1954). Basinward, in central Pennsylvania and southern Ohio, where the shales pinch out and the sandstones take on similar appearances, the Medinan formations become indistinguishable, and are here referred to as the Tuscarora Sandstone (Cate, 1961).

The Medina is everywhere disconformably underlain by the red shales and minor siltstones (green) of the Queenston Formation (Richmond in age). The Queenston-Whirlpool contact is very distinctively sharp and regionally flat, with only minor undulations. This contact is generally considered to be a disconformity of unknown duration, and based on lithostratigraphic relationships, it is placed at the Ordovician-Silurian boundary; however, the paucity of fossils in both the Whirlpool and Queenston make it

Figure 2-3. Cross-section of the Cataract Group between the Niagara Gorge and Hamilton, Ontario. Note that the thickness of the Whirlpool decreases westward from about 8 m at Niagara Falls to about 4 m at Hamilton, and that the Manitoulin, which overlies the Whirlpool northwest of Stoney Creek, gives way to the Cabot Head (or Power Glen) at Niagara. The Cataract Group plus the Thorold Sandstone (not shown) constitute the Medina Group, a term which is used in Pennsylvania, New York, and Southern Ontario, east of Hamilton. Although not indicated in this diagram, the unit overlying the Whirlpool at Niagara Falls, is more commonly referred to as the Power Glen Shale, which consists of the Cabot Head, Manitoulin, and Fish Creek.

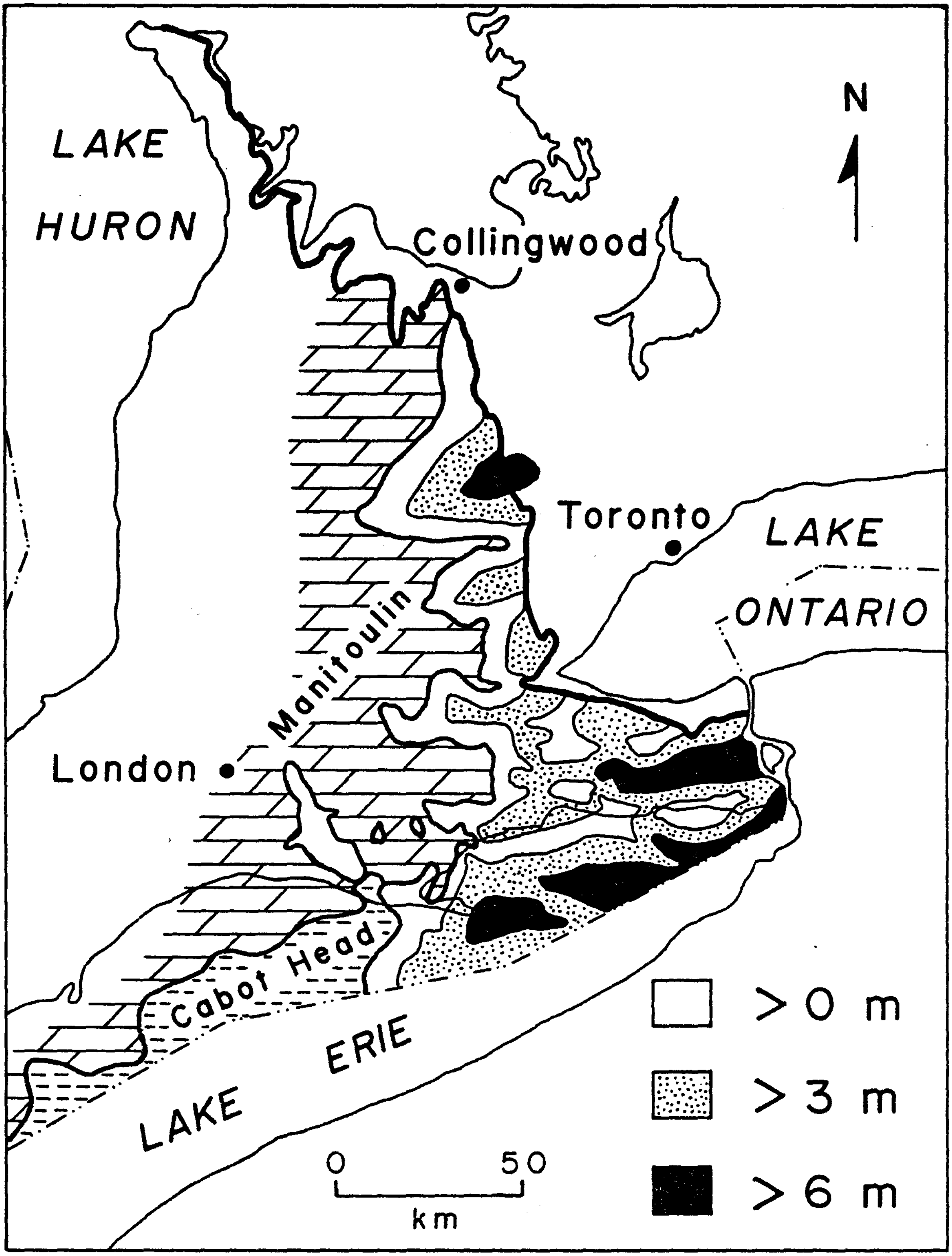

HAMILTON
70 km
NIAGARA FALLS
W
E
H
N
L. ONT.
L. ERIE
GRIMSBY
CABOT HEAD
MANITOULIN
WHIRLPOOL
QUEENSTON
8 m
L. SILURIAN
CATARACT GP.
U. ORD.

difficult to determine the significance of this contact. The top 30 cm or so of the Queenston consists of clayey, green shale, which is probably the result of a bleaching of the red shale by percolating ground waters (Caley, 1940).

The Whirlpool Sandstone (the 'White Medina' of the drillers), named by Grabau (1909) for the 8 m of sandstone overlying the Queenston Shale in the Niagara Gorge, is the medium-to thick-bedded, fine-grained, cross-bedded, quartzose sandstone that forms the base of the Medina Group. Figure 2-4 shows the Whirlpool's distribution and thickness variations in the subsurface of Southern Ontario. In the study area, the Whirlpool reaches a maximum thickness of 9 m at Thorold (Williams, 1919); however, the maximum reported thickness is 34 m in Chemung County, New York (Fisher, 1954). In the east, the Whirlpool pinches out along the Niagara Escarpment between Medina and Rochester, New York (leading Grabau, 1913, to believe that the Whirlpool is a local formation unconnected to any eastern source), and to the west and southwest, the Whirlpool is replaced by the Manitoulin Dolomite and Cabot Head Shale, respectively (Fig. 2-4).

From Grimsby, Ontario, to Medina, New York, the Whirlpool grades upward into 10 to 15 m of dark grey to green, calcareous, arenaceous shale with thin interbeds of light grey, fine-grained, calcareous sandstone. These beds constitute the Power Glen Formation (Liberty and Bolton,

Figure 2-4. Distribution and thickness variability of the Whirlpool in the subsurface of Southern Ontario. The Whirlpool's thickness is quite variable regionally, showing an overall thinning to the west and northwest. Note that to the northwest, the Whirlpool is replaced by the Manitoulin Dolomite, and to the southwest, by the Cabot Head Shale. After Sanford, 1969, and Martini and Kwong, 1985.



LAKE HURON
Collingwood
N
Toronto
LAKE ONTARIO
Manitoulin
London
Cabot Head
LAKE ERIE
0
50
km
> 0 m
> 3 m
> 6 m

1956; Bolton, 1957). The Power Glen corresponds to Fisher's (1954) Fish Creek Shale, Manitoulin Dolomite, and Cabot Head Shale, which all lie between the Whirlpool and Grimsby Sandstones east of Stoney Creek, Ontario, but because the Manitoulin, which is used to separate the Fish Creek from the Cabot Head, is not consistently present east of Stoney Creek, the name Power Glen is a more appropriate one to use (Liberty and Bolton, 1956).

Northwest of Stoney Creek, Ontario, the Whirlpool is gradationally overlain by 1.2 to 8 m (Bolton, 1957) of grey-brown to buff, medium crystalline, argillaceous (sometimes arenaceous), and fossiliferous dolomitic limestones of the Manitoulin.

The Cabot Head Formation, which forms the upper half of the Power Glen Shale southeast of Stoney Creek, gradationally overlies the Manitoulin north of Lake Erie, but in most of Lake Erie and areas to the south, the Cabot Head overlies the Whirlpool. In the study area, the formation is 11 to 21 m thick (Bolton, 1957) and consists of green, grey, and red shales with thin interbeds of grey, calcareous sandstones and silty limestones.

Overlying the Cabot Head and Power Glen Formations are 1.2 to 13.7 m (Bolton, 1957) of red shales and sandstones constituting the Grimsby Formation. The lower contact is lithologically gradational, but is arbitrarily drawn on the basis of colour change from grey to red

(Kilgour, 1972).

The 1.4 to 4 m (Bolton, 1957) of light grey, fine-grained quartzose sandstones with thin green to grey shale and siltstone partings overlying the Grimsby constitute the Thorold Sandstone, which forms the top of the Medina Group. Its lower contact with the Grimsby varies from sharp to gradational, and is usually drawn on the basis of colour change.

As an additional note, the name Medina appears to be reserved only for those Lower Silurian rocks present in Pennsylvania, New York, and Southern Ontario, east of Hamilton. Northwest and west of Hamilton, changes in facies warrant the change of name to the Cataract Group, which does not include the Thorold Sandstone (Williams, 1919; Liberty and Bolton, 1956; Bolton, 1957). For a historical review of the terminologies proposed for the Lower Silurian sediments, see Fisher (1954), Bolton (1957), and Winder (1961).

DEPOSITIONAL ENVIRONMENT OF THE MEDINA GROUP

A marginal environment of sedimentation is suggested by the Medina's correspondence in regional distribution to Yeakel's (1962) zone of mixed marine and nonmarine sedimentation. Knight (1969), working in Ohio, and Martini (1966, 1971, 1974), along the Niagara Escarpment, have both proposed a deltaic-shallow marine environment (complete with fluvial channel, distributary bar, beach, longshore bar, and prodeltaic sediments) for the Medina. Below is a brief review of previous interpretations proposed for the formations of the Medina.

Previous work on and environmental interpretations proposed for the Whirlpool Sandstone have been reviewed thoroughly by Bolton (1957), Seyler (1981), Martini and Salas (1983), and Salas (1983). The upper part of the Whirlpool, displaying body fossils and abundant bioturbation and wave-formed structures is undoubtedly marine in origin. The environment of the lower Whirlpool, however, is not so obvious. An aeolian origin has been proposed by Wilson (1903), Grabau (1913), Williams (1919), Lockwood (1942; cited in Bolton, 1957), Geitz (1952), and Fisher (1954). Shallow marine interpretations have included a longshore bar and beach complex (Martini, 1966, 1971, 1974) and a barrier island complex (Seyler, 1981). The most recent workers on the Whirlpool (Middleton, 1982; Middleton et al., 1983; Martini and Salas, 1983; Salas, 1983) believe the lower Whirlpool's sedimentological characteristics are more consistent with a braided fluvial than a shallow marine or aeolian origin.

The Manitoulin is a shallow, open marine, inner to outer shelf carbonate (Martini, 1966) showing evidence of occasional storm influence (Duke, 1982; Leggitt, 1985). The Cabot Head Shale (Power Glen) possibly represents a prodeltaic environment (Fisher, 1954; Martini, 1972) with proximal to distal offshore sedimentation (Bolton, 1957; Duke, 1982). Previous interpretations for the Grimsby have included beach (Gillette, 1940; cited in Bolton, 1957), deltaic (Pelletier, 1953), and littoral environments (Williams, 1919; Caley, 1940; Fisher, 1954; Martini, 1971), but the presence of Bouma sequences passing up into hummocky cross-stratification suggests a shallowing from distal to proximal offshore environments (Duke, 1982). The Thorold Sandstone possibly represents beach, tidal flat (Martini, 1974), and shoreface (Duke, 1982; Pemberton, 1979) environments, and therefore caps off the progradational sequence.

The Medina (Cataract) Group is therefore a marginal deposit, initially recording a regressive phase, then a transgressive, and finally another regressive phase in sedimentation. A transgression began sometime during the Whirlpool's deposition on the Queenston Shale, and continued on until late in the deposition of the Cabot Head, when renewed clastic input effected a progradation of the shoreline back to the northwest.

STRUCTURAL SETTING

The study area of this thesis is located in the Continental Interior province of the Appalachian-Caledonian orogenic belt (Thompson and Sevon, 1982). The Continental Interior is the northwesternmost structural province, and is separated from the Michigan Basin in the west by the Findlay-Algonquin Arch (Fig. 2-2). The rocks present in the Continental Interior province (Ordovician, Silurian, and Devonian systems) have undergone so little deformation from the Appalachian orogeny that they appear nearly flat lying at the individual outcrop. Actually, the major structural feature of the Niagara Peninsula is that of a monocline with a southerly dip of 5.3 m per kilometer. In the northern part of the study area, the dip is 3.8 m per kilometer south 25 degrees west (Caley, 1940). Evidence of faulting in the study area is very rare.

All outcrop sections measured for this study are located along the Niagara Escarpment, an erosional escarpment formed by the differential erosion of resistant dolomites and soft shales. The escarpment extends from upper New York State west and northwest to Tobermory, Ontario (Hewitt, 1971), and provides the only outcrop exposures of the Silurian rocks. In the Hamilton-Niagara region, the Escarpment takes on the form of a single scarp, whereas, in upper New York State and in the Georgetown area, multiple scarps are present, with the Whirlpool Sandstone being one of the scarp-formers (Hewitt, 1971).

CHAPTER 3

FACIES DESCRIPTIONS

This chapter describes the eleven facies recognized in the Whirlpool Sandstone. In this study, the term "facies" is used in a descriptive manner rather than in an interpretative manner; however, some of these facies do carry certain environmental and genetic implications, and these will be examined later in some detail in Chapter 7.

The facies in this study were recognized and defined in the field on the basis of two main characteristics: sedimentary structures (both primary and secondary) and lithology. Colour, bedding, texture, and fossil types are other criteria often used in defining facies (Reading, 1978), but in the Whirlpool, variations in each of these are either nonexistent or too subtle to allow these factors to play a major role in the defining of the facies.

As previously mentioned (see Chapter 1), the Whirlpool consists of two very distinct parts, or units: an upper unit and a lower unit, each of which, with the exception of one or two facies, contains facies not found in the other. A list of the Whirlpool's facies is presented below (facies codes are after Miall, 1978, and Rust, 1978a):

Upper Unit

Sl: low-angle cross-laminated sandstone

Sb: bioturbated sandstone

Sw: wavy-laminated sandstone

Shcs: hummocky cross-stratified sandstone

S/F: interbedded sandstone and shale

Lower Unit

St: trough cross-laminated sandstone

Sr: ripple cross-laminated sandstone

Sh: horizontally- (plane) laminated sandstone

Sp: planar tabular cross-laminated sandstone

Sl: low-angle cross-laminated sandstone

Sm: massive sandstone

Sc: convolute laminated sandstone

Sw: wavy-laminated sandstone

Most of these facies are in agreement with those proposed by Salas (1983), with the exception of his large scour (D), epsilon cross-bedding (E), pinch and swale (H), and calcarenite/arenaceous dolomite (K) facies. These facies are not used here because they were either not observed in the outcrops and cores of this study or, if they were present, they were given more appropriate names or incorporated into other facies. The classification scheme used for the large scale (set thickness greater than 5 cm) cross-bedding constituting facies St and Sp is based on that suggested by McKee and Weir (1953) and Harms et al. (1982).

The lithologies of the facies in this study were, for the most part, determined by petrographic analysis, using the sandstone classification scheme of Folk (1974). The classification of bioturbation is based on the degree of primary bedding destruction and follows the scheme suggested by Reineck (1963; cited in Reineck and Singh, 1980) (see Chapter 5). The modal grain sizes of the facies are expressed as a range in phi units according to the Amstrat grain size scale; a conversion to millimeters is presented below:

-0.5 - -1.0 phi	=	1.410 - 2.000 mm	(vcU)
0.0 - -0.5 phi	=	1.000 - 1.410 mm	(vcL)
0.5 - 0.0 phi	=	0.710 - 1.000 mm	(cU)
1.0 - 0.5 phi	=	0.500 - 0.710 mm	(cL)
1.5 - 1.0 phi	=	0.350 - 0.500 mm	(mU)
2.0 - 1.5 phi	=	0.250 - 0.350 mm	(mL)
2.5 - 2.0 phi	=	0.177 - 0.250 mm	(fU)
3.0 - 2.5 phi	=	0.125 - 0.177 mm	(fL)
3.5 - 3.0 phi	=	0.088 - 0.125 mm	(vfU)
4.0 - 3.5 phi	=	0.062 - 0.088 mm	(vfL)

TROUGH CROSS-LAMINATED SANDSTONE (St)

This facies occurs at every section south of Orangeville. It is generally restricted to the lower half of the Whirlpool and comprises a greater percentage of the total Whirlpool thickness in the southern part of the study area, reaching a maximum of about 80% at the Niagara Gorge sections, than it does in the north, where it reaches a minimum of 10% at Cannings Falls. Its abundance in cores is difficult to discern because trough and planar tabular cross-stratification can appear quite similar in cores; however, neither appears to be an important facies in the cores measured.

The trough cross-strata generally occur in cosets of two to twelve sets, the average being four, although single, isolated sets are also quite common. Sets range in thickness between 0.06 and 0.8 m (averaging 0.26 m), and coset thicknesses range between 0.2 and 5.8 m (Niagara Glen) (see Fig. 4-23a), although thicknesses of less than 1 m are most common. This facies has irregular and erosional upper and lower contacts that may vary up to 1 m in relief.

The geometry of the sets varies from outcrop to outcrop and depends on the orientation of the outcrop face with respect to the paleoflow direction. In most cases, sections are longitudinal, displaying lenticular to wedge-shaped sets that persist laterally for one to four meters, extending to as much as 11 m at some localities (Lockport). Transverse sections through cosets of trough cross-bedding are not as common (see Fig. 4-11); however, such sections through single, isolated sets are more common and display symmetrical troughs that range in width from 1 to 14 m (average is 3.6 m) and in depth from 0.3 to 0.85 m (average is 0.6 m) (Fig. 3-1a).

The foresets of the trough cross-laminations are generally well defined, except when the facies occurs at the base of the Whirlpool; here many are poorly defined. In longitudinal section the foresets are concave upwards, have tangential lower contacts, and have dips ranging between 11 and 29 degrees (average is 20 degrees). On bedding planes, foresets of isolated troughs are nearly concentric and show downstream concavity (see Fig. 4-26a). Where numerous sets of troughs occur on bedding planes, foreset truncations by adjacent troughs produce large scale rib-and-furrow structures (Fig. 3-1b). These are particularly well developed at The Whirlpool section.

Foresets range in thickness between 0.3 and 2 cm (averaging 0.7 cm) and generally maintain a constant thickness along their lengths; however, a thinning upwards along the foresets has been observed at a few localities (e.g. Artpark).

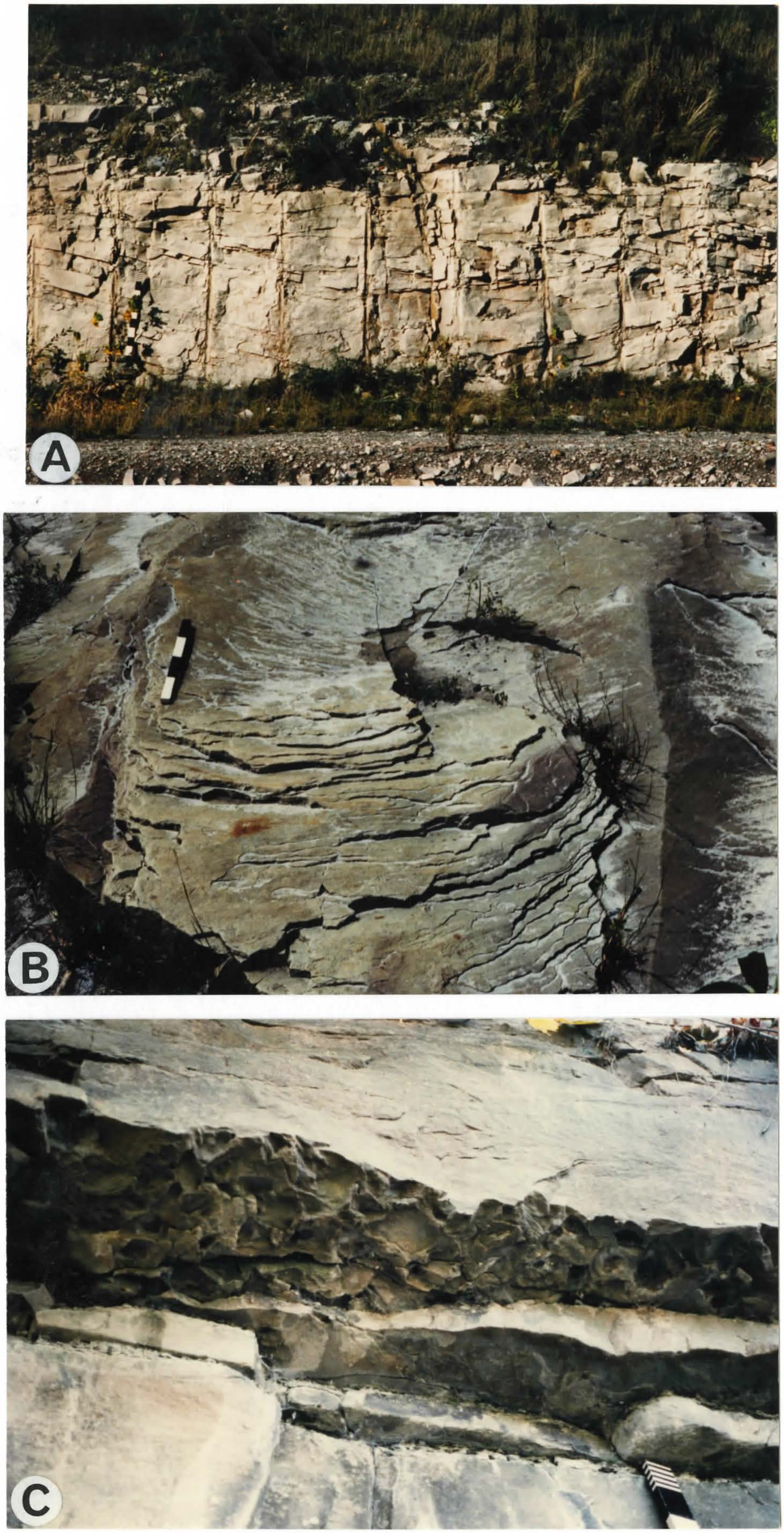
Elongate, dark greenish grey, silty shale clasts, occupying less than 5% of the facies by volume, and averaging 1.2 cm in length and 0.2 cm in width, occur in over 70% of the trough cross-bedded units measured. These shale clasts are rarely preserved on the weathered face of the outcrop. The clasts lie parallel to the foresets

Figure 3-1. Features of facies St, trough cross-laminated sandstone.

a) A transverse section through a large (15 m wide), symmetrical trough in a unit displaying facies St. The paleocurrent is towards the west-northwest. Note that the trough is being cut on the right (north) by another trough. Scale is 1 m long. From Lockport railway cut, west wall, near bridge.

b) Large scale rib-and-furrow structures formed by the truncation of trough foresets by adjacent troughs. These are best developed on the extensive bedding plane at The Whirlpool section. The paleocurrent direction is into the picture, parallel to the scale. The scale is 40 cm long. From The Whirlpool bedding plane, 3.8 m from the base of the Whirlpool.

c) Bottom view of a scour surface in the Niagara Gorge showing the typically large size (up to 10 cm diameter) of the shale clast molds. Divisions at tip of scale are 1 cm. From Devil's Hole, 2.5 m from the base of the Whirlpool.



(although a few have been observed to lie obliquely) and are generally evenly distributed along the length of the foresets.

Lithologically, this facies is a well sorted, unfossiliferous, fine-grained subarkosic arenite to quartzarenite with rounded and moderately spherical grains. Grain size varies (ranging from 1 - 0.5 phi to 3.5 - 3 phi) both regionally and vertically, being coarsest in the south and at the base of the Whirlpool (both average 2.5 - 2 phi). Overall average grain size is also 2.5 - 2 phi. Some local occurrences of coarsening-upward sequences are present, but these are generally few in number.

Minor elements of this facies include horizontal laminations, ripple cross-laminations, shale layers, and planar tabular cross-laminations. Small (0.5 cm in diameter) spherical weathering cavities (Calow, 1983), or spherical cementation rosettes (see Fig. 4-23b) (G.V. Middleton, personal communication), are common occurrences in this facies, but they usually only occur in the lower 0.6 m of the Whirlpool and in sections east of Hamilton, where the grain size is coarsest.

In the Niagara Gorge sections, scour surfaces occur within this facies. These surfaces are highly irregular in vertical section, varying up to 1.4 m in relief, and contain abundant irregularly-shaped shale clast moulds, ranging in size from 2 to 7 cm (average is 4 cm) (Fig. 3-1c). Some pits still retain the dark greenish grey, silty clay clasts that had originally occupied the holes.

Mineralization occurs in the lower 0.3 m of the Whirlpool, where chalcopyrite and pyrite are present as cement and replacement of phosphatic grains (Martini and Salas, 1983).

RIPPLE CROSS-LAMINATED SANDSTONE (Sr)

This is the most widespread and commonly occurring facies of the Whirlpool, although on average it never really comprises more than 16% of the Whirlpool thickness at anyone locality. It is generally a more important component of the Whirlpool northwest of Balls Falls than south-east of this locality, reaching a maximum of about 70% at Primrose.

The ripple cross-laminated facies contains two morphologically and genetically distinct types of ripple cross-laminations and has, therefore, been subdivided into two subfacies: a current ripple cross-laminated and a symmetrical ripple cross-laminated subfacies.

Subfacies Src: Current Ripple Cross-laminated Sandstone

This facies is the more commonly occurring of the two subfacies and occurs in 21 of the 30 outcrops and cores studied. The greatest thickness of facies Src occurs at Lavender, where it is 2.45 m thick. This facies comprises a significant portion of most of the outcrops, but at some localities the ripple cross-laminations occur as minor elements in other facies and are not laterally or vertically extensive enough to constitute a separate facies. Facies Src is generally not restricted to any specific portion of the Whirlpool vertical sequence.

The facies generally occurs as a tabular- to lenticular-shaped body of ripple cross-laminated cosets that range from 0.04 to 1.4 m and average about 0.3 m in thickness. Upper and lower bounding surfaces of the facies are erosional. Ripple cross-laminated sets range in thickness between 0.2 and 4 cm and average about 1 cm.

The shape of the sets is variable and depends largely on the orientation of the outcrop with respect to the paleocurrent direction; transverse sections, on which the ripple cross-laminations appear as micro trough cross-laminations, are the most common (Fig. 3-2a). Longitudinal sections are not common, but where present, show horizontal, lenticular-to wedge-shaped sets containing 1 to 2 mm thick, low-angled (average is 11 degrees), tangential foresets. Climbing ripple drift is present at a few localities; in most cases it is present as Type A (Jopling and Walker, 1968), which is characterized by gently inclined (about 7 degrees in this case) sets of ripple cross-laminations that lack preservation of the stoss sides. Type B climbing ripples (where both the lee and stoss sides are preserved),

Figure 3-2. Two common appearances of facies Src, current ripple cross-laminated sandstone.

a) Micro trough cross-laminations exposed in transverse section. The paleocurrent is either into or out of the picture. Scale is approximately 2 cm wide. From The Jolley Cut, Section B, 1.3 m from the base of the Whirlpool.

b) Small scale rib-and-furrow structures exposed on a bedding plane surface. The paleocurrent is towards the top of the picture, parallel to the scale. The scale is 40 cm long. From The Jolley Cut, between section B and the path, 0.8 m from the base of the Whirlpool.


A


B

showing ripple drift, or migration downstream are present only at the Jolley Cut, but here they constitute just a small portion of a trough cross-bedded facies.

On bedding plane exposures, the most common surface expression of the ripple cross-laminations are rib-and-furrow structures (Fig. 3-2b). The ribs are on average 8 cm apart, and between them lie concave downcurrent foresets, which are reliable indicators of the paleocurrent direction. Ripple fans are not a widespread occurrence; however, they do occur in abundance at Whirlpool State Park, where they are usually found at the toe of exhumed trough slipfaces (see Fig. 4-26b).

This facies is an unfossiliferous, well to very well sorted, occasionally calcareous, subarkosic arenite to quartzarenite, with rounded, moderately spherical grains ranging in size from 4 - 3.5 phi to 2.0 - 1.5 phi (usually being coarsest when the facies occurs in the lower 1/3 of the Whirlpool), with an average of 3.5 - 3 phi. The facies is usually grey to buff grey in colour, except in a few localities (The Whirlpool and core 240), where, it is observed to be dark brown or brownish red in colour.

Shale rip-up clasts are not a major component of this facies; however, they do occur at a few locations. The clasts are elongate, averaging 6 mm long (range is 2 to 20 mm) and 2 mm wide, lie parallel to the cross-laminae, and are composed of a greyish green silty shale. Other minor elements of this facies include parallel laminations, planar tabular cross-laminations, isolated troughs, and thin (0.5 to 4 cm thick) shale layers.

<u>Subfacies Srs: Symmetrical Ripple Cross-laminated Sandstone</u>

This facies is generally thin and tabular in form (ranging from 0.07 to 0.5 m in thickness), laterally persistent on outcrop scale, and usually found just below (and also within) the interbedded sandstone and shale facies, which occurs in the top 1/3 of the Whirlpool; however, a few occurrences of symmetrical ripples have also been observed stratigraphically lower than this (e.g. at Cataract and Artpark; see Fig. 4-31).

Bedding planes show straight to slightly sinuous, rounded to slightly sharp, rarely bifurcating ripple forms, with ripple indices ranging from 10 to 35 and averaging 15. Preferential transport is evident from the internal arrangement of the ripple laminations. Laminae average 1 mm in thickness and are occasionally accentuated by thin shale drapings lining remnants of ripple troughs. This can be observed in its extreme at the Kenilworth Ave. outcrop where a 0.13 m thick unit shows flaser bedding grading up into lenticular bedding (see Fig. 4-17a).

Like facies Src, facies Srs is a clean, unfossiliferous, subarkosic arenite with well sorted, rounded, and moderately spherical grains that average 3.5 -

3 phi in size. Synaeresis cracks and possible horizontal feeding trails have been observed on bedding planes at a few localities.

HORIZONTALLY- (PLANE) LAMINATED SANDSTONE (Sh)

This facies consists of very fine-grained, horizontally, parallel laminated sandstone. It is a fairly widespread facies, occurring in 14 of the 19 outcrop sections and in 2 of the 11 cores measured; however, in most cases it constitutes a very small proportion (11% on average) of the total Whirlpool thickness at any one locality. The Medina section is an exception, however, as this facies may possibly constitute up to 40% of the Whirlpool at this locality. Greater abundances of this facies (up to 59%) have been reported in quarries in the Halton Hills region (Salas, 1983). The occurrence of this facies is generally not restricted to any particular level in the vertical sequence.

The plane laminated sets, or beds, have an average thickness of 0.14 m and a range of 0.03 to 0.4 m, and generally occur in cosets of two to eight sets (Fig. 3-3a); however, at a few of the Niagara Gorge sections the number of sets in a coset may be significantly greater than this. The true abundance is indeterminable because the facies is situated near the top of the Whirlpool where much erosion

Figure 3-3. Features and typical appearances of facies Sh, horizontally-laminated sandstone.

a) A 30 cm thick coset of horizontal laminations (just above top of scale) overlain and underlain by trough cross-laminated units. Scale is 1 m in length. From Whirlpool State Park, almost directly across from The Whirlpool section bedding plane, 2 m above the base of the Whirlpool.

b) Close up of the horizontal laminations, showing their typical horizontal, planar, and parallel nature. Note the abundance of spherical weathering cavities in this unit. Lens cap (52 mm) for scale. From The Whirlpool section between section A and the bedding plane, 4.2 m from the base of the Whirlpool.

c) Heavy mineral shadows developed on a bedding plane surface. These are well developed and abundant in the Georgetown area (Cheel, 1984; Salas, 1983) but not in the study area of this thesis. The paleocurrent is to the right (note current crescents). Scale has centimeter divisions. From Brockton Quarry, south of Georgetown.


A


MINOLTA
B


C

has occurred. The Medina section possibly contains the greatest thickness of this facies (3 m), but its true thickness is rather difficult to determine due to the largely inaccessible nature of the outcrop. Upper and lower contacts of this facies are sharp and erosional at most outcrops.

Most of the laminations are very parallel and planar (Fig. 3-3b) and show no discordance with the regional bedding; that is, they are essentially horizontally lying. The laminations are generally well defined by abundant opaque minerals, which have a tendency to accumulate along planes between the laminations. The laminae range in thickness from 0.5 to 10 mm and average of 4 mm.

Good bedding plane exposures of the plane laminations showing well developed current and parting step lineations are few and far between. Heavy mineral shadows (Fig. 3-3c) (Cheel, 1984), which are abundant and well developed in a few of the Halton Hills quarries (New Smithson, Brockton, and Rice and McHarg) (Salas, 1983), are not observed at any of the localities in this study. A bedding plane exposure of plane laminations near the base of the Niagara Glen section displays good parting lineation and is reddish brown in colour, indicating a relatively high concentration of opaque heavy minerals (Cheel, 1984), but heavy mineral shadows, if present, are not well developed here.

This facies is an unfossiliferous, occasionally calcareous, very well to well sorted subarkosic arenite with moderately spherical and well rounded grains averaging 3.5 - 3 phi in size. This grain size remains fairly constant both regionally and vertically, although at a few localities, grain sizes between 2.5 - 3 phi are present near the base of the Whirlpool.

Greenish grey shale rip-up clasts are not an important component of this facies, occurring in this facies at only four localities. These clasts are elongate, averaging 1 cm long, and lie parallel to the laminations. No bedding plane exposures were available to reveal the orientation of the clasts with respect to the sense of the paleocurrent flow.

Other minor elements of this facies include thin ripple cross-laminated interlayers, occasional 0.5 cm thick shale partings, and current crescents on top of bedding plane surfaces (Fig. 3-3c).

PLANAR TABULAR CROSS-LAMINATED SANDSTONE (Sp)

This facies, which generally occurs in the lower two-thirds of the Whirlpool, is not a very abundant or commonly occurring facies. On average it comprises 5% of the total thickness of the Whirlpool, but this can vary, ranging anywhere from 1% to 29% (Jolley Cut). Unlike the previous facies, there appears to be no regional trend in the abundance of planar tabular cross-laminations.

The planar tabular cross-laminae always occur in single sets (Fig. 3-4a), with the exception of one occurrence (at Devil's Hole) of a coset consisting of three sets (Fig. 3-4b). The sets range in thickness from 0.06 to 0.90 m and average 0.19 m. The upper bounding set surface is erosional. The lower surface is characteristically irregular in appearance.

Regardless of the orientation of the outcrop face with respect to the paleoflow, the sets of this facies are tabular in form and persist laterally for 1 to 7 m, occasionally extending as much as 40 m.

The foresets of the planar tabular cross-laminae are very well defined. Most sections through this facies are longitudinal (Fig. 3-4a,b) to oblique with respect to paleoflow, and display planar foresets (sometimes having slightly tangential relationships with the lower set surface) with dips ranging between 19 and 30 degrees and averaging 24 degrees. Foresets range in thickness between 0.3 and 1.7 cm and average 0.7 cm. At one locality (Devil's Hole) foreset tops in each set are truncated by 0.14 m (on average) thick cosets of micro trough cross-laminations formed by flow perpendicular to that which formed the planar tabular cross-laminations (Fig. 3-4b). In plan view the planar tabular foresets' traces are straight to slightly

Figure 3-4. Facies Sp, planar tabular cross-laminated sandstone.

a) A longitudinal section through part of a 0.9 m thick set of planar cross-laminations. This is the greatest set thickness observed in the study area. Note the irregular, erosional nature of the upper bounding set surface. The scale is 40 cm long. From The Jolley Cut, section D, about 0.5 m above the Whirlpool's base.

b) Photo showing one and one-half sets of a coset containing three sets of planar tabular cross-laminations. The lower set of planar cross-laminations is 25 cm thick. Note the typical irregularity of the lower bounding set surface, and the erosional nature of the top surface. A 5 cm thick coset of ripple cross-laminations with a (paleocurrent into or out of the photo, normal to that of the planar cross-laminations) separates the two planar cross-laminated sets. From Devil's Hole, 4.7 m from the Whirlpool's base.

sinuous and are spaced 1 cm apart. Only one transverse section was observed and unexpectedly it showed slightly troughy laminations (at The Jolley Cut, section D).

Lithologically, this facies is a light grey (sometimes mottled red), unfossiliferous, moderately to well sorted sandstone with rounded grains ranging in size from 3.5 - 3 phi to 2.5 - 2 phi, and averaging 3 - 2.5 phi. There appears to be a slight fining of this facies northwards.

Silty shale rip-up clasts are not a major component of this facies. They occur in 50% of the facies units measured, and generally occupy about 1% of the facies by volume. In all the outcrops, the shale has weathered out leaving behind elongate holes, 0.5 to 4 cm long (average is 0.8 cm), that are oriented parallel to the foresets.

Other minor elements of this facies include spherical weathering cavities and the aforementioned ripple cross-laminations.

LOW-ANGLE CROSS-LAMINATED SANDSTONE (Sl)

Low-angle cross-strata are not a common occurrence in the Whirlpool outcrops. They appear more frequently in the cores, but mostly as minor elements within other facies. The low-angle cross-laminated facies generally constitutes between 3% and 9% of the total thickness of the Whirlpool, however a maximum of 44% occurs at the Kenilworth Avenue section. Both the upper and lower parts of the Whirlpool contain this facies.

Cross-strata that dip at angles less than 15 degrees (Reineck and Singh, 1980) are generally considered to be low-angled. The cross-laminae of this facies have dips ranging between 3 and 12 degrees; the average is 6 degrees. The foresets range in thickness between 0.1 and 0.8 cm and average 0.4 cm.

Single sets of cross-laminae are as common in this facies as cosets with two to three sets. Sets range in thickness from 0.06 to 0.6 m (Fig. 3-5) and average 0.17 m. Sets are typically tabular- to wedge-shaped and persist laterally for 1 to 5 m. Within cosets, each successive set may either dip in the same or opposite direction as the set below, and the laminae within one set are commonly truncated from above by those of the overlying set.

The facies takes on a slightly different appearance in the lower part of the Whirlpool than in the upper part. In the lower part, the cross-laminae are planar and parallel to each other (Fig. 3-5), while in the upper part, although some examples of this facies do show planar and parallel cross-laminae, most show parallel, gently curving, sometimes slightly undulating (wavelength about 1 m) cross-laminae. Understandably, these cross-laminations may be easily mistaken for hummocky cross-stratifications (HCS). To be

Figure 3-5. An example of facies Sl, low-angle cross-laminated sandstone, in the lower part of the Whirlpool. Note the planar, parallel nature of the cross-laminations, which, in this case are dipping about 7 degrees to the left (southeast). The set is 0.6 to 1 m thick. Hammer is 33 cm long. From Kenilworth Avenue, 0.3 m above the Whirlpool's base, located at 60 m on the horizontal scale of Figure 4-19.

classified as HCS, the exposure of a unit had to be good and extensive enough to show the features (see facies HCS) characteristic of HCS, otherwise the unit was placed in the low-angle cross-laminated sandstone facies.

Lithologically, this facies is a light grey (one occurrence of red), unfossiliferous, well sorted, quartzarenite with well rounded, moderately spherical grains ranging in size from 2 - 1.5 phi to finer than 4 - 3.5 phi and averaging 3.5 - 3 phi.

Silty shale clasts occur in 37% of the facies units measured. They are elongate, averaging 0.5 cm long (range is 0.1 to 5 cm) and 0.2 cm wide, lie horizontal or parallel to the cross-strata, and occupy less than 1% of the facies by volume.

Trace fossils were observed in two of the fourteen facies units measured. These units were located in the upper part of the Whirlpool and displayed Skolithos burrows and horizontal hypichnial and epichnial feeding tracks.

MASSIVE SANDSTONE (Sm)

The massive sandstone facies is quite widespread throughout the study area, but it occurs in only one half of the total number of sections (both core and outcrop) measured. The facies constitutes between 3% and 80%, but generally averages 15% of the total thickness of the

Whirlpool.

The massive facies, as the term implies, has sandstone beds that lack detectable lamination. A few of the cores, however, showed minor occurrences of faint lamination (horizontal, planar low-angle, and ripple cross-laminations), but these were not observed in outcrop.

In most cases, the massive facies occurs at or within 0.5 m of the base of the Whirlpool; however, it is not restricted to this level, for it also occurs at higher stratigraphic levels. The thickness of this facies ranges anywhere from 0.04 to 2.25 m. Upper and lower bounding surfaces are generally erosional, or sharp, but gradational contacts are also quite common. The outcrops are generally too poor to determine the shapes of these contacts, but when the lower contact is with the Queenston, the surface is seen to be essentially planar on a scale of tens of meters, but quite irregular on a much smaller (tens of centimeters) scale.

The massive sandstones are light grey, well sorted, commonly calcareous subarkosic to quartzarenites with rounded to well rounded, moderately spherical grains. Locally, concentrations of hematitic cement impart a dusky red colour to the facies. Grains in the basally located massive sandstones show a slight fining northward from 2 - 1.5 phi at the Cataract to 4 - 3.5 phi at Osler Bluff. Overall, the grain size of this facies ranges from 2 - 1.5

phi to finer than 4 - 3.5 phi and averages 3.5 - 3 phi. Both inverse and normal grading occur in just under half of the sections measured; however, the grain size difference is never more than one phi interval in the fine to very fine sand range.

Silty shale rip-up clasts occur in just 13% of the facies units measured. They are elongate, averaging 0.6 cm long (range is 0.1 to 0.9 cm) and 0.1 cm wide, and show no preferred orientation.

Other constituents of this facies include spherical weathering cavities and thin (2 to 8 cm) intervals of ripple and low-angle cross-lamination and convolute lamination. There are no signs of dewatering structures, fossils, or burrowing.

Mineralization occurs in the basally situated massive sandstones where pyrite is present as cement and as a replacement of phosphatic (?) grains.

CONVOLUTE LAMINATED SANDSTONE (Sc)

The convolute laminations are not a commonly occurring facies (occurring in only 5 of the 30 sections measured), and they appear to occur more abundantly in the cores than in the outcrops. The facies is restricted to the lower part of the Whirlpool and comprises between 4% and 26% of the Whirlpool's total thickness. It appears to be most commonly found in association with facies Sm.

The convolute laminations form units 0.2 to 1.1 m in thickness, with an average of 0.7 m. Contacts with overlying and underlying units are either gradational or sharp.

The structures of the convolution are better revealed in outcrop than in core. The two outcrops containing this facies show the two varieties of deformation present in the Whirlpool. The Artpark displays ball-and-pillow structures (Fig. 3-6a), 0.5 m in diameter, while Balls Falls shows just convoluted laminae. Here, as in many of the cores, deformation of the laminae is slight at the base of the unit and increases in intensity upwards, forming sharp anticlines and more gentle synclines near the top (Fig. 3-6b,c). Fold axes are inclined in a downcurrent direction, as determined from adjacent cross-laminated units. The thickness of the laminations in this facies range from 0.1 to 1 cm and average 0.4 cm.

This facies is a light to dark grey, sometimes calcareous, subarkosic to quartzarenite with rounded, to well sorted, moderately spherical grains ranging in size from 4 - 3.5 phi to 3 - 2.5 phi and averaging 3.5 - 3 phi.

Silty shale rip-up clasts are present in 60% of the units measured. They are elongate, ranging from 0.2 to 1 cm and averaging 0.3 cm long, and are oriented parallel to the convoluted laminations.

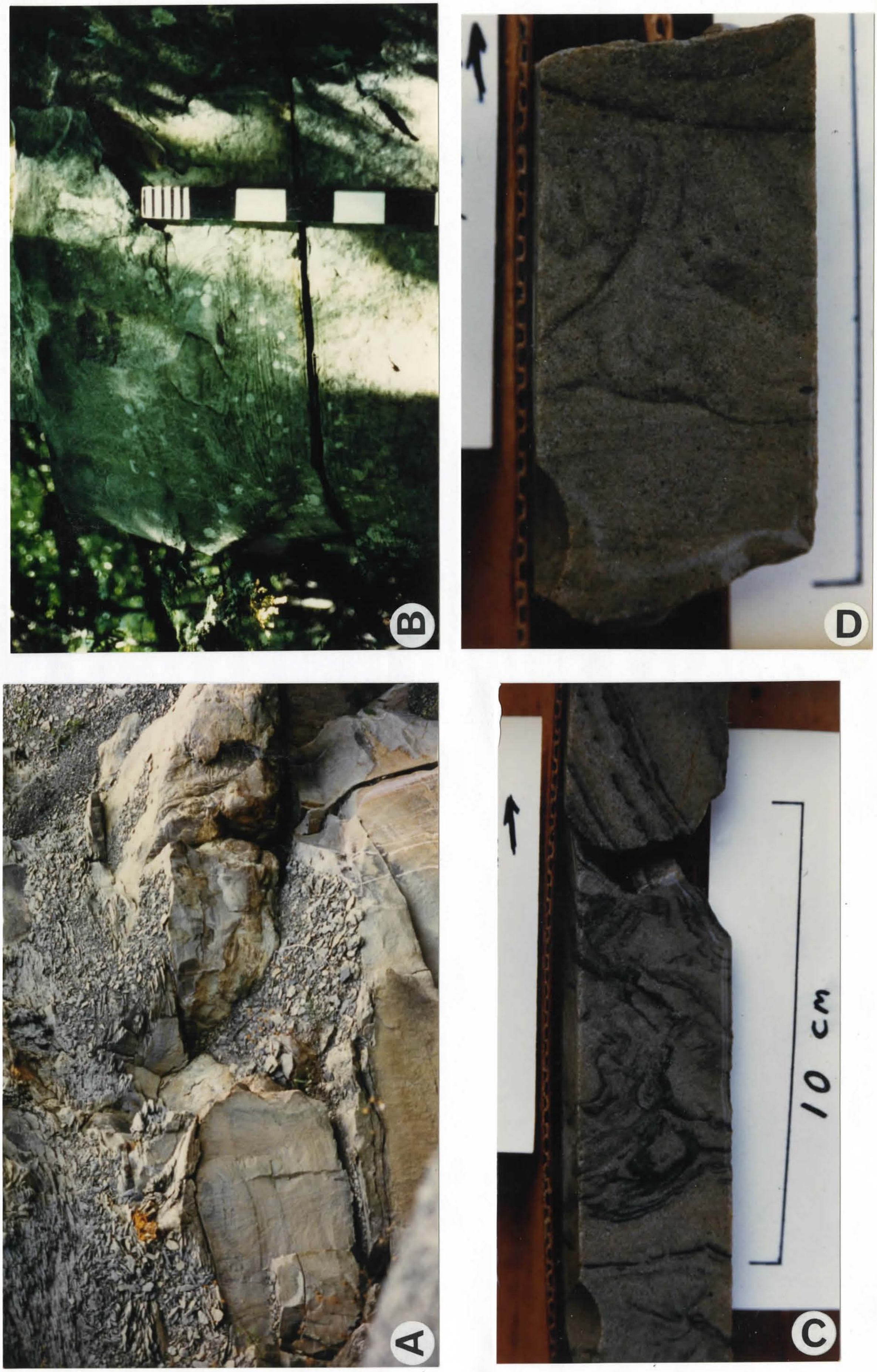
Figure 3-6. Three varieties of facies Sc, convolute laminated sandstone.

a) Ball-and-pillow structures. Left ball-and-pillow structure is about 0.5 m wide. From Artpark, about 150 m south of the escarpment, 7 m above the Whirlpool's base.

b) Convolute lamination in outcrop. Note how the low-angle, parallel, and planar laminations at 30 cm from scale's top grade upward into strongly deformed laminations, displaying sharp anticlines and gentle synclines. Large divisions on scale are 10 cm in length. From Balls Falls, section E, 4 m above the Whirlpool's base.

c) Convolute laminations in the cores, here interpreted as minor slump structures. Arrow indicates up. From core 240, 3.5 m above the Whirlpool's base.

d) Possible dish and pillar structures. Positive identification of these structures in cores is made difficult by their resemblance to trough cross-laminations. Arrow indicates up. From core 240, directly overlying the unit shown in Fig 3-6c, 4 m above the Whirlpool's base.


B
D
A
C
10 cm

Other constituents of this facies include layers (up to 10 cm thick) of massive sandstone and thin (1 cm) sets of ripple cross-laminations. Dish and pillar structures (?), another type of physically induced deformation, overlie the convolute laminated unit in core 240 (Fig. 3-6d). The recognition, or positive identification of these structures in cores, however, is made difficult by their close resemblance to trough cross-laminations. No fossils or trace fossils are present in this facies.

BIOTURBATED SANDSTONE FACIES (Sb)

The bioturbated sandstones are a widespread and abundant facies, occupying from 6% to 99% of the total thickness of the Whirlpool. The facies occurs in only the upper part of the Whirlpool, and in the cores, where the upper part constitutes a greater percentage of the Whirlpool, the bioturbated sandstones are most abundant. The cores show a trend of decreasing abundance of facies Sb from the west to the east.

Units in which bioturbation is the most prominent feature are placed into the bioturbated sandstone facies; in this case, bioturbation (which reflects the amount of laminae disturbance by burrowing organisms) ranges from moderate to complete (Reineck, 1963; cited in Reineck and Singh, 1980). Such strong bioturbation is reflected by a ropy or knotted textural appearance of the outcrop face (Fig. 3-7a). Sandstone beds displaying similar or lesser degrees of bioturbation are also present in facies S/F; there they are considered a 'subfacies' within that facies.

Unit thicknesses are variable, ranging from 0.15 to 1.96 m, but generally the units average less than 0.7 m in thickness. Bed thicknesses, as determined from outcrop sections, range between 0.1 and 0.45 m, and average 0.24 m. Beds are tabular and laterally extensive on the scale of the outcrop.

The bioturbation in this facies is most often complete (Fig. 3-7b), although it may range anywhere from moderate to complete, often increasing in intensity up the section until it grades, usually, both lithologically and biogenically, into the Manitoulin or Cabot Head; lower facies contacts are similarly gradational, although sharp contacts with the last shale layer in facies S/F are also quite common. Remnants of pre-existing laminations (in patches a few centimeters long), usually wavy and horizontal in nature, are present in some units; laminae thicknesses range from 0.1 - 2.5 cm, averaging less than 1.0 cm.

Both deformative (i.e. nondescript) and figurative (Schafer, 1972) bioturbation structures (hypichnial, exichnial, and endichnial) are present. The figurative structures include Palaeophycus, Arenicolites, Lingulichnus, Chondrites, Teichichnus, and possible Asterosoma, Scoyena,

Figure 3-7. Facies Sb, bioturbated sandstone.

a) Typical appearance of completely bioturbated sandstone (B) in outcrop. Note the ropy or knotted textural appearance of the sandstone, and also the large (23 cm long) elongate, irregularly-shaped, shale rip-up clast 20 cm to the left of the scale. This photo is of the entire upper Whirlpool at The Jolley Cut. Note how the bioturbated sandstone grades upward into the Manitoulin (M). A possible HCS bed (H), showing a sharp, erosive base and low-angle, convex-upward and concave-upward laminations, sharply overlies the lower part of the Whirlpool (LW). Scale is 40 cm long. From The Jolley Cut, section B, 3.5 to 4.5 m above Whirlpool's base.

b) Typical appearance of completely bioturbated sandstone in the westernmost cores. In this case, the sandstone laminations have been completely disturbed by abundant Chondrites burrows. Scale is 10 cm long and the arrow indicates up. From core 106, 4.5 m above the Whirlpool's base.


M
B
H
LW
A


B

and Scalarituba traces, with Chondrites (Figs. 3-7b, 3-15b) being the most commonly occurring. Fossils, generally constituting less than 3% of the facies, are present in 32% of the sections having this facies, and include rugose coral, crinoid, and gastropod fragments.

Elongate, horizontally-lying, silty, shaly rip-up clasts occur in 37% of the sections bearing this facies. They are quite large, with lengths ranging from 1 to 25 cm (averaging less than 10 cm) and widths, 1 to 1.5 cm (Fig. 3-7a). Internally, they display very distinct, horizontal and parallel laminae with thicknesses of about 1 mm.

The bioturbated sandstone facies is composed of very fine-grained, well sorted sandstone with varying amounts (0% to 50%) of interstitial mud, which imparts an olive grey colour to the rock. Grains are well rounded to rounded and moderately spherical, and range in size from 2.5 - 2 phi to finer than 4 - 3.5 phi, and average 3.5 - 3 phi. The sandstones are always dolomitic (the dolomite content increasing upwards) in sections where the Whirlpool is overlain by the Manitoulin Dolomite, but this is not always the case when it is overlain by the Cabot Head Shale. Glauconite occurs in a few of the cores, and pyrite, mostly in trace amounts, is scattered throughout the sandstones, sometimes forming the lining of endichnial burrows.

Minor elements of this facies include horizontal, wavy, and symmetrical ripple cross-laminations, massive sandstones, and vugs filled with celestite crystals.

HUMMOCKY CROSS-STRATIFIED SANDSTONE (Shcs)

The hummocky cross-stratified sandstones (HCS), restricted in occurrence to the upper part of the Whirlpool, are not a commonly occurring or abundant facies. The facies constitutes 4% to 48% of the Whirlpool's total thickness, but generally averages about 10%. The HCS facies is present in only three outcrops and possibly two cores. Some uncertainty is attached to the two present in the cores; although they show the characteristics of and the structures commonly associated with HCS, without the lateral control that outcrops provide, it is difficult to place any great confidence in their actual presence.

HCS is a relatively new sedimentary structure, although it was first described (as 'giant ripples') in 1899 by Gilbert, who noticed it at various stratigraphic levels within the Medina Group. Since its rediscovery by Campbell in 1966, much has been written about the characteristics and structures commonly associated with HCS (e.g. Goldring and Bridges, 1973; Harms et al., 1975; Dott and Bourgeois, 1982; Walker et al., 1983; and Duke, 1985a,b,c).

By definition, HCS is characterized by non-intersecting, low-angle (less than 15 degrees) cross-laminations that curve both convex-upward ('hummocks') and concave-upward ('swales'). Intersections between laminae (second order surfaces) are either angular or tangential and also may be either 'truncating' or 'terminating' in nature (Duke, 1985c). HCS is commonly associated with certain other sedimentary structures. Dott and Bourgeois (1982) have proposed an ideal sequence for the structures commonly associated with HCS. In ascending stratigraphic order of occurrence, the divisions are: hummocky cross-stratification (H), flat lamination (F), cross-lamination (X), and mudstone (M), one or all of which may be slightly to thoroughly bioturbated. Walker et al. (1983), however, prefer to include a sharp-based, massive and/or graded base (B) and a parallel laminated (P) division, such that the sequence becomes BPHFXM (Fig. 3-8). Take note that not all of these divisions occur with HCS all the time.

In the Whirlpool, the HCS facies, which, in this thesis, includes both HCS and its associated structures, takes on a slightly different appearance at each outcrop. In general, the hummocky cross-laminations are typical, showing slightly curved, convex- and concave-upward, low-angle cross-laminations, which conform to the underlying second-order surface. Only one section, Lockport, shows more planar-like low-angle cross-laminations. Second-order boundaries are usually 'truncating', and the laminations intersecting these surfaces are commonly tangential. The dips of the laminations range from 5 to 15 degrees, but

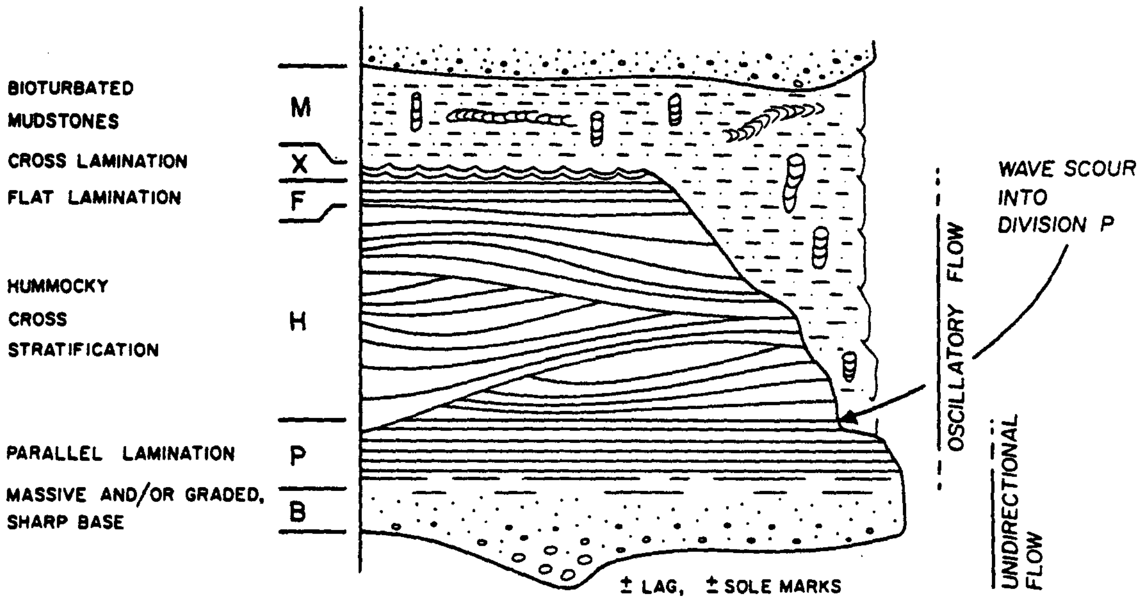


Figure 3-8. Hummocky cross-stratification and its associated sedimentary structures are shown here in an ideal sequence proposed by Walker and others (1983).

generally average about 10 degrees. Occasional lateral thickening and thinning of the laminae are responsible for the large range in strata thickness (0.2 to 3 cm), but generally the laminae average less than 0.5 cm in thickness.

With respect to the ideal sequence mentioned above, the divisions present in this facies vary depending on the mode of the facies' occurrence. The facies occurs both as amalgamated HCS sequences and as a single sequence, or bed, within the interbedded sandstone and shale facies (S/F). When it occurs within facies S/F, it will be referred to as a subfacies (S/Fhcs) of facies S/F; as a matter of convenience, however, the features of subfacies S/Fhcs will be described in this section.

Amalgamated Hummocky Cross-stratified Sequences (Shcs.A)

The amalgamated HCS sequences consist of amalgamated individual HCS beds, or sequences, showing an absence of M and a few of the other divisions normally found above division H. Two of Duke's (1985c) four types of amalgamated HCS sandstones are present within the Whirlpool: hummocky to bioturbated amalgamated HCS (Shcs.Ah-b) and dominantly bioturbated amalgamated HCS (Shcs.Ab) (Fig. 3-9).

Hummocky to bioturbated amalgamated HCS (Shcs.Ah-b). This type of amalgamated HCS occurs at the Kenilworth Avenue section (Fig. 3-10a), where it comprises 48% of the Whirlpool's thickness, and possibly in core 240. The number

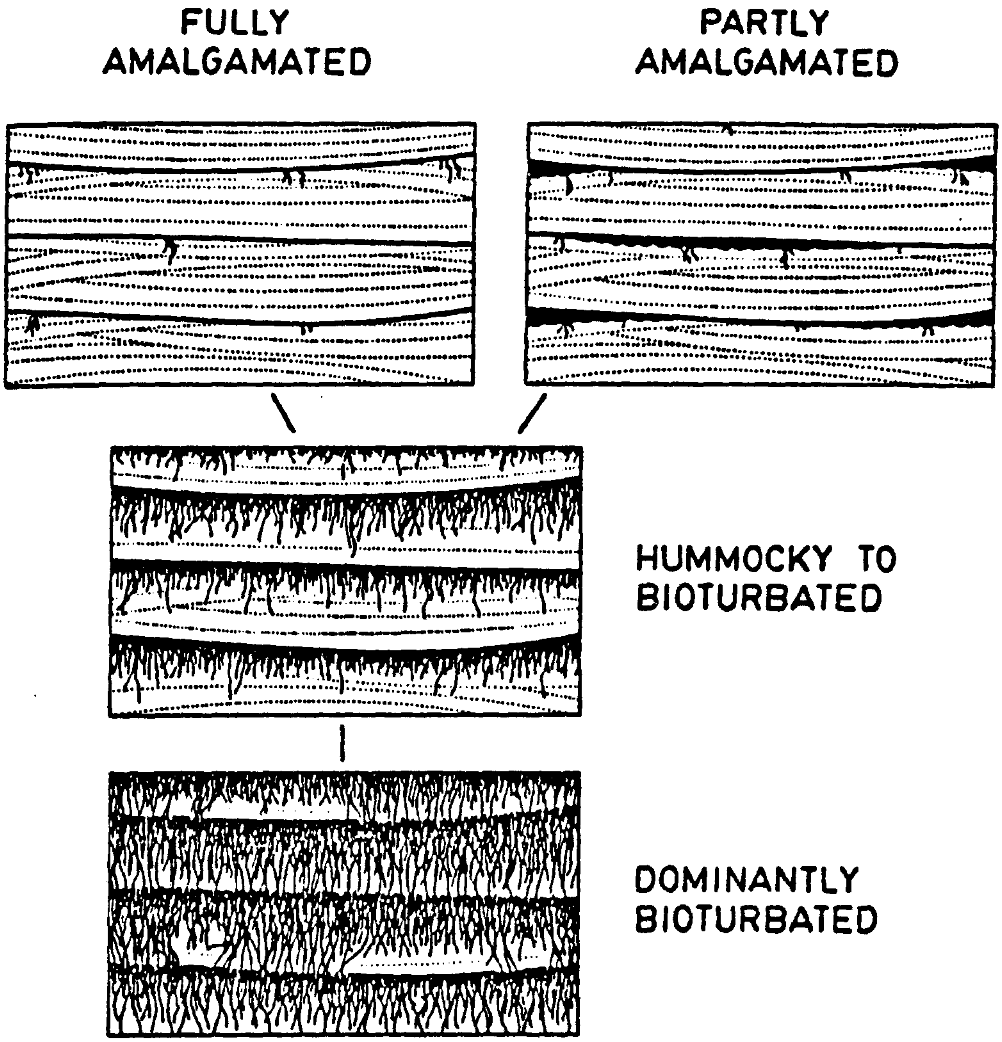


Figure 3-9. Duke's (1985c) four types of amalgamated hummocky cross-stratified sandstone. Two of these have been observed in the Whirlpool: hummocky to bioturbated and dominantly bioturbated.

Figure 3-10. Hummocky to bioturbated amalgamated HCS (facies Shcs.Ah-b).

a) An example of hummocky to bioturbated amalgamated HCS, showing the presence of at least four amalgamation units. Three units are clearly visible. The fourth begins 33 cm from the bottom of the scale and is about 3 cm thick (see photo below). Note the tabular form of the units, the slight upward concavity of the internal laminations, and the upward increase in the thickness of the bioturbated interval. Scale is 40 cm long. From Kenilworth Ave., at 53 m (see horizontal scale in Fig. 4-19), 1.7 m above Whirlpool's base.

b) Close up of Figure 3-10a (at far left) showing the details within three amalgamation units. Note that the base of each unit is sharp and truncates the thoroughly bioturbated part of the underlying unit. The bioturbated part of each unit shows an upward increase in bioturbation intensity. A massive division appears to be present at the base of the uppermost amalgamation unit (where the scale reads 300 cm). Scale has centimeter and inch divisions. Same location as Figure 3-10a.


A


B

of individual amalgamated HCS sequence beds, or 'amalgamation units' (Duke, 1985c), present varies laterally, ranging from two to about seven (Fig. 4-18), and the thickness of this facies varies accordingly from 0.5 to 1.1 m. The amalgamation units are essentially tabular in form, but may show slight pinching and swelling. The amalgamation unit thicknesses range from 0.03 to 0.25 m, but are usually about 0.15 m. Some units exist across the entire length of the outcrop, but most pinch out or become truncated by other units after about 10 to 15 m.

Each amalgamation unit is characterized by a laminated lower part and a thoroughly bioturbated upper part (Fig. 3-10b). The base of each amalgamated unit (first-order surface; Duke, 1985c) is sharp and truncates the biogenic structures of the underlying unit. The basal surface, where exposed, only shows abundant horizontal trace fossils in convex hyporelief; no sole markings are present. Occasionally scouring occurs, but never for more than 10 cm in relief.

In these hummocky to bioturbated amalgamated HCS units, divisions F, X, and M are missing, due either to erosion caused by the emplacement of the overlying unit or to thorough bioturbation. Division B (massive, with occasional shale rip-ups) occurs in places, but generally the unbioturbated parts of the units are just laminated. The laminations are so gently curved that it is at times difficult to tell whether division P or H, or both are present. (The lack of well-defined curvature of the laminations may lead some to question the appropriateness of calling this facies HCS. Some may prefer the term 'lam. scrams.'; however, the characteristics of this facies are very similar to those of the 'sublittoral sheet sandstones' described by Goldring and Bridges (1973), and these have since been identified as exhibiting HCS. Brenchley (1985) lists variations in the HCS model that can be expected.) The bioturbation in the upper part is thorough; however, the intensity of the bioturbation decreases downward from where it is truncated by the overlying unit to where it grades into the laminated part of the same unit (Fig. 3-10b). A few Skolithos and Teichichnus burrows can be made out amidst the thoroughly bioturbated sandstone. The thicknesses of these bioturbated tops varies, ranging from 1 to 7 cm.

Bioturbated amalgamated HCS (Shcs.Ab). This type of amalgamated HCS differs from the hummocky to bioturbated type in having a much greater thoroughly bioturbated:laminated ratio; in fact, laminated intervals are sporadic throughout the outcrop, and are rarely continuous laterally for more than 1 m. This type of amalgamated HCS occurs only at one section, the Jolley Cut.

The number of amalgamation units within the facies is generally greater than four. Thickness of individual amalgamation units varies from 0.03 to 0.2 m, and that of the bioturbated portions, 1 to 10 cm. From what remains of the original primary structures, the laminations appear to be low-angled (possibly division H), and are on average 1 cm thick.

The bioturbated portion within each unit has a gradational lower contact with the laminated lower part, with the bioturbation degree rapidly increasing to 'thoroughly bioturbated' before it is sharply truncated above by laminations of the overlying amalgamated unit. Some Skolithos and Teichichnus burrows are present in the bioturbated intervals.

Locally, only a hint of pre-existing laminae is preserved, and if it were not for the fact that these units are stratigraphically equivalent to those already recognized as HCS, they could easily be mistaken for facies Sb.

HCS in the Interbedded Sandstone and Shale Facies (S/Fhcs)

Single HCS beds, or sequences, occur in facies S/F, but usually there is only one occurrence within the entire S/F facies at any one locality.

The HCS beds are essentially tabular (see Fig. 3-7a), although some pinching and swelling occurs, and are laterally extensive on the scale of the outcrop. Beds range from 0.06 to 0.48 m in thickness, but average around 0.1 m.

The basal surface is flat and sharp with the underlying shale, occasionally scours (no more than 10 cm) into this shale, and displays a moderate abundance of _Palaeophycus_ and nondescript horizontal burrows in convex hyporelief. The top surface (also sharp) is flat to gently undulating, with a wavelength of 10 to 15 m and a height reaching as much as 0.2 m (Fig. 3-11a) (e.g. Lockport).

The number of divisions present exceed that which is found in the amalgamated HCS units. In all occurrences, a lag of shale rip-ups occurs just above the base, followed, then, by division H. Division F is sometimes present, as is division X, symmetrical ripples, which have wavelengths of 0.14 m and heights of 1 cm, and which occasionally show vertical aggradation and slight preferential drift (Fig. 3-11b). Division M is always present and is commonly bioturbated (with _Chondrites_). However, bioturbation is not always restricted to this division: the top surface of the HCS bed displays a low abundance of _Palaeophycus_ and other nondescript horizontal burrows in convex epirelief, as well as a few _Skolithos_ and _Lingulichnus_ burrows, which extend down into the top of the HCS bed. Bioturbation (if present) near the top is occasionally thorough and may constitute up to 0.1 m of the thickest HCS beds (Fig. 3-11c).

The grain size of the HCS sequences in the Whirlpool ranges from 2.5 - 3 phi to 3 - 3.5 phi. The sandstone is a subarkosic arenite, sometimes calcareous, with grains that

Figure 3-11. Facies S/Fhcs, HCS in interbedded sandstones and shales.

a) Photo showing the geometry and sharp base of an HCS bed, which lies just below the 1 m long scale. This particular bed has an undulating top surface, with a wavelength of 10 to 15 m. From Lockport road cut, 4.4 m above the Whirlpool's base.

b) Close up of the above showing details of the internal structures present. Note how the low-angle cross-laminations of division H (HCS) grade up into flat laminations (F), which, in turn, grade up into vertically aggrading, slightly drifting symmetrical ripples (X). Scale divisions are 10 cm.

c) Same HCS bed as above but 10 m to the right, showing a thoroughly bioturbated top (note two Skolithos burrows). Hammer tip rests in a large (0.5 m long) cavity, possibly a weathered-out shale rip-up clast.


A


X
F
H
B


C

are well sorted, rounded, and moderately spherical. Mineralization is limited to traces of authigenic pyrite.

Elongate, horizontally-lying, silty, shaly rip-up clasts are usually present, found evenly distributed throughout or concentrated at the base of the HCS bed or amalgamation unit. They range in size from 0.2 to 10 cm, but generally average around 1 cm in length.

Fossils are relatively rare in facies Shcs. A few rugose coral and brachiopod fragments were found at one section only (Kenilworth Ave.), the former being the more abundant of the two. Trace fossils, occurring as epichnial, endichnial, and hypichnial traces, are generally abundant and consist mainly of Palaeophycus, Lingulichnus, Teichichnus, Skolithos, and several nondescript forms.

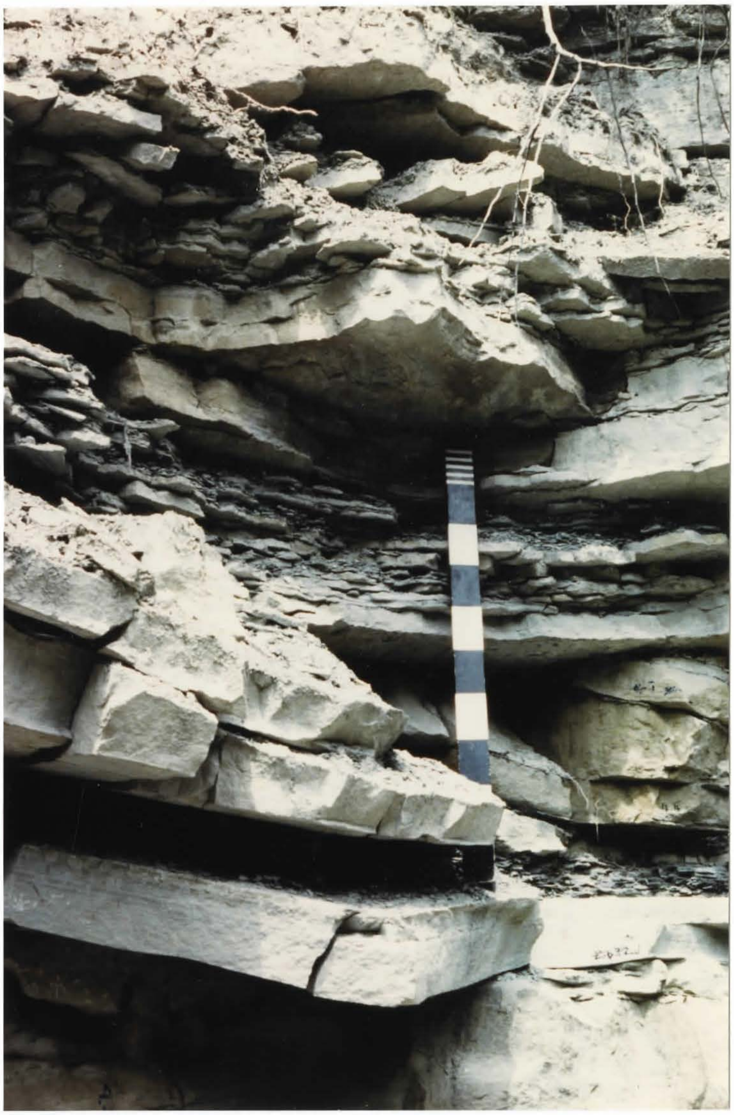
INTERBEDDED SANDSTONE AND SHALE (S/F)

This facies, as the name implies, consists of interbedded fine-grained sandstones and shales. Its occurrence is limited to the upper portions of the Whirlpool only. Although it is quite widespread throughout the area of study, it is only present in 62% of the cores and outcrops measured. The thickness of the facies varies from section to section, ranging from 0.4 to 2.5 m, but there does not appear to be any regional trends. The relative thickness, or the percentage of the Whirlpool the facies occupies, however, does show regional trends: from Duntroon, where it is 30%, it declines steadily southward to Kenilworth (5%), and from here it increases eastward to Lockport, where it is 35%. Generally, the facies constitutes greater than 20% of the Whirlpool's thickness.

Facies S/F is essentially tabular in form; however, at a few outcrops (e.g. the Lockport railroad cut) basal scouring is quite prominent (greater than 1 m) and results in a more irregularly shaped facies (See Fig. 4-35b). Lower and upper bounding facies surfaces are sharp and gradational, respectively, the upper passing up into the Manitoulin to the northwest, and into the Cabot Head, to the west and east. Quite commonly the lower facies surface is marked by the presence of shale clast lags and/or the symmetrical ripples of facies Srs.

The sandstone beds are tabular in form, laterally extensive on the scale of the outcrop, have sharp bases and tops, and average less than 10 cm (range is 0.2 to 48 cm) in thickness. The shales are very recessive in outcrop and are laterally extensive on the scale of the outcrop (Fig. 3-12). Shale layers range in thickness between 0.05 and 70 cm, but generally average less than 5 cm. The sandstone:shale ratio varies from outcrop to outcrop and vertical trends are apparent in a few exposures. The ratio ranges from 1:1.8 to 2.8:1, but normally there is a predominance of sandstone in the facies, producing an average ratio of 2:1. At any one

Figure 3-12. Typical appearance of facies S/F, interbedded sandstone and shale, in outcrop. Lower 2 cm of photo show the lower part of the Whirlpool. Note its sharp contact with the upper part. Scale is 1 m in length. From Cataract, west side of gorge (far left side of Fig. 4-13) 4 to 6 m above the base of the Whirlpool.



outcrop the ratio may remain constant vertically, but in some exposures the upward variations, or trends in shale and sandstone thicknesses may result in an upward decreasing or increasing sandstone:shale ratio. Some shale layers do occur stratigraphically lower than facies S/F, but they are not considered a part of facies S/F until they become more regularly interbedded with the sandstone beds.

The sandstone beds contain a variety of internal primary sedimentary structures of which horizontal laminations and symmetrical ripples are the most commonly occurring. These two often occur in the same bed, with the horizontal laminations in the lower half passing up into the symmetrical ripples at the top. Both interference and straight-crested (sometimes bifurcating) forms of symmetrical ripples are present (Fig. 3-13a,b). Symmetrical ripple cross-stratified sets range in thickness between 2 and 4 cm, but generally average 3 cm in thickness. Ripple crests are rounded and yield wavelengths ranging from 5 to 20 cm (average is 11 cm) and heights ranging from 0.2 to 1.5 cm (average is 1 cm); consequently, the ripple index is also quite variable and ranges from 6.5 to 16. Occasionally, sand-filled ridges, possibly formed by synaeresis (Fig. 3-14a), occur in the troughs between ripple crests.

Other structures present in the sandstone beds are low-angle (less than 15 degrees) cross-laminations, HCS,

Figure 3-13. Two forms of symmetrical ripples in facies S/F.

a) Interference ripples developed on the top of a sandstone interbed. Canadian quarter for scale. From Lockport railway cut, east wall.

b) Straight-crested, slightly sinuous, bifurcating symmetrical ripples on the top of a sandstone interbed. Note the presence of abundant Lingulichnus burrows and a few crinoid ossicles. Canadian quarter for scale. Lockport railway cut, east wall.


A

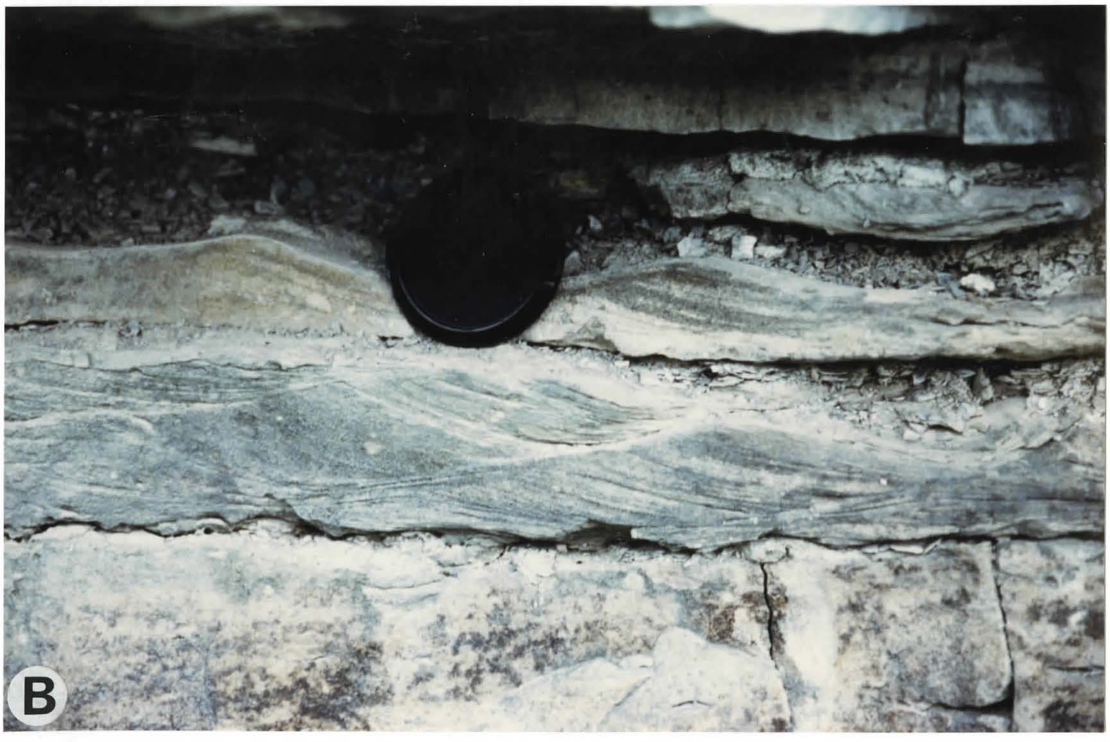

B

Figure 3-14. Other features of facies S/F.

a) Synaeresis cracks on the top of a sandstone interbed. Lens cap is 58 m in diameter. From Lockport railway cut, east wall.

b) Well developed climbing symmetrical ripples. Note the symmetrical form of the top surface of the beds (near lens cap). Drift direction is to the west. Lens cap is 58 mm in diameter. From The Jolley Cut, section D, 2.7 m from the bottom of the section.


A


B

bioturbated sandstone, massive sandstone, and wavy laminations. Beautiful symmetrical, aggradational and climbing ripple sets (angle of climb is 12 degrees) occur at one section (Jolley Cut) (Fig. 3-14b); their origin from drifting symmetrical ripples is inferred from their symmetrically rippled upper bedding surface. The thickness of these and other cross- and horizontal laminations in the sandstone beds of facies S/F ranges from 0.03 to 0.8 cm and averages 0.2 cm. Desiccation cracks and wrinkle marks occur at the Lockport railroad cut (see Fig. 4-36). Desiccation cracks also occur in the Georgetown area (Salas, 1983) and possibly in the Corbetton (OGS) core.

Bioturbation is quite common in the sandstone beds of facies S/F (Fig. 3-15a). Quite often internal bioturbation is difficult to see. Its presence, however, is revealed on the top and bottom surfaces of sandstone beds, where a diversity of trace fauna produce varying degrees of bioturbation ranging from slight to very strong; in most cases, the degree of bioturbation increases upwards. The traces are preserved as endichnial and convex epirelief and hyporelief forms, and the most commonly occurring forms include: Palaeophycus, Teichichnus, Chondrites, Lingulichnus, Skolithos, Diplocraterion, unknown horizontal and vertical to oblique burrows, and many nondescript biogenic structures (see Chapter 5, Table 5-1 for a more complete list of trace fossils). Take note that not all of

Figure 3-15. Bioturbation in facies S/F.

a) Thorough bioturbation of the top of a sandstone bed (an HCS bed, in this case). Note how the thickness of the bioturbated interval varies laterally. Pen for scale. From Lockport road cut 4.3 m above the Whirlpool's base.

b) Thorough bioturbation of the silty shale interlayers by Chondrites burrows (white protruding burrows). Pen for scale. Lockport road cut, 4.3 m above the Whirlpool's base.

these traces occur at every section. The shales, too, are moderately to very strongly bioturbated and contain mostly sand-filled burrows (exichnia) of Chondrites (Fig. 3-15b). (See Chapters 4 and 5 for pictures.) The Whirlpool's trace fossils consist of those generally associated with the Skolithos and Cruziana ichnofacies, with the Skolithos assemblage generally found on the tops of the sandstone beds, and the Cruziana assemblage, in the shale layers and on the base of the sandstone beds.

Fossils are not overwhelmingly abundant in this facies. Their sporadic occurrence is limited to only six, possibly seven forms: brachiopods, gastropods, ostracods, crinoids, bivalves, corals, and possibly trilobites. The trilobite fragments (which may possibly be flakes of mica) and crinoid ossicles are commonly found concentrated (not together) in thin (2 mm) layers between laminations within the sandstone beds.

The sandstones in this facies are light grey subarkosic arenites with variable amounts of carbonate cement. Generally, the carbonate content increases upwards in the section. The grains are well sorted, well rounded, moderately spherical, and range in size from finer than 4 - 3.5 phi to 3 - 2.5 phi; the average is 3.5 - 3 phi. Grain sizes at the base of facies S/F show a slight fining to the west and northwest, and grain sizes within the facies, itself, show a fining upward in section. The shales in facies S/F are silty and range in colour from greenish grey to olive black, reflecting, no doubt, the variability in the silt content.

Grey, silty shale rip-up clasts are present in 53% of facies S/F's occurrences. They are elongate, averaging 1.5 cm (range is 0.2 to 10 cm) in length and 0.5 cm (range is 0.2 to 1.5 cm) in width, and lie parallel to the internal laminations.

Mineralization is minor and occurs only as traces of authigenic pyrite and limonite.

WAVY-LAMINATED SANDSTONE (Sw)

This facies is characterized by horizontal-lying, very fine-grained sandstone laminations that are bounded above and below by very irregular, or wavy, shaly partings of variable thicknesses. The facies looks very much like the wavy flaser bedding or wavy bedding of Reineck and Wunderlich (1968), but the ripple cross-laminations characterizing the sandstone layers of these two structures are not present in the sandstone laminations of facies Sw.

The wavy-laminated sandstones are a widespread and commonly occurring (present in 52% of the sections measured) facies in the study area. The facies is located in both the lower and upper units of the Whirlpool, but it is more commonly found in the upper portion. Facies Sw constitutes from 3% to 73% of the Whirlpool's thickness at any one section, but generally it makes up less than 15% of the Whirlpool.

In outcrop, the facies is generally tabular- to wedge-shaped and may or may not extend throughout the entire length of the exposure. The thickness of facies Sw is quite variable, ranging between 0.15 and 1.96 m, but it generally averages around 0.5 m in thickness. The upper and lower bounding surfaces of the facies may be either sharp or gradational.

The beds in this facies are tabular, laterally extensive (on the scale of the outcrop), and range in thickness from 1 to 30 cm. On average the beds are 15 cm thick, but in the northernmost sections the average bed thickness is considerably less than this (usually no greater than 5 cm).

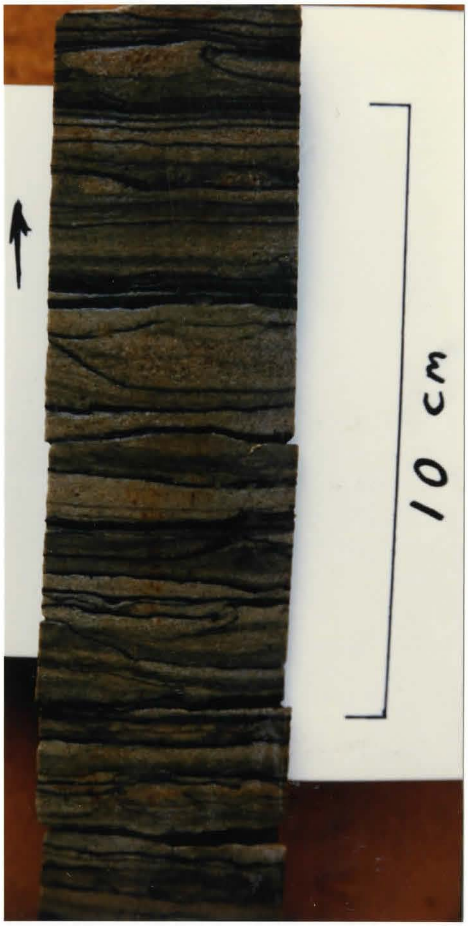
As previously mentioned, the wavy-laminated nature of this facies is defined by the presence of horizontal, irregularly spaced wavy (relief is no greater than 1 cm) shale partings. Within a single exposure of this facies, shale partings of the same or variable thicknesses (or definitions) may be present. These partings range in thickness from less than 0.5 mm to an extreme of 20 mm, but generally they are very thin and average about 1 mm thick. Laterally, these shale partings are usually continuous and non-parallel, although discontinuous and parallel varieties also occur. Vertically, there is no regularity to the spacing of these partings. In those exposures where shale parting thicknesses are variable, the thicker, or darker, more prominent, partings are generally spaced 2 to 45 mm apart (average is less than 10 mm). Between these shaly layers, the sandstone may be massive or contain very faint, horizontal, wavy laminations with thicknesses ranging from 0.5 to 10 mm and averaging 3 mm (Fig. 3-16).

Facies Sw is a very fine-grained, medium grey, subarkosic arenite with well sorted, rounded to well rounded, moderately spherical grains ranging in size from finer than 4 - 3.5 phi to 3 - 2.5 phi and averaging 3.5 - 3 phi. The facies is not necessarily calcareous or dolomitic, but it usually is when it occurs in the upper unit of the Whirlpool. Glauconite is not an important lithologic component of this facies, but small amounts of these grains are present in two of the cores measured.

Green, silty shale rip-up clasts occur in 40% of the sections containing facies Sw. These clasts are elongate (average length is 1 cm; range, 0.2 to 1 cm; and width, 0.3 cm) and are horizontal-lying.

Bioturbation of this facies is not all that common, for it occurs in only 26% of the total facies units measured and in only 42% of those occurring in the upper portion of the Whirlpool. The degree of bioturbation ranges from weak to moderate, often with the degree increasing upwards within

Figure 3-16. An example of facies Sw, wavy-laminated sandstone. Note the wavy, continuous, non-parallel nature of these laminations. Also note the variable thickness of the shaly partings. The laminations show no signs of bioturbation. Arrow indicates up. From core 240, 2.5 m above the Whirlpool's base.


10 cm

the facies. Ichnofauna are generally nondescript, but some *Chondrites* and possible *Rhizocorallium* or *Teichichnus* traces are also present.

Fossils are generally rare in this facies; they occur in one section only (core 108). This minor occurrence (1 to 2% per unit volume) consists largely of fragments of brachiopod shells and crinoid ossicles.

Other minor elements of facies Sw include symmetrical ripples and ripple (asymmetric) cross-laminations.

CHAPTER 4

SECTION DESCRIPTIONS

INTRODUCTION

This chapter contains the descriptions of the 19 outcrops and 11 cores measured for this study. The locations of the sections are shown in Figure 1-1. More details concerning the location of each section can be found in Appendix 1.

Each section description is fairly detailed, concentrating on the facies present, lateral facies relationships, and thicknesses of units, sets, and foresets. Information concerning lithology, facies, facies sequences, fossils, trace fossils, and grain size is conveyed in detailed section diagrams accompanying each description. Where considerable lateral variability in facies occurred at any one locality, more than one section was measured.

As has already been established, the Whirlpool consists of two parts: an upper unit, generally constituting one-third of the Whirlpool's total thickness, and a lower unit. In the field, both of these units are very distinct from each other. The lower unit is generally shale-free and unfossiliferous, and has its own suite of facies (see Chapter 3). The upper unit, on the other hand, has fossils and trace fossils, and it, too, has its own suite of facies, of which facies S/F is most prevalent. The interpretations accompanying each section diagram are discussed in Chapter 7, which deals with the environments and hydrodynamic interpretation of the Whirlpool at the various sections. To avoid any suggestions of the environment or mode of formation at this point, especially as this chapter is intended to be purely descriptive, the Whirlpool's two parts will be referred to here as the 'upper' and 'lower' parts, or units.

In most cases the Whirlpool classifies petrologically as a subarkosic arenite to quartzarenite with variable amounts of silica and calcareous cement. The sandstone has a speckled salt-and pepper appearance which is due to the presence (less than 1%) of very fine-grained, rounded, light brown to black phosphatized fossil fragments. These fossil fragments occur everywhere in the study area and at all levels within the Whirlpool. Further details concerning the petrography of the Whirlpool can be found in Chapter 6.

Paleocurrents were obtained at most sections from a variety of directional features, such as parting lineation, rib and furrow, large troughs, current crescents, planar tabular cross-laminations, trough cross-laminations, and current crescents. Local paleocurrent trends are shown on the section diagrams, while regional trends are shown in Figures 4-42 to 4-44 at the end of this chapter.

The top part of the Whirlpool is gradational with the overlying Power Glen Shale and the Manitoulin Dolomite. Therefore, where the upper boundary of the Whirlpool is placed is quite arbitrary. In this study the location of the boundary is based primarily on lithology; that is, the Manitoulin begins where the carbonate content exceeds 50% of the rock, and the Power Glen, where the amount of shale exceeds the amount of sandstone.

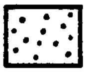
Figure 1-1, which shows the locations of all the sections measured for this study, also indicates those sections that are rather poorly exposed because of weathering, incompleteness of exposure, or inaccessibility due to the presence of waterfalls. This is intended to give the reader an indication of which of the measured sections being discussed are based on sufficient or reliable data. For example, most of the waterfall sections (Mitchell's Mills, Osler Bluff, Lavender, Cannings Falls, and Medina) were difficult to measure, and the resulting section diagrams for each are primarily based on observations made from several rock samples collected at various intervals within the section. Contacts between some units were never really observed, and are therefore approximately located on most of the section sketches.

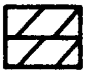
A legend for the section diagrams is provided in

Figure 4-1. Legend for the section diagrams.

LEGEND

LITHOLOGY

 sandstone

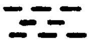
 dolomite

 shale

 silty/sandy dolomite

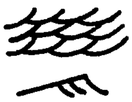
 silty, shaly dolomite

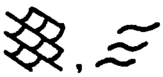
 calcareous/dolomitic

 shaly

SEDIMENTARY STRUCTURES

 trough cross-laminations

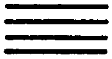
 current ripple cross-laminations

 climbing current ripple cross-laminations

 symmetrical ripples

 climbing symmetrical ripples

 simple flaser bedding

 horizontal laminations

 planar tabular cross-laminations

 low-angle cross-laminations

 convolute laminations

 ball-and-pillow structures

 continuous wavy laminations

 discontinuous wavy laminations

 HCS

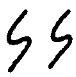
 synaeresis cracks

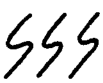
 dessication cracks

 scour marks

TRACE FOSSILS

 sporadically to weakly bioturbated

 moderately to strongly bioturbated

 very strongly to completely bioturbated

Arenicolites

Asterosoma

Chondrites

Conostichnus

Diplocraterion

Lingulichnus

Palaeophycus

Phycodes

Rhabdoglyphus caliciformis

Rhizocorallium

Rusophycus

Scalarituba missouriensis

Scoyena

Skolithos

Teichichnus

Tylichnus

FOSSILS

brachiopods

corals

crinoids

gastropods

ostracods

pelecypods

OTHER

covered

shale rip-up clasts

scour surface

spherical weathering cavities

celestite vugs

pyrite, chert

G glauconite

red coloration

Q, M Queenston, Manitoulin

PG, CH Power Glen, Cabot Head

paleocurrents: azimuth, trend

symmetrical ripple
crestline orientation

crestline orientation and
drift direction

CONTACTS

gradational

approximate

Figure 4-1.

SECTION DESCRIPTIONS

Mitchell's Mills

The northwesternmost occurrence of the Whirlpool is at Mitchell's Mills, an old, abandoned mill site (Williams, 1919; Fisher, 1954). At this locality, 2.3 m of the Whirlpool are exposed at the base of a 10 m high waterfall. The actual contact with the Queenston is not exposed here but occurs about 50 m downstream, bringing the total Whirlpool thickness to about 3.3 m. The Whirlpool's thickness is constant throughout the length of the exposure, which is about 20 m in length.

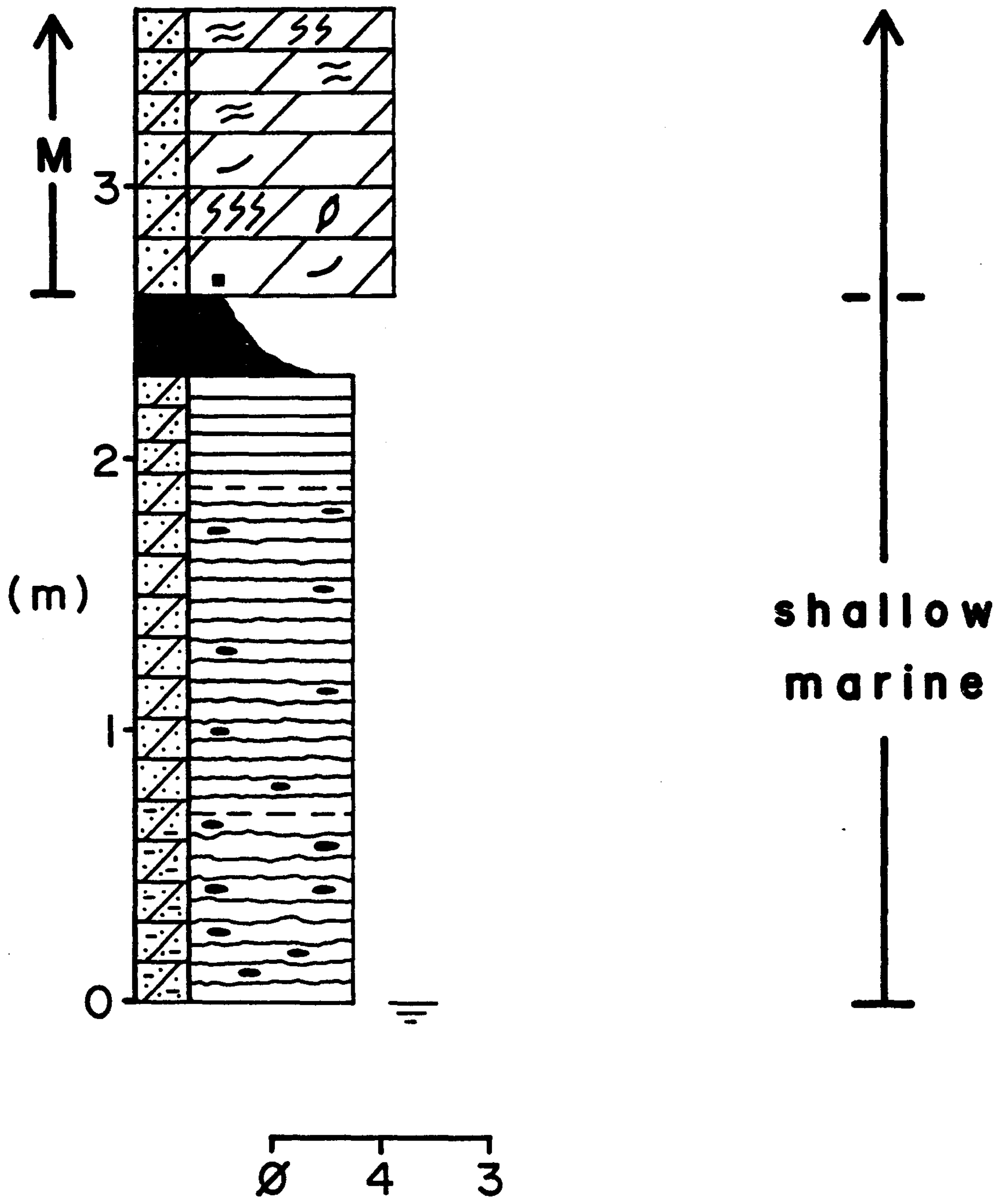
The Whirlpool at this locality consists of very thin (1 to 2 cm), medium grey, silty-looking beds interbedded with thin layers of shale (the presence of the shale layers is inferred from the nature of the weathering of the section). But a thin section at 1.2 m shows that the Whirlpool, at least at this level and above, is in fact a medium crystalline, silty (coarse) dolostone. This of course raises questions about the Whirlpool's actual presence here, for the distinction between the Manitoulin and Whirlpool is based purely on lithological grounds; however, four reasons exist for making the Whirlpool at

Mitchell's Mills the one exception to the rule: 1) the outcrop appearance of the 'Whirlpool' at Mitchell's Mills is very much unlike the typical outcrop appearance of the Manitoulin Dolomite (light brown, medium-bedded, fossiliferous, and bioturbated dolomite) in this region; 2) the 'Whirlpool's' outcrop appearance at Mitchell's Mills closely resembles the Whirlpool at Osler Bluff, where it is a very fine-grained dolomitic sandstone; 3) the lithology of the 'Whirlpool' here is based on only one thin section and does not truly represent the lithology of other beds, which may be more sandy in composition; 4) the Mitchell's Mills section most likely records the pinching out of the Whirlpool, and may yield valuable information regarding the adjacent environment and its relationship with that of the Whirlpool. For these reasons, the interval resembling the Whirlpool at Mitchell's Mills will be recognized as the Whirlpool Sandstone.

Despite the possible lithologic differences, the section displays recognizable facies based on the sedimentary structures present (Fig. 4-2). In the lower 1.8 m, the Whirlpool contains wavy-laminated (parallel and continuous) beds (scattered with shale clasts) interbedded with thin (less than 2 mm) layers of shale. In the lower 0.7 m of this unit, the wavy shale partings responsible for the waviness are thicker, almost to the point of being interlaminated with the silty dolostone (?).

Figure 4-2. The Mitchell's Mills section. A shallow marine depositional environment is proposed for the Whirlpool here (see Chapters 7 and 8).

MITCHELL'S MILLS



This unit is overlain by a horizontally laminated interval. Beds are thin (1 to 2 cm) and contain faint horizontal, planar laminations that are less than 0.5 mm in thickness.

At 2.3 m there is a 0.3 m thick interval of shale which has weathered back considerably, producing a natural break in the stratigraphic section; the top of the Whirlpool is placed at the top of this shale layer.

In sharp contact with the shale is the Manitoulin, which, with its light brown colour, fossils, and bioturbated texture, is in its typical form. The dolostone beds are medium-bedded and silty, and contain a few pelecypod fragments. Faint wavy laminations occur at the 3.2 m level.

The grain size of the silt in the Whirlpool is 4 - 4.5 phi and remains fairly constant throughout the vertical section.

The Whirlpool at this locality appears to be unfossiliferous and unbioturbated, but this conclusion is only based on the examination of a small sample of hand specimens.

No paleocurrent indicators were found at this section.

Osler Bluff

The northernmost exposure of the Whirlpool occurs in a lower subsidiary scarp of the Niagara Escarpment at Osler Bluff. The Whirlpool outcrops in a small stream, where it and the Manitoulin Dolomite form a small, 4 m high, 8 m wide waterfall. The exposed thickness of the Whirlpool here is 2.4 m. Its total thickness is not known, for the contact with the Queenston could not be located anywhere downstream (it is hidden under soil and rubble), but the absence of additional step falls downstream suggests that its thickness is likely not much greater than what is actually exposed.

The Whirlpool at Osler Bluff is a grey to dark grey, very fine-grained (4 - 3.5 to 3.5 - 3 phi), dolomitic sandstone which weathers into very thin to thin (1.5 to 5 cm), laterally persistent, buff-coloured beds.

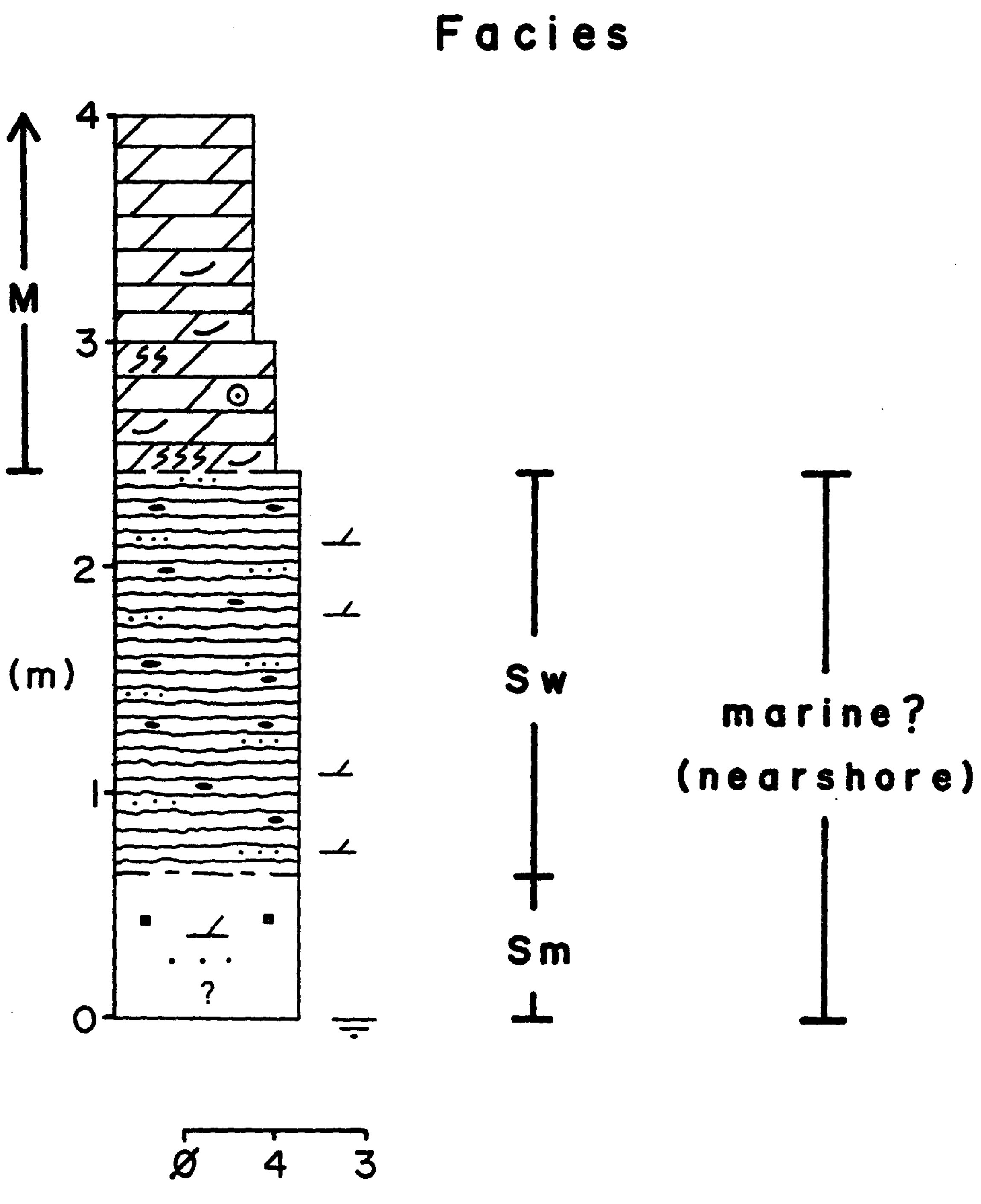
Two facies are present (Fig. 4-3), facies Sm and Sw, of which the wavy-laminated facies is the more abundant of the two. The boundary between the two facies, as indicated on the section diagram, could only be approximated.

Facies Sm occurs in the lower 0.65 m of the measured section. The sandstone appears to be structureless, but this may in fact be due to the great abundance of pyrite mineralization, which may obliterate or hide the presence of any sedimentary structures. The sandstone is dolomitic and has a grain size of 3 - 3.5 phi.

The rest of the Whirlpool consists of the wavy-laminated facies, and is 1.75 m in thickness. The lower 0.35 m of this unit contains parallel, continuous wavy

Figure 4-3. The Osler Bluff section. Although no fossils or trace fossils were found in the Whirlpool, a nearshore environment of deposition is proposed, based on the facies present and the outcrop appearance, which is very much unlike the other lower Whirlpool outcrops. (See Chapters 7 and 8.)

OSLER BLUFF



laminations (averaging 2 mm thick) with no shale clasts present. In the rest of the unit, the wavy laminations (also 2 mm thick) are nonparallel and continuous to discontinuous and have 0.5 to 1 cm long, greenish-grey shale clasts. The sandstone of this unit is dolomitic and has a grain size of 4 - 3.5 phi. No fossils or trace fossils were observed in this unit or the one below. Likewise, no paleocurrent indicators were found.

The Whirlpool grades into the Manitoulin above. The grading occurs over an interval of about 0.5 m, but the actual contact is placed at the 2.4 m level (about half way down the waterfall), where there is a distinct change in the lithology and outcrop appearance of the rock. The Manitoulin Dolomite is thin- to medium-bedded, blotchy light brown to grey in colour, and medium crystalline. Bioturbation is weak, and fossils (mostly brachiopod fragments) are more abundant in the lower 0.5 m (about 5% by volume) than they are above.

Duntroon

The best exposure of the Whirlpool in the northern region of the study area occurs in an old abandoned quarry situated on the eastern edge of a low scarp, just west of Duntroon. The best, and perhaps the only, remaining exposure of the Whirlpool is in the northeast corner of the quarry (upper lift), where the Whirlpool is exposed for only 3 to 4 m along the north quarry wall. Good bedding plane exposures occur in small patches in the eastern part of the quarry. The quarry displays both the upper and lower parts of the Whirlpool (Fig. 4-4 and Fig. 4-5), and provides abundant paleocurrent data generally unobtainable in the other northern sections.

The maximum exposed thickness of the Whirlpool is 2.6 m. The contact with the Queenston below is not visible, but is hidden under about 1.5 m of debris covering the base of the escarpment; therefore, the total Whirlpool thickness is at most 4 m thick.

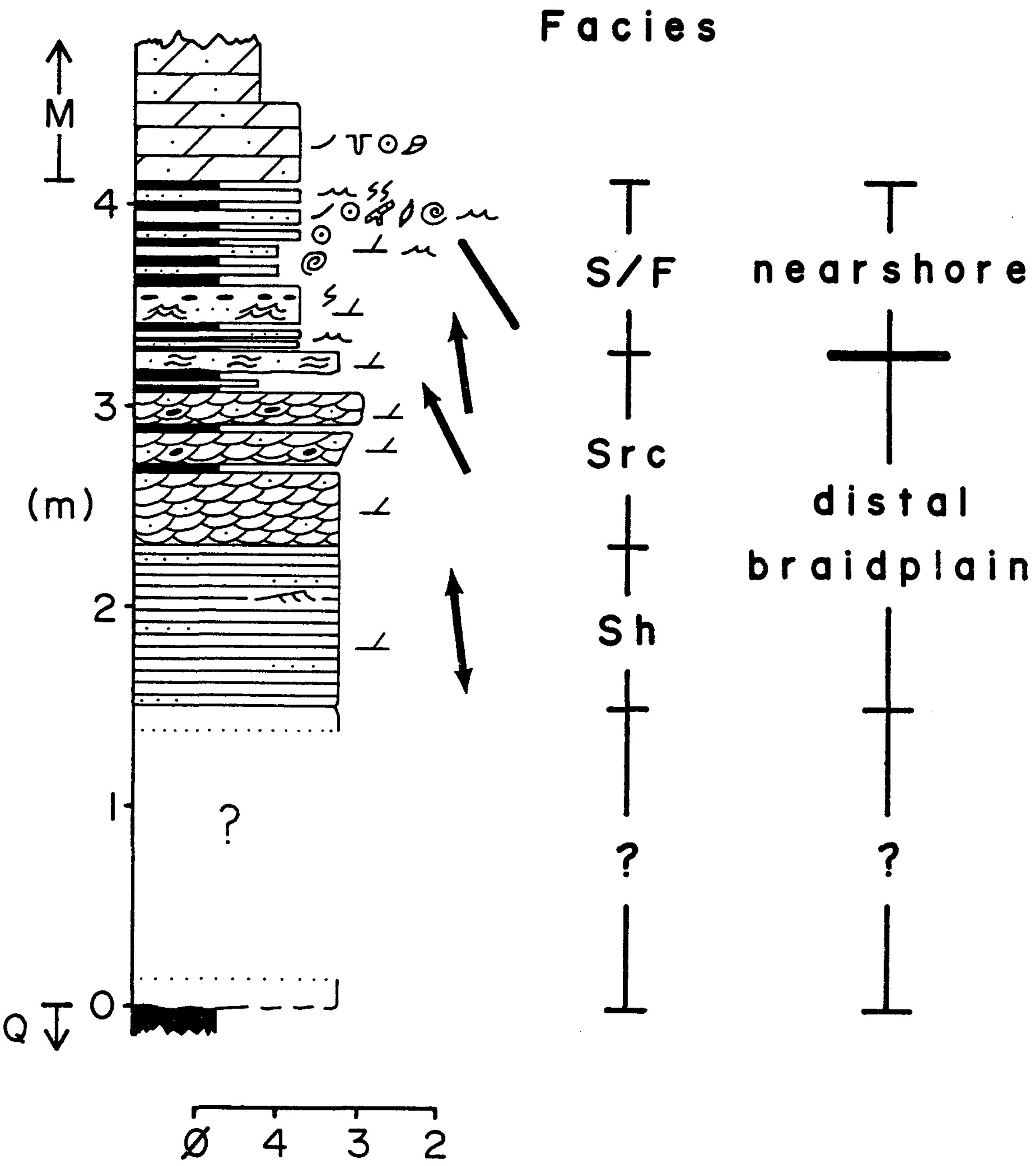
At this locality, the Whirlpool is a very fine-grained calcareous sandstone, with the carbonate content increasing upwards in the section. Shale interlayers are more common here than in sections south of Duntroon. The grain size is very fine, and fines upwards from 3.5 - 3 to 4 - 3.5 phi.

Unit #1 consists of 0.8 m of facies Sh, horizontal laminations. Laminations average 0.4 cm in thickness. On the bedding planes, lamination surfaces display parting step lineation indicating a 353 -173 degree paleoflow. Superimposed on one surface there is a single occurrence of an isolated, elliptical-shaped set of rib and furrow with a paleoflow of 348 degrees.

Overlying unit #1 is a 0.75 m thick ripple cross-

Figure 4-4. The Duntroon section. The lower part of the Whirlpool is interpreted as sheetflood deposits on a distal braidplain. The upper Whirlpool represents deposition within a low-energy nearshore environment. Occasional storm interruption is suggested by the presence of thin sandstone beds. See Chapters 7 and 8 for a more thorough discussion.

DUNTROON



Facies
M
Q
4
3
2
1
0
(m)
?
Ø 4 3 2
S/F
Src
Sh
?
nearshore
distal
braidplain
?

Figure 4-5. Photograph showing the Duntroon section from 2.3 to 4.5 m above the Whirlpool's base. Ten centimeters below the top of the scale (40 cm long) is the approximate location of the boundary separating the lower and upper parts of the Whirlpool. The Manitoulin/Whirlpool contact is located about 1.5 cm above the top of the photo (far left). From the upper lift of the quarry, northeast corner.

laminated (facies Src) unit that shows the first occurrence of shale layers (thicknesses range from 1.5 to 2.5 cm) in the section. The shale appears to be nonbioturbated.

The ripple cross-laminated beds average around 0.15 m in thickness. The unit contains 0.5 cm long shale clasts at the 3.0 m level, which coincides with the coarsest (3 - 2.5 phi) sandstone interval.

On one bedding plane, there is an unusual preservation of these ripples (possibly capped-off ripples; Fig. 4-6a), but in general they appear as micro trough cross-laminations and, on bedding plane surfaces, as rib-and-furrow structures. The paleocurrent is to the northwest (333 degrees). At the top of the unit, ripple drift occurs and indicates a 352 degree paleoflow.

Unit #3, representing the upper part of the Whirlpool, is facies S/F, its base being marked by the first appearance of symmetrical ripples. Its total thickness is about 0.85 m. Sandstone beds are generally very thin. On the basis of sandstone and shale bed thickness, lithology, and colour, two very distinct portions of this unit can be recognized. In the lower, which is about 0.5 m thick, the sandstone/shale ratio is lower (1:1). Sandstone beds average 0.5 to 1 cm thick (except one bed at the 3.5 m level), and shale layers, 1 cm thick. The sandstone beds are a grey colour and have a smaller carbonate and fossil content. In the upper portion, the sandstone/shale ratio is

Figure 4-6. Features of the Duntroon section.

a) Capped-off current ripples in the lower part of the Whirlpool. These are believed to be the result of the planing action of waves during waning or low stages in the braided river, or the result of wind abrasion during low stages when the ripples were temporarily emergent (see Chapters 7 and 8). Paleocurrent direction is difficult to determine. The white tip of the scale points in the north direction. Scale is 40 cm long. From a bedding plane, about 2.3 m above the Whirlpool's base.

b) Close up of Figure 4-5 (see bed above scale in Figure 4-5), showing a structure that looks like a gutter cast, but which is probably either a burrow or loading structure. Scale rests approximately on the contact between the upper and lower parts of the Whirlpool. Scale is divided into 10 cm intervals. From 3.5 m above the Whirlpool's base.

2:1; the sandstone beds average 2 cm thick, and the shale, 1 cm thick. The sandstone beds are a light brown colour, except for a few light grey, siltier-looking beds. They have a greater diversity and abundance of fossils (see Fig. 4-4), and have a carbonate content which increases upwards. This upper portion of unit #3 represents the transition into the Manitoulin above.

A peculiar structure, looking like a gutter cast within a sandstone bed (Fig. 4-6b), but which is probably either a loading structure or burrow, occurs at the 3.5 m level.

The beds within unit #3 are structureless, wavy-laminated, or symmetrically rippled. Symmetrical ripples are rarely well developed, but those that are show well rounded crests. Orientations of the crests average 327 to 147 degrees, with a preferential drift of 67 degrees.

Fossils present in unit #3 include generally well preserved specimens of ostracods, brachiopods, crinoids, gastropods, and corals (in order of abundance). Palaeophycus and some nondescript traces are the only trace fossils present.

The lower boundary of the Manitoulin is placed at the 4.1 m level where there is a marked change in the appearance and lithology of the rock; the Manitoulin Dolomite is medium-bedded, light brown in colour, rarely interbedded with shale, and there are no light grey, silty beds present. Fossils present include numerous fragments of rugose corals, pelecypods, and crinoids. The dolostone is an unsorted biosparite.

Lavender

The Whirlpool and Queenston form a small, 15 to 20 m wide, 3 m high waterfall in a creek just southeast of Lavender. The upper part of the Whirlpool has been eroded away, leaving only the lower part, which is 2.6 m thick here.

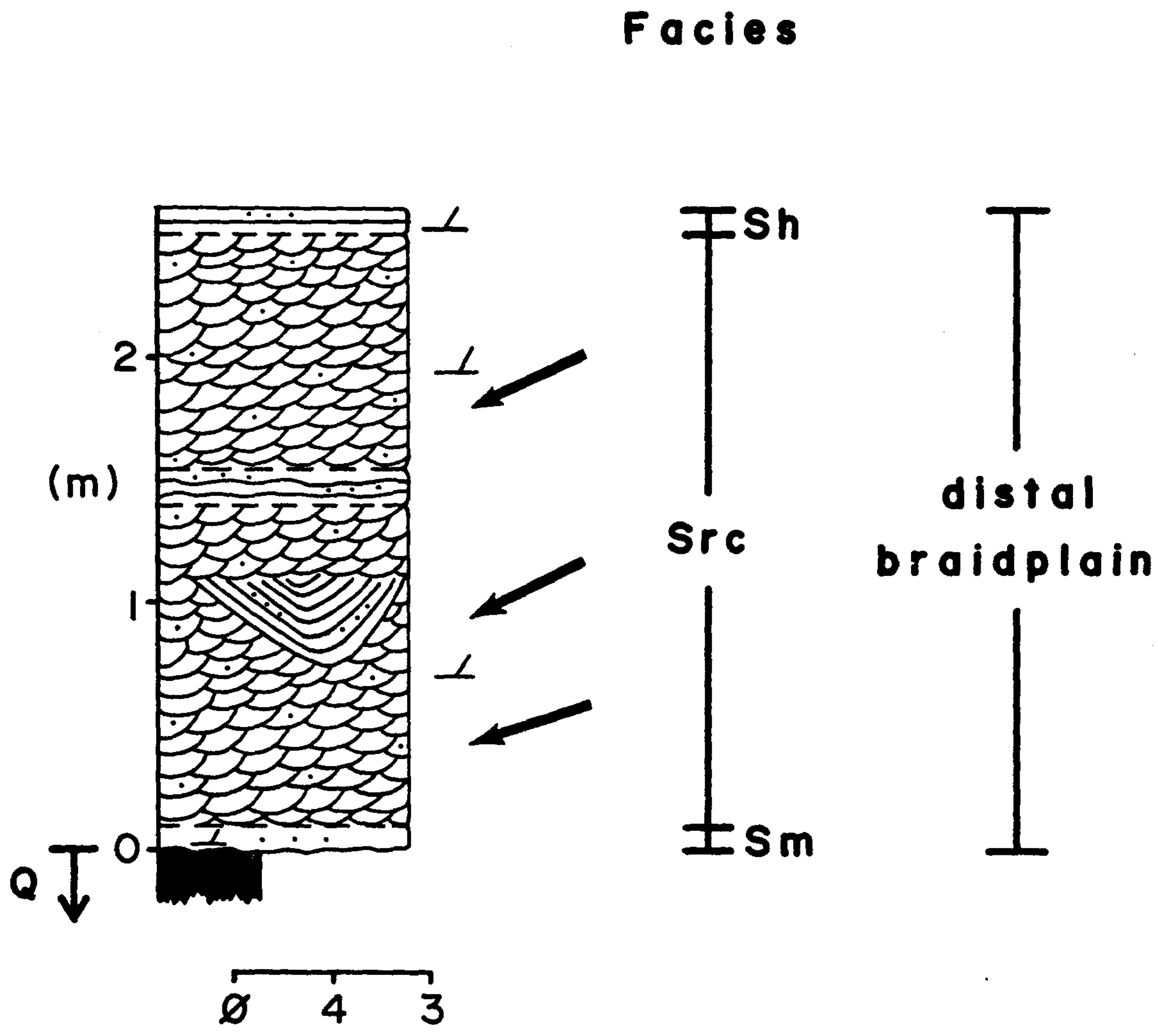
The Whirlpool is quite weathered here. Weathering has produced very thin to thin (range is 2 to 6 cm; average is 5 cm), laterally extensive, tabular beds that have slightly undulating (rather than perfectly planar) bedding surfaces. The rock is a calcareous sandstone with a grain size of 3.5 - 3 phi. No shale interlayers appear to be present.

About 1 m of the Queenston shale is present at the base of the waterfall. It is red in colour, except at the top, where there is about 0.1 m of green shale. The Queenston/Whirlpool contact is in its typical form here: it is sharp, horizontal-lying, and slightly undulating, and small protuberances, appearing on the base of the Whirlpool, project into the top of the Queenston.

Three of the Whirlpool's facies are present here

Figure 4-7. The Lavender section. Only the lower part of the Whirlpool is exposed here and it is interpreted as sheetflood deposits in a distal braidplain environment. The occurrence of trough cross-laminations (note the isolated trough at the 1 m level) in sections north of Cannings Falls is very rare. See Chapters 7 and 8 for a more thorough discussion of interpretations.

LAVENDER



(Fig. 4-7). The contacts between them could only be approximately located, and are therefore shown as such on the section diagram.

The lowermost facies, forming unit #1, is 0.1 m thick and displays facies Sm (massive sandstone).

Unit #2 consists of 2.4 m of the ripple cross-laminated facies (facies Src). Current directions obtained from rib-and-furrow structures indicate a 249 degree paleoflow. The unit is tabular in form and laterally persistent throughout the extent of the outcrop except in one area where it is scoured by a small asymmetric trough. This trough is 2.6 m wide, 0.4 m deep, and has 0.5 cm thick laminae that are concordant with the lower trough surface. The paleocurrent responsible for the trough flowed to the southeast (243 degrees). Another minor occurrence, this time of wavy laminations (laminae are 0.6 cm thick), is present in the middle of unit #2 and occupies 0.15 m of the vertical section.

Horizontal laminations of facies Sh form unit #3, which is at least 0.1 m thick. The top of this unit forms the top of the waterfall.

Primrose

The Whirlpool outcrops discontinuously for about 50 m along the west and east banks of the Boyne River just north of Primrose. The Whirlpool totals 2.5 m in thickness, and it consists only of those facies constituting the lower part of the Whirlpool.

The beds are a light grey colour, but weather (most beds are quite weathered) a tan colour. Beds range in thickness from 0.01 to 0.7 m (the thickest beds occur near the base), but they generally average around 0.1 m thick.

At this locality, the Whirlpool is a calcareous-cemented sandstone with grains ranging in size from 3 - 2.5 to 3.5 - 3 phi (see Fig. 4-8 for vertical grain size variation).

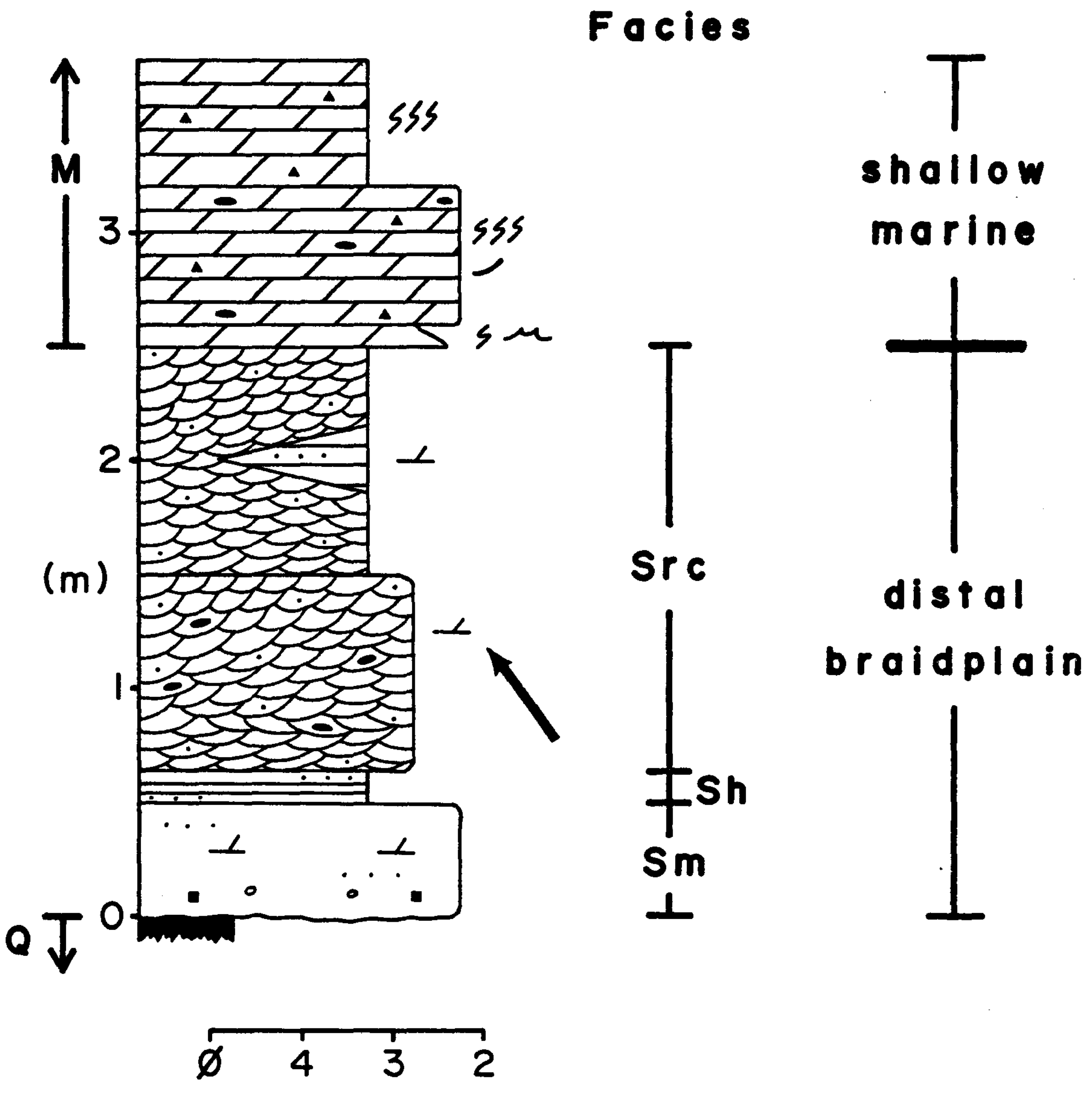
The top 4 cm of the Queenston Shale are exposed at the base of the Whirlpool. Its colour, a bluish grey-green, is typical of the shales in contact with the Whirlpool base.

The lateral exposure of the Whirlpool base is rather limited, but, from what is exposed, the Queenston/Whirlpool contact appears to be sharp, horizontal-lying, and gently undulating. The sole of the Whirlpool is unexposed.

The three facies present at Lavender are also present at the Primrose section (Fig. 4-8). The lowermost, forming unit #1, is the massive sandstone facies (facies Sm), and is 0.5 m thick. The lower part of the unit displays abundant pyrite mineralization and spherical cementation rosettes (weathering cavities) which are about the same size (0.5 to 1 cm) as those observed at the Niagara Gorge sections.

Figure 4-8. The Primrose section. Note that the upper Whirlpool is absent and that the Manitoulin rests sharply on the lower Whirlpool. As at Lavender and Duntroon, the lower Whirlpool here possibly represents sheetflood deposits in a distal braidplain environment (see Chapters 7 and 8).

PRIMROSE



Facies
M
3
2
(m)
1
0
Q
Src
Sh
Sm
shallow
marine
distal
braidplain
Ø
4
3
2

Unit #2 consists of 0.14 m of horizontal laminations (facies Sh) that average 0.5 cm in thickness.

Erosionally overlying unit #2 is unit #3 (1.85 m thick), which consists of facies Src, and, as at Lavender, it is the principle facies of the section. The lower half of the unit is coarser and contains 1 cm long, 0.2 cm wide shale clasts. A 0.3 m thick interval of horizontal laminations (3 mm thick) occurs upstream at the same stratigraphic level as the upper part of unit #3; the relationship between the two structures is not known.

The section through unit #3 is generally transverse, exposing micro trough cross-laminations with troughs that are 1 cm deep, but some exposures of rib-and-furrow structures, are also present. Readings from these structures give a paleocurrent of 323 degrees.

The upper part of the Whirlpool, normally exposing interbedded sandstone and shales, is not at all present at the Primrose section. The Manitoulin Dolomite appears to rest sharply on unit #3. Internally, the lower 0.1 m of the Manitoulin contains horizontal laminations and symmetrical wave-like structures; no form ripples are present. The dolostone is thin-bedded, fine-crystalline, medium- to dark grey-coloured (weathers grey-brown), and contains less than 1% quartz grains, which decrease in abundance upwards. The Manitoulin is structureless (due to bioturbation), and contains brachiopod fragments, shale clasts, and abundant leached chert nodules in some intervals.

Cannings Falls

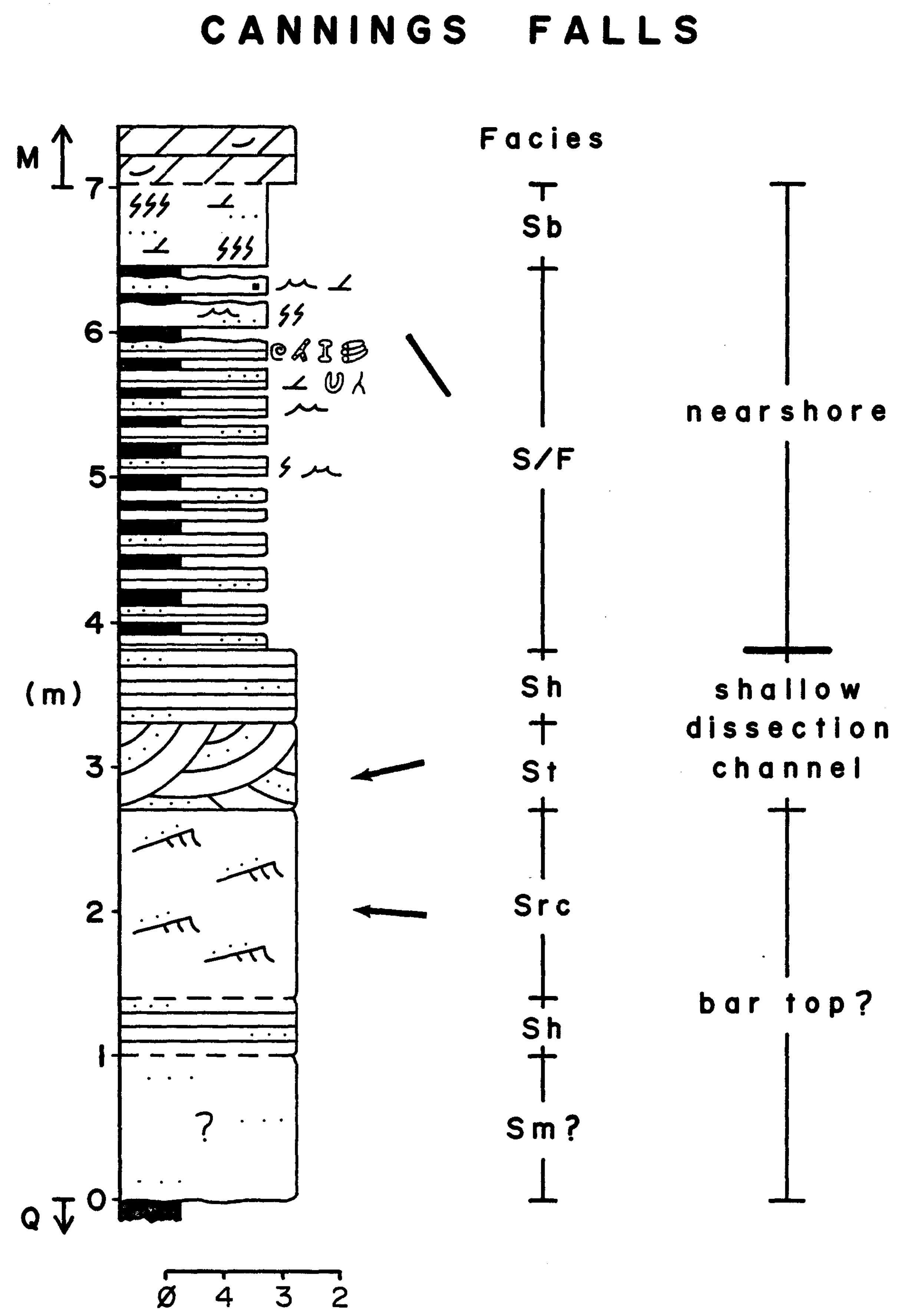
The Whirlpool outcrops at Cannings Falls on the northern tributary of the Nottawasaga River. The entire Whirlpool (7 m thick) is exposed at these falls, which really consists of two falls: an upper falls, exposing the upper part of the Whirlpool, and a lower falls (actually a series of steps), exposing the Whirlpool's lower portion (Fig. 4-9). The outcrop has a limited lateral exposure, and the lower 1 m of the section is inaccessible. The Cannings Falls section is best viewed in mid to late summer when low water levels expose most of the bedding plane surfaces.

The Whirlpool, here, is a light- to medium-grey (weathers tan), very fine-grained sandstone, with the grain size decreasing upwards in the section from 3 - 2.5 to 3.5 - 3 phi. Beds are very thinly- to thickly-bedded.

About 9 m of the Queenston Shale are exposed at the falls. Its contact with the Whirlpool is, as usual, horizontal-lying, sharp, and slightly undulating.

Because unit #1 is inaccessible, it is difficult to know for sure what facies it consists of; however, because there is no visible cross-bedding, and because most of the other sections north of Cannings Falls begin with a massive sandstone unit, it is possible that unit #1 consists of

Figure 4-9. The Cannings Falls section. The lower Whirlpool possibly represents a bar top and shallow dissection channel (this interpretation is based on rather limited lateral exposure). The upper Whirlpool represents deposition within a low-energy nearshore environment. Sandstone interbeds displaying waning flow structures suggest that this environment was occasionally interrupted by large storms. Note the upward increase in the degree of bioturbation, reflecting the increasing distance from the shoreline (see Chapters 7 and 8).


CANNINGS FALLS
Facies
M
7
6
5
4
(m)
3
2
1
0
Q
?
Ø 4 3 2
Sb
S/F
Sh
St
Src
Sh
Sm?
nearshore
shallow dissection channel
bar top?

facies Sm. The unit is probably about 1 m thick (the top contact shown in Fig. 4-9 is approximate).

The presence of parting lineations on bedding planes suggests that unit #2, which is 0.4 m thick, consists of facies Sh. Sets of horizontal laminations average 0.1 m in thickness. The upper contact with unit #3, as shown on the diagram, is approximate.

Unit #3 (1.3 m thick) consists of facies Src, current ripple cross-laminated sandstones. Rib-and-furrow structures on bedding planes indicate a paleocurrent of 275 degrees.

Unit #4 is 0.6 m thick and is trough cross-laminated (facies St). The unit, as seen on bedding planes, features large scale rib-and-furrow structures, an isolated trough, and a dune slipface with continuous, sinuous ripples (wavelength = 10 cm) oriented roughly perpendicular to the trough crestline. Paleocurrents obtained from these structures are to the southwest (246 degrees). Sets of trough cross-laminae reach a maximum of 0.5 m in thickness.

Horizontal laminations of facies Sh occur again in unit #5, which is 0.6 m thick. Horizontal-laminated (laminae are 0.5 cm thick) sets are on average 0.1 m thick.

The upper part of the Whirlpool overlies unit #5, and begins with an unusually thick occurrence of facies S/F (interbedded sandstone and shale). The sandstone beds range in thickness from 1 to 25 cm, and the shale, 1.5 to 13 cm, producing a sandstone/shale ratio varying from 3:1 to 2:1. Internally, the sandstone beds contain horizontal laminations (0.3 to 0.4 cm thick) and/or symmetrical ripples. The symmetrical ripples are sinuous-crested, oriented at 325 to 145 degrees (preferential drift to 229 degrees), and have an average ripple index (L/H) of 15. Trace fossils are rare to nonexistent in the lower portion of the unit, but increase in abundance upwards. These are mostly hypichnial traces consisting of (in order of abundance) Palaeophycus, Teichichnus, Arenicolites, Rhabdoglyphus caliciformis, and nondescript traces. A few gastropod fragments are also present. Possible casts of shrinkage casts are present on the sole of some beds. The shale layers of unit #6 are bluish-grey in colour and are thoroughly bioturbated. Unit #6 is also characterized by an upward increasing trend in the carbonate content.

Unit #7 (0.6 m thick) consists of bioturbated sandstone (facies 4b). The unit is very dolomitic and thoroughly bioturbated. Its upper contact with the Manitoulin is located approximately 0.4 m from the top of the falls.

The Manitoulin, here, is a medium grey (weathers brown), medium- and irregularly bedded silty dolostone and dolomitic limestone. Shale interlayers are very thin.

Cataract

The entire Whirlpool (5.75 m thick) is exposed for a total of about 150 m on both sides of a gorge cut by the Credit River. The great length of the outcrop makes it an ideal exposure for documenting lateral facies relationships. Unfortunately only 30 m of the outcrop, on the west side of the gorge, are actually accessible; the description of the Cataract site is based on this exposure.

The Whirlpool is fine- to very fine-grained (ranging from 2 phi to 3 - 3.5 phi), and is generally uncalcareous, except at the base and in the upper part of the Whirlpool. Bedding is generally thick to very thick in the lower part of the Whirlpool, and thin, in the upper part.

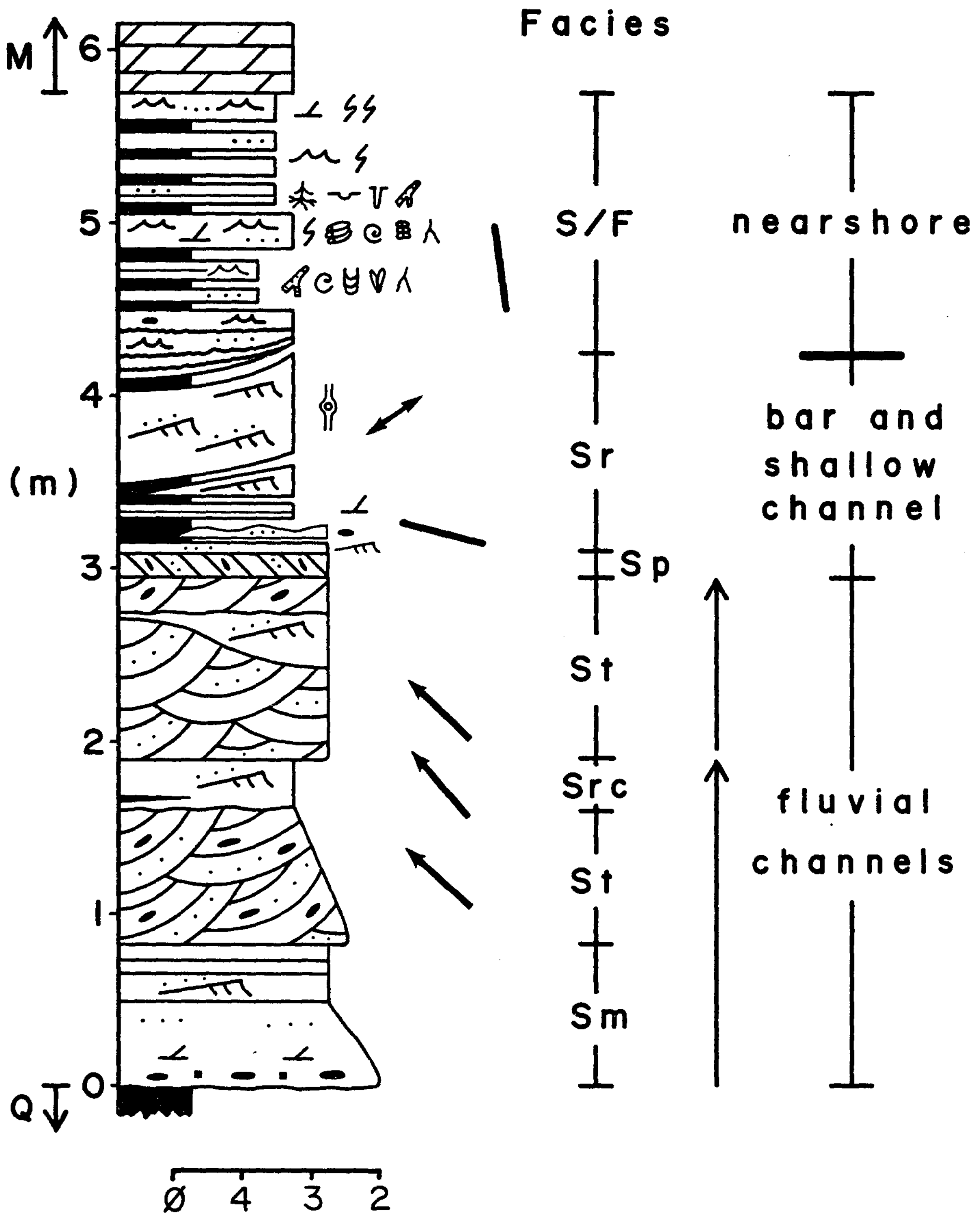
The Cataract section consists mostly of facies St, Src, and S/F, although minor amounts of facies Sp, Sm, Sw, and Sh also occur (see Fig. 4-10 for the facies sequence).

The sharp, horizontal-lying, very gently undulating lower contact of the Whirlpool rests on the red Queenston Shale, the top 30 cm of which are grey-green in colour. Shale clasts (0.7 cm long) are concentrated in a 2 cm interval above the base, and pyrite mineralization is quite abundant in the lower half of unit #1, which displays facies Sm.

Trough cross-laminations (facies St) constitute a significant portion of the Cataract section. They are best

Figure 4-10. The Cataract section. The diagram summarizes the features that are exposed along the west side of the gorge near the waterfall (compare with Fig. 4-13). See Chapter 7 for an interpretation of this section.

CATARACT



M
6
5
4
(m)
3
2
1
0
Q
Ø 4 3 2
Facies
S/F
Sr
Sp
St
Src
St
Sm
nearshore
bar and shallow channel
fluvial channels

exposed on the east side of the gorge, where they form a tabular unit extending laterally for about 100 m, consisting of well developed, symmetrical troughs crosscutting each other and other facies in a southwestward direction (Fig. 4-11). The trough sets are much larger (3 m wide, 0.5 m deep) than those typically found in the Whirlpool. Shale clasts, 1 cm long and oriented parallel to the foresets, occur in this facies at various levels. Trough cross-laminations are on average 0.7 cm thick. The paleocurrent is to the northwest (313 degrees).

Current ripple cross-laminations (facies Src) occur quite commonly throughout the section. The ripple cross-laminations are 0.3 cm thick, and form sets averaging 1 cm in thickness. The bounding surfaces of the sets and of the facies are erosional. Rib-and-furrow structures and some ripple drift indicate a northwest (319 degrees) paleoflow. The base of the thick ripple cross-laminated bed at 3.6 m displays interesting scour (?) marks which show a distinct lineation (235 to 55 degrees) and which appear to protrude from and curve around circular holes (obviously obstacles of some sort) in the base of the bed (Fig. 4-12a). The holes average 1 cm in diameter.

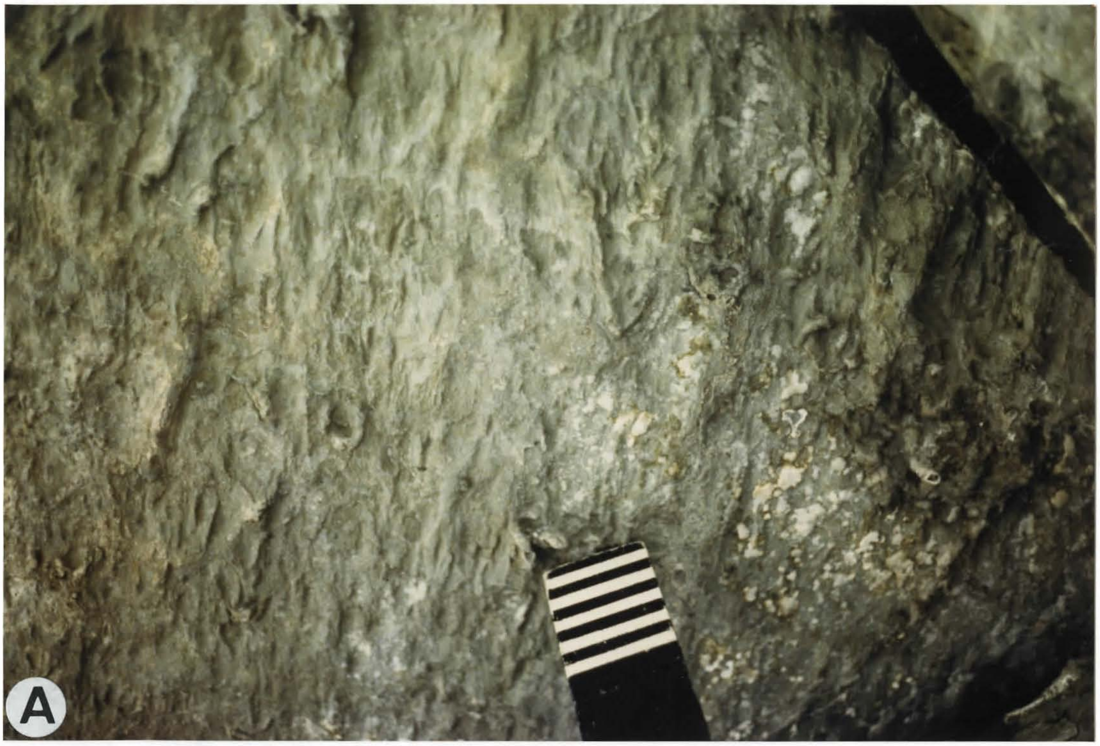
A single occurrence of facies Sp occurs at the 3 m level. Only one set is present; it is 0.15 m thick, and its cross-laminations are planar, 0.6 cm thick, and northward-dipping at about 25 degrees. Shale clasts are concentrated

Figure 4-11. A transverse view of facies St on the east side of the gorge. The troughs, which are unusually large for facies St, average 3 m in width and 0.5 m in depth, and crosscut each other to the right (southwest). Paleocurrent direction is to the northwest (313 degrees). Note the sharp and planar nature of the Queenston/Whirlpool contact. From Cataract, entire lower Whirlpool, east wall.

Figure 4-12. Features of the Cataract section.

a) Possible scour marks on the base of a current ripple cross-laminated sandstone bed (lower Whirlpool). Note the distinct linearity of the protruding ridges and how they curve around some of the holes (an earlier obstacle). Small divisions on the scale are in centimeters. From Cataract, west side of gorge, 3.6 m above the Whirlpool's base, approximately located at 18 m on the horizontal scale of Figure 4-13.

b) A photo of the lower half of the upper Whirlpool showing evidence of scouring into the lower Whirlpool. The bar on the photo marks the contact between the upper and lower Whirlpool, the location of which is based on other evidence not shown in the photo (see Figs. 4-10 and 4-13). The photo covers approximately 1.5 m of vertical section. From Cataract, west side of gorge. On Figure 4-13, the photo represents the area at 4 m on the horizontal scale and 4 to 5.5 m on the vertical.


A


B

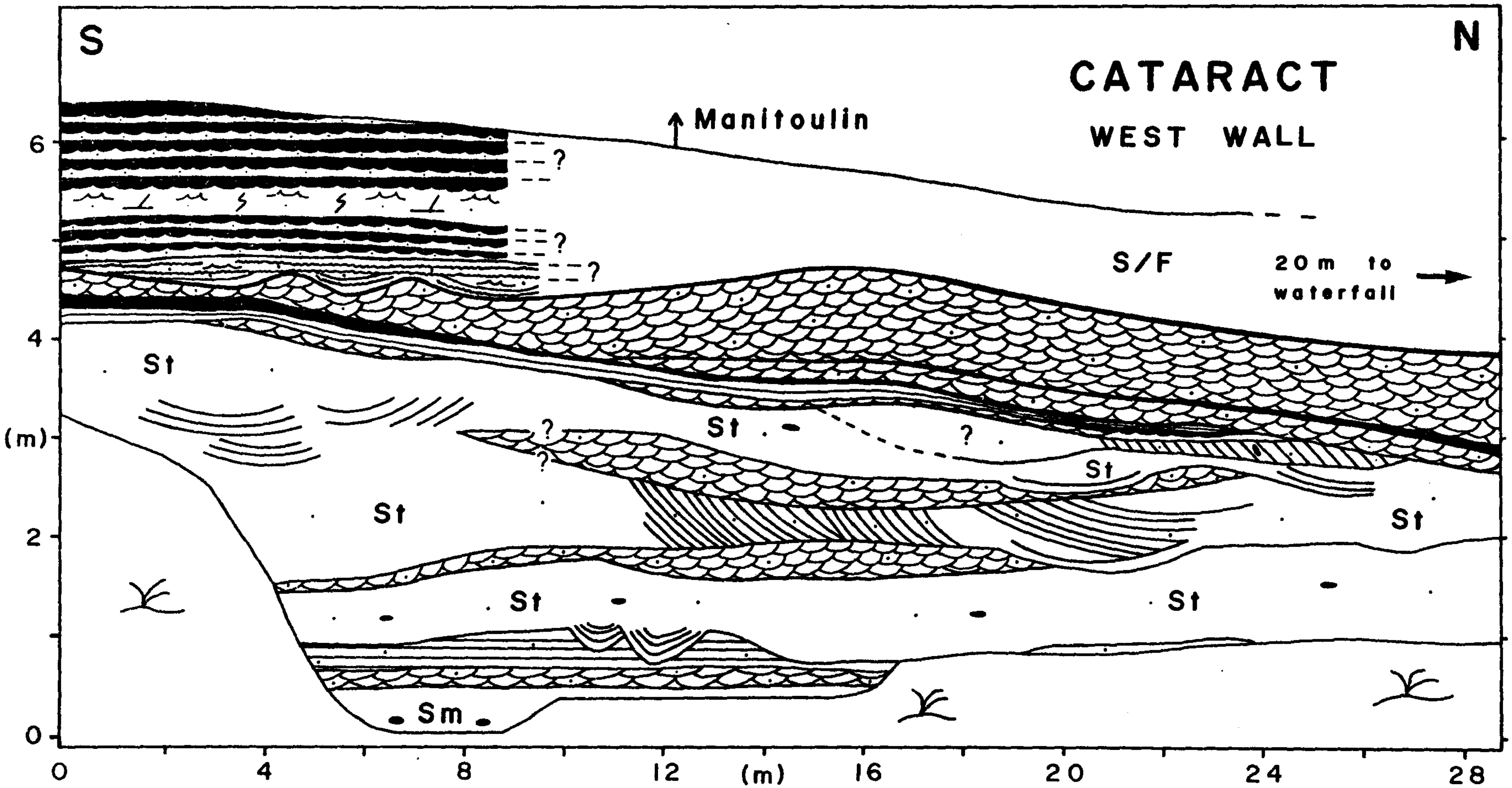
at the base of the set and are imbricated parallel to the foresets.

There are a few occurrences of thin shale (dark grey) layers, or partings, in the lower part of the Whirlpool; they appear to be unbioturbated.

Although the first appearance of symmetrical ripples (trending 285 to 105 degrees) and thick shale layers occurs at the 3.2 m level (both usually mark the base of facies S/F), the lower boundary of the unit containing facies S/F is placed just above the 4 m level, where the shale and thinner sandstone interbeds containing symmetrical ripples become more regularly interbedded.

This unit is characterized by interbedded shale and very thin-to medium-bedded sandstone (see Figs. 3-12 and 4-12b). The sandstone beds have flat and sharp bases, horizontal internal lamination, and symmetrically rippled tops (crests are oriented 355 to 175 degrees; RI = 8). The sandstone/shale ratio for the entire unit is 2.5:1. The sandstone is primarily dolomite-cemented, with the dolomite content increasing upwards in the unit. Bioturbation of the shale and sandstone begins at the 4.5 m level and increases in intensity upwards. Endichnial, hypichnial, and epichnial forms are present and include: Palaeophycus, Chondrites, Conostichnus (or Monocraterion), Tylichnus, Teichichnus, Diplocraterion, Skolithos, grazing trails, and nondescript burrows. Synaeresis cracks occur both on the tops of beds

Figure 4-13. Sketch of Cataract's west wall showing the geometry and lateral facies relationships of all the units exposed along this 30 m long outcrop. Portions of this exposure are covered, as shown. The trough cross-laminations are not well defined on this side of the gorge. Only those exposed well enough to be traced are indicated on the diagram, otherwise the trough cross-laminated units are indicated by 'St'. The interval indicated by 'S/F' represents the upper part of the Whirlpool.


S
N
CATARACT
WEST WALL
Manitoulin
S/F
20m to waterfall
St
St
St
St
St
St
St
Sm
?
(m)
0
2
4
6
0
4
8
12
(m)
16
20
24
28

(between ripple crests) and on the bottoms of beds. A few specimens of gastropods, bivalves, and crinoids are also present. The top of this unit grades lithologically into the Manitoulin above. The base of the unit, however, is sharp and shows evidence of scouring, as is shown by the presence of a few 3 m wide, 0.3 m deep scour-and-fill structures (Fig. 4-12b).

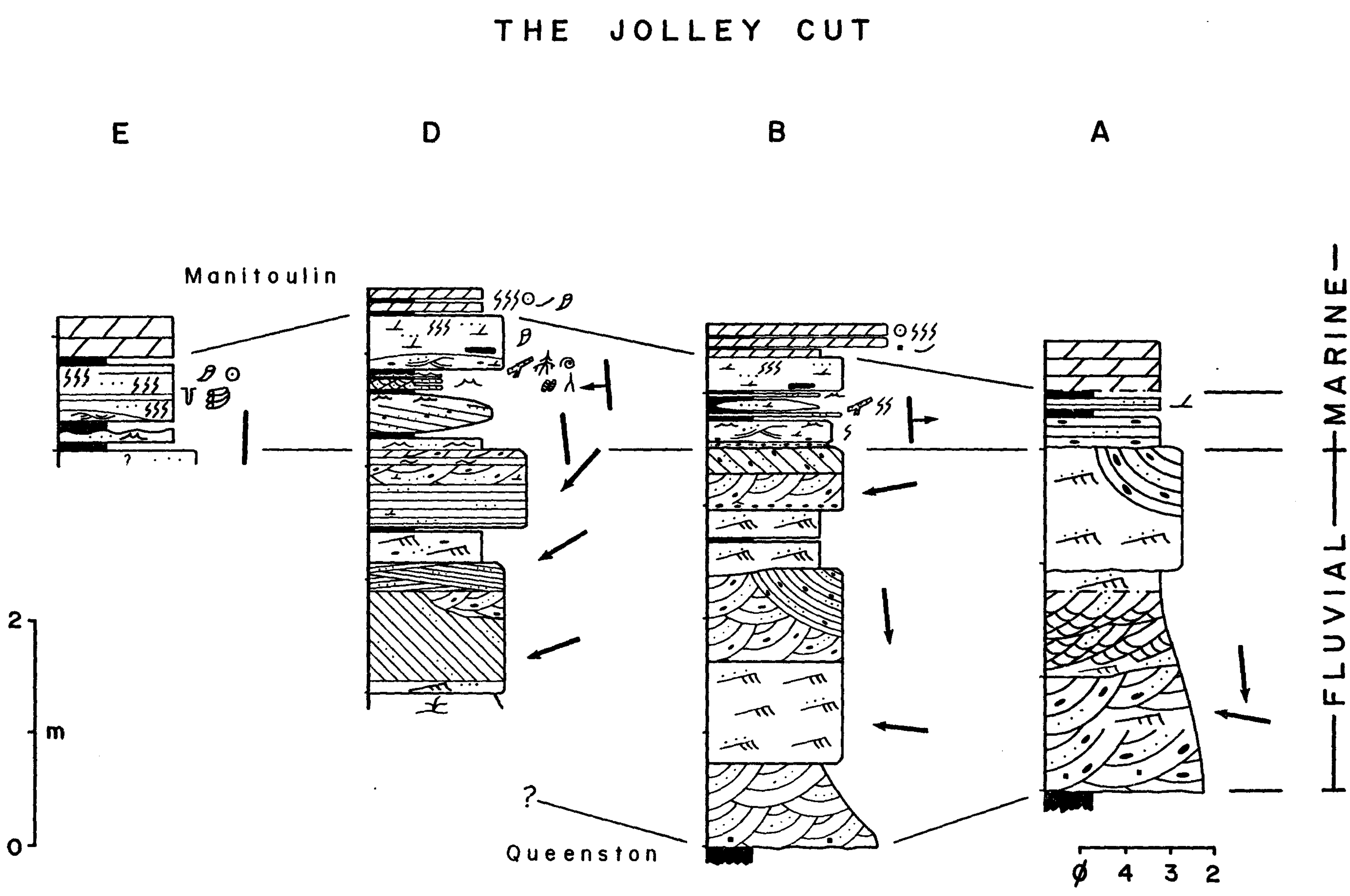
The geometry and lateral facies relationships of all the units on the 30 m long outcrop are shown in Fig. 4-13. Note that most of the lower unit boundaries are erosional, and that although most of the units are laterally extensive, there is a considerable amount of scouring and crosscutting, producing irregular to lenticular shaped unit bodies.

The Jolley Cut

The Whirlpool is exposed in its entirety (4.3 m) at the Jolley Cut, where 350 m + of continuous lateral exposure provides ideal conditions for documenting lateral facies relationships. Four of the sections measured are included here (Fig. 4-14) to show the similarities or variabilities of the features existing along the exposure; their locations are shown in Figure 4-15, which is a sketch of the outcrop's walls.

The two parts of the Whirlpool are markedly different from each other: the upper part is very thinly-

Figure 4-14. Diagram showing the four sections measured at The Jolley Cut. Refer to Figure 4-15 for the locations of these sections along the extensive exposure. Note the sharp contact separating the lower Whirlpool from the upper. Note, also, the lateral variability in the thickness of the upper Whirlpool. Section E displays an example of Duke's (1985c) dominantly bioturbated amalgamated HCS, which may be present at sections D and B, as well. An interpretation of The Jolley Cut section is given in Chapter 7.


THE JOLLEY CUT
E
D
B
A
Manitoulin
Queenston
?
2
m
0
Ø 4 3 2
MARINE
FLUVIAL

to medium-bedded, calcareous, fossiliferous, and displays typical facies, while the lower part is very thickly-bedded, uncalcareous, has rare shale interbeds, and also displays typical facies. Grain size of the Whirlpool ranges from 3 - 3.5 to 2 phi and generally fines upwards.

The Queenston is not naturally exposed but can be reached by digging; the contact with the Whirlpool is sharp, but its geometry cannot be observed. Pyrite and chalcopyrite mineralization is abundant within a 0.5 m interval above the base.

With the exception of section D, whose features are so untypical of this exposure, the Jolley Cut section, best represented by sections A and B, shows an abundance of facies St, Src, and S/F. Other facies present include facies Sh, Sp, Sb, Srs, Sl, and Shcs.Ab.

The trough cross-laminated units are laterally extensive and display cosets containing up to 4 sets of trough cross-laminae. The cross-laminae average 0.7 cm in thickness and form sets averaging 0.2 m thick. Evidence of backflow and low stage ripple formations can be found in one set at section A (1.5 m level). Shale clasts (1 cm long and imbricated parallel to the foresets) occur in most of the trough cross-laminated units. Readings from the trough cross-laminations indicate a southwestern (231 degree) paleoflow. One final characteristic of the trough cross-laminated units is the existence of large symmetrical troughs (3 m wide and 0.4 m deep; laminations are 0.7 cm thick and contain shale clasts) which scour into and even terminate the lateral persistence of some units. Readings from these troughs indicate a paleocurrent to the south (174 degrees), with possible westward (274 degrees) migration (but reliable measurements are difficult to obtain because of the massive bedding).

The current ripple cross-laminations (facies Src) form laterally extensive units with erosional lower bounding surfaces. The sets, which may be in groups of 23 or more, average 0.8 cm in thickness and contain laminae averaging 0.1 cm in thickness. The average paleocurrent, as determined from rib-and-furrow structures, is to the west (271 degrees). The ripple cross-laminated units are also scoured by large troughs of similar shape and dimensions as those in the trough cross-laminated units.

The unit containing facies S/F is fairly constant in thickness (0.4 m) through most of the outcrop, but there are areas (e.g. west of section B and in the area between sections D and E) (Fig. 4-14) where its thickness is significantly reduced. The beginning of this unit is marked by the first appearance of symmetrical ripples, a shale clast lag, or a thick shale layer. The sandstone/shale ratio varies but generally ranges from 2:1 to 3:1. The sandstone interbeds are tabular to lenticular in shape and have flat, sharp bases and symmetrically rippled tops (crests are rounded, strike 177 to 357 degrees, and drift in the direction of 265 and 87 degrees; RI = 12). Both bioturbation and carbonate content increase upwards in the section. The trace fauna generally occur as epichnial and hypichnial forms that include abundant Palaeophycus, Chondrites, Skolithos, and minor occurrences of ?Rusophycus, and nondescript burrows. Synaeresis cracks occur on both bed tops and bottoms. Fossils, which are generally very low in abundance here, include corals, brachiopods, gastropods, and a possible Orthoceras (Hewitt, pers. comm, 1985; Grant, 1900) (one gastropod observed). The shale interlayers (light grey in colour) are also bioturbated.

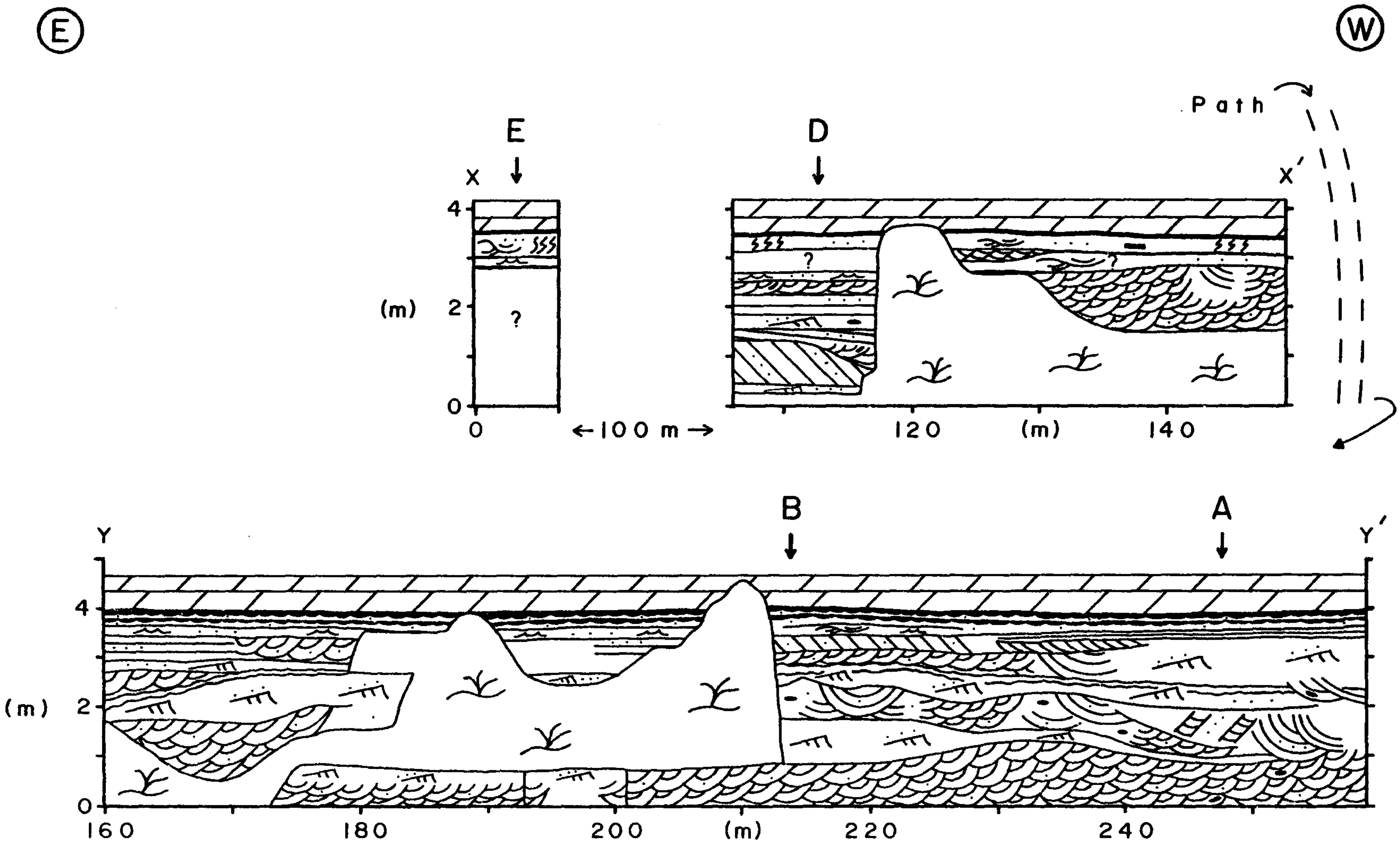
HCS is present in two forms. Section B and maybe D display the S/Fhcs type (see Fig. 3-7a), which, in these particular sections, maybe confused with facies Sl. Section E displays facies Shcs.Ab (bioturbated amalgamated HCS), which may be confused with facies Sb.

Overlying the interbedded sandstone and shales is a unit (0.1 to 0.4 m thick) of bioturbated sandstone (see Fig. 3-7a). The unit is completely bioturbated, displaying nondescript trace fauna, and contains very large, elongate, internally laminated shale rip-up clasts (9 cm long, 1.5 cm wide) and a few rugose coral specimens. As the unit grades lithologically into the Manitoulin above, sand content decreases and carbonate content increases.

The Jolley Cut has two occurrences of facies Sp

Figure 4-15. Sketch of the 350 m + long exposure at The Jolley Cut showing the relationships and lateral distributions of the facies. Cross-section X-X' is situated on the east side of the path, and section Y-Y', on the west. See text for a discussion of this diagram. Note that the vertical scale is exaggerated 4 times. See Figure 4-14 for detailed diagrams of each of the sections shown (A,B,D, and E).

THE JOLLEY CUT



(section D and B); both are single set occurrences. The set thickness at section D (0.9 m) is greater than that observed anywhere in the study area (see Fig. 3-4a). Sections are oblique, exposing southwestward-dipping (dip at 19 to 25 degrees) planar cross-strata that are 1 cm in thickness. The paleocurrent is 250 degrees.

Figure 4-15 shows the relationships and lateral distributions of the facies at the Jolley Cut section. The important things to note are that: 1) the contacts between most of the units are erosional; 2) there is little lateral variation in the abundance, or importance, of certain facies (facies St and Src, to be specific) throughout much of the exposure (the exception to this is section D, which displays a suite of facies untypical of the Jolley Cut section. The area showing its relationship with the rest of the section is unfortunately covered by debris, but the fact that the change occurs over such a short distance is significant in itself.); 3) units are generally laterally persistent, but there are variations in thickness due to erosion from units above; and 4) large troughs scour into facies St and Src and show a westward migration (about 274 degrees).

Kenilworth Avenue

The Whirlpool (2.5 m thick) is exposed in its entirety for 112 m at the foot of Kenilworth Avenue in

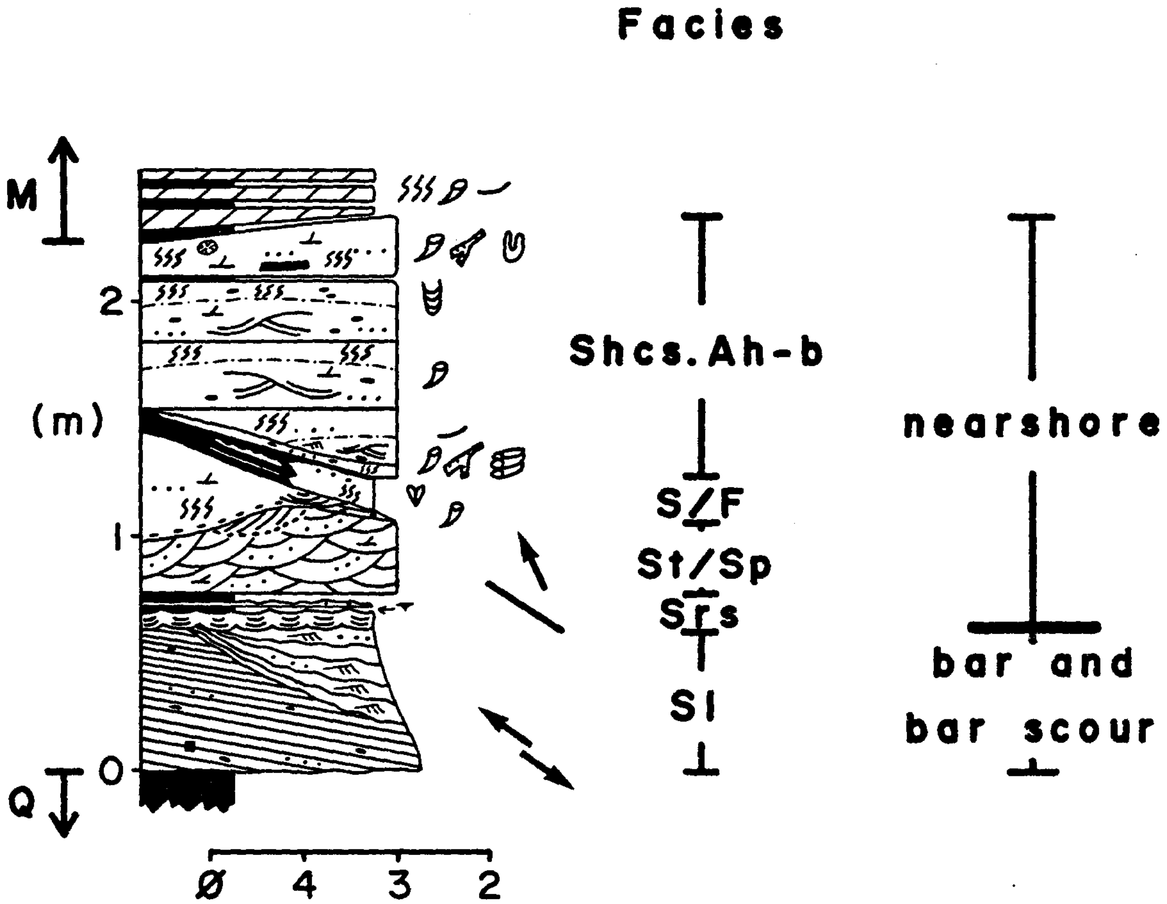
Hamilton. The unusual thinness for such a southern section, the possible lack of a 'lower part', the facies types, the lateral variability of the facies, and the lack of typical 'upper unit' facies (namely facies S/F), all make this a very interesting section to study. The section displays some unusual features that are difficult to classify according to the proposed facies scheme. Figure 4-16 is based on the exposure around 30 m (see horizontal scale in Fig. 4-19); however, it also attempts to summarize the important features of the entire outcrop.

The Whirlpool is generally calcite-cemented and very fine- to fine-grained, with grain sizes ranging from 3 - 2.5 to 3.5 - 3 phi. Beds are very thinly- to thickly-bedded. The lower contact with the red Queenston Shale (the top 20 cm are green in colour) is not naturally exposed, but it can be reached by digging.

Unit #1 (0.6 to 1 m thick) contains low-angle, planar, cross-laminations (facies Sl) that dip at about 6 degrees in two directions (305 and 125 degrees). Pyrite mineralization is quite abundant at the base. Laminae are 0.5 cm thick and contain 0.7 cm long shale clasts oriented parallel to the laminae. One interesting feature of unit #1 is the presence of a series of beds which vary from very thin (millimeters) wavy laminae and which fan out and thicken laterally over a 6 m distance to form beds 10 cm in thickness. The bed tops are symmetrically rippled (RI = 12,

Figure 4-16. The Kenilworth Avenue section. The diagram summarizes the features of this 112 m long exposure but is primarily located at 30 m on the horizontal scale of Figure 4-19. Note the unusual thinness (0.6 to 1 m) of the lower Whirlpool and of the lower and upper parts combined. The interpretation of this section is discussed in Chapter 7.

KENILWORTH AVE.



strike is 251 to 71 degrees), but internally the beds appear to be current ripple cross-laminated.

Unit #1 is unfossiliferous and does not display any trace fossils. The upper bounding surface of the unit has symmetrical ripples that strike 303 degrees and have a RI of 10.

Unit #2 (0.13 m thick) contains simple flaser and lenticular bedding (Fig. 4-17a). The section is transverse, exposing symmetrically rippled sandstone (crests strike about 123 to 303 degrees) with 2 mm thick shale drapes filling in the trough areas of the flaser beds. The symmetrically rippled laminae are 1 mm thick and are in phase with one another. The flaser beds have a sandstone/shale ratio of 3:1, and the lenticular beds, 1:1.5. No trace fossils or fossils are present. Possible desiccation cracks occur on the sole of the lenticular sandstone beds. Unit #2 pinches out around the 40 m mark.

Unit #3 appears to be a cross between facies Sp and St. The foresets (3 mm thick) are planar to curved, dip at about 6 degrees, and form sets 0.1 m in thickness. The paleocurrent is to the northwest at 334 degrees. The unit also contains an 8 m long, 0.37 m deep scour (?), which, due to its differential weathering, appears to be completely bioturbated. The lower surface of the scour is irregular and contains small (0.5 cm long) shale clasts. A few rugose corals and branching feeding traces, which are the first

Figure 4-17. Features of the Kenilworth Avenue section.

a) Simple flaser bedding possibly passing up into lenticular bedding. This is the only known occurrence of simple flaser bedding in the Whirlpool. Scale divisions are 10 cm in length. Photo from 0.6 m above the Whirlpool's base, 30 m along the horizontal scale of Figure 4-19.

b) Photo showing the nature of the hummocky to bioturbated amalgamated HCS unit (unit #5). Note the sharp, erosional nature of the base of unit # 5 (at base of scale), and the large, irregularly-shaped cavities (weathered-out shale rip-up clasts) lining its base. The entire Whirlpool is shown in this photo. The lower Whirlpool (unit #1) lies below the base of the scale and consists of low-angle cross-laminations (see Fig. 3-5). The upper Whirlpool at this site (60 m on the horizontal scale of Figure 4-19) consists entirely of amalgamated HCS. Possibly as many as six amalgamation units are present. The top of unit #5 grades up into the Manitoulin. The contact is placed at 0.6 m above the top of the scale. The scale is 40 cm long.

occurrence of fossils and ichnofauna in the section, occur at the top of unit #3.

Unit #4 is difficult to classify, but appears to be a thin unit of facies S/F that grades to the right into a single bed of bioturbated sandstone, and to the left, into a single layer of green-grey shale. Fossils are rare; only one, a pyritized pelecypod shell, was found in the single sandstone bed. The shale layer is scoured into twice by the overlying unit and is eventually cut out by one of these scours.

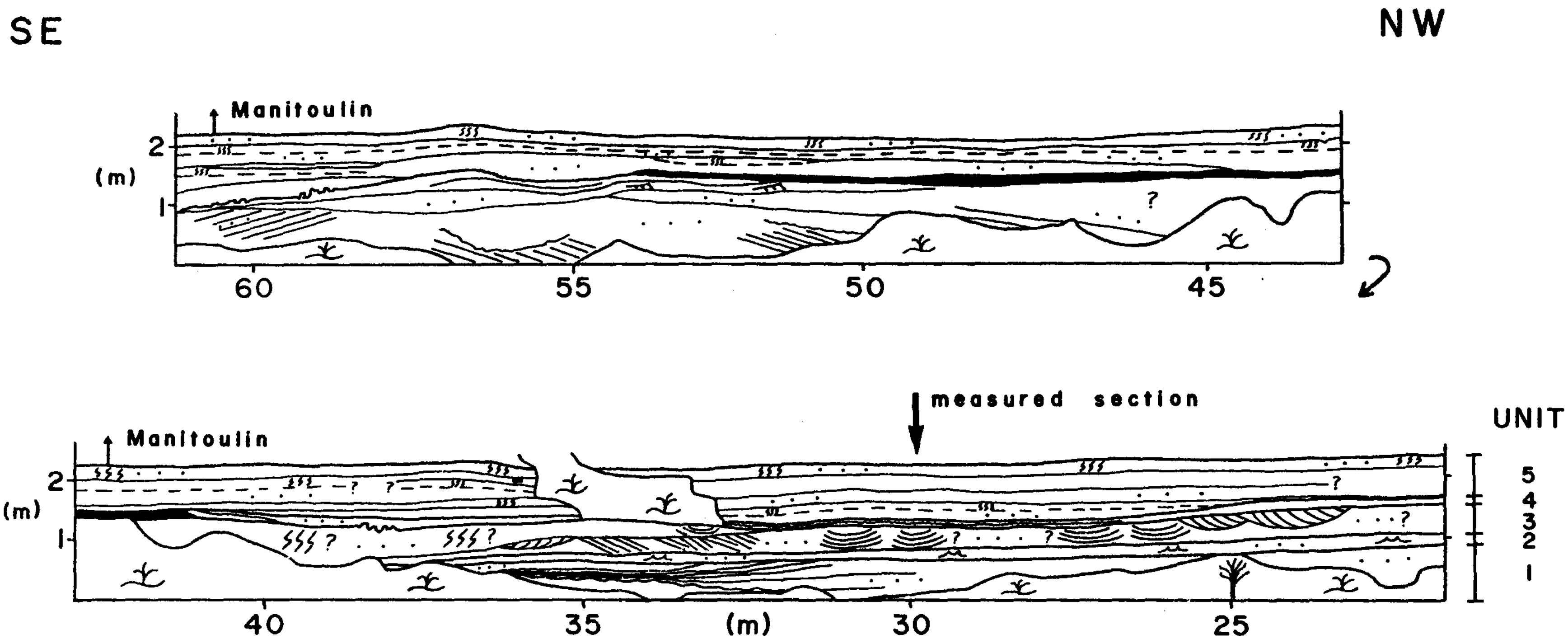
The only occurrence in the study area of facies Shcs.A (hummocky to bioturbated type) is in unit #5. The characteristics of the amalgamated HCS beds in this unit were described in detail in Chapter 3 and will not be repeated here.

The lower bounding surface of unit #5 is sharp and erosional, occasionally lined with very large (0.1 m diameter), irregularly shaped rip-up clasts (Fig. 4-17b). The upper surface grades lithologically into the Manitoulin Dolomite. The unit is essentially tabular in shape, except where scouring occurs, and varies in thickness from 0.56 to 1.1 m, occupying a maximum of 48% of the entire section. The number of amalgamation units varies laterally from about two to a maximum of about seven (Fig. 4-18) (the greatest number occurs where the unit is thickest). Each amalgamation unit can be easily identified by its sharp,

Figure 4-18. Unit #5, showing the presence of at least seven amalgamation units. Each amalgamation unit can be identified by its sharp, flat base, which scours into the bioturbated top of the underlying unit. The top of unit #5, which is the top of the Whirlpool, is at the top of the scale. Note that the uppermost amalgamation unit is thoroughly bioturbated. Scale is 1 m in length. Photo from about 62 m on the horizontal scale of Figure 4-19.

Figure 4-19. Sketch of the wall of the Kenilworth Avenue exposure, showing the lateral facies relationships. In unit #5, the solid lines represent the bases of amalgamation units, and the dashed lines, the boundary between the laminated and bioturbated parts of an amalgamation unit. See text for a brief discussion of this diagram. Vertical scale is not exaggerated.

KENILWORTH AVE.



flat base, which scours into the top of the underlying unit, and its bioturbated top (the thickness of the bioturbated tops increases upward in the section). While only one or two beds may be traced throughout the entire length of the outcrop, most are eventually truncated laterally by above units. Rugose corals (less than 1%) are well preserved and found throughout the unit. Trace fossils are abundant and include Palaeophycus (must abundant), Teichichnus, Skolithos, nondescript burrows, and possibly Arenicolites. The top bed of the unit is thoroughly bioturbated and contains celestite-filled cavities and large (0.25 m long), elongate, internally laminated shale clasts. This bed may belong to facies Sb, but it is considered here to be a thoroughly bioturbated amalgamation unit.

Figure 4-19 is a sketch showing the lateral facies relationships of 40 m of the Kenilworth Avenue section. Important things to note are that: 1) all unit contacts are erosional; 2) there is considerable lateral variation of and within the facies, or units. Some units thin or pinch out laterally (e.g. units 2,3, and 4); and 3) unit 5 scours into unit 4 twice (at 55 m and 40 m), and to the left of 55 m, it scours out unit 4 completely and rests erosionally on what is believed to be unit 1.

Balls Falls

The Whirlpool outcrops discontinuously for about 400 m along the sides of a ravine cut by Twenty Mile Creek. At this locality, the Whirlpool is 5.2 m thick, displays both upper and lower parts, and yields abundant paleocurrent information. The sandstone is generally very fine- to medium-grained (varying from 3.5 - 3 to 2 - 1.5 phi), noncalcareous, except in the upper unit, and is medium- to thickly-bedded. The regional dip is less than 5 degrees to the southeast.

The underlying Queenston is covered by soil but may be reached by digging. The Queenston/Whirlpool contact, what little of it can be seen, is, as usual, sharp, slightly irregular, and horizontal-lying in nature.

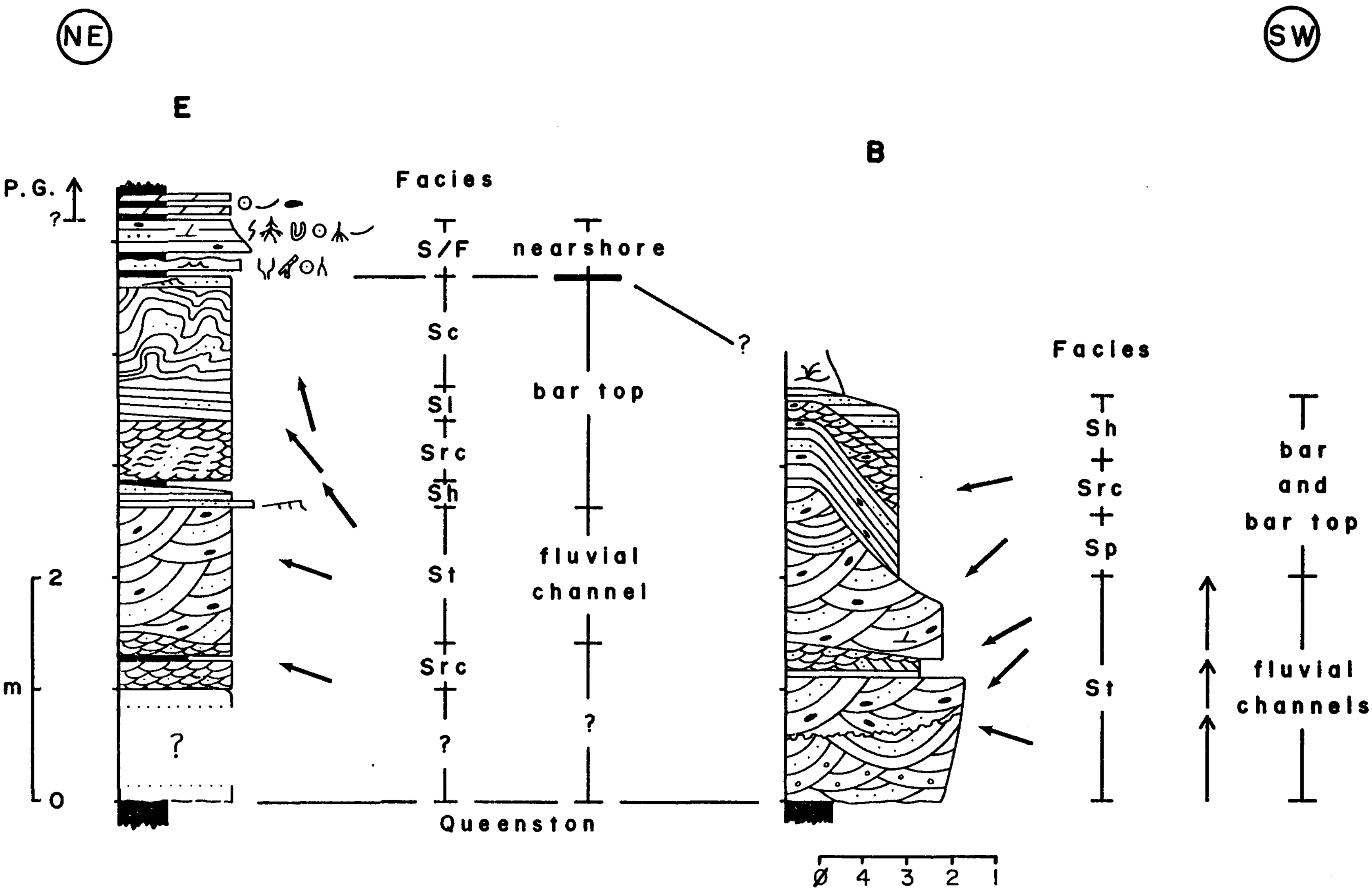
Section B (Fig. 4-20) shows the typical appearance of the Whirlpool at Balls Falls, while section E shows an interesting deviation from this norm.

The Balls Falls exposure is predominantly trough cross-laminated (facies St) with smaller or minor amounts of facies Src, Sh, Sl, Sc, Sp, and S/F. Most of the units are irregular in shape due to the erosional nature of their bounding surfaces.

In the units displaying facies St, the trough cross-laminated sets (average thickness is 0.25 m) occur in cosets containing up to seven sets. Foresets are 0.7 cm thick, and

Figure 4-20. The Balls Falls section, showing two of the sections measured along this 400 m long exposure. Section B represents the typical appearance of the exposure, while section E shows a deviation from this norm. The interpretations presented are discussed more fully in Chapter 7. See Appendix 1 for the locations of sections B and E at Balls Falls.

BALLS FALLS



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have shale clasts (averaging 1 cm long) oriented parallel to the laminations. The paleocurrent is to the west (273 degrees) and, as seen by the crosscutting relationships of the sets, there appears to be a southwestward (about 192 degrees) migration. In some areas an irregular scour surface, scouring a maximum of 0.25 m, is present and can be traced over a 20 m distance. The facies St units, especially those near the Whirlpool's base, also contain a few large troughs. These troughs are symmetrical, range in width from 3 to 14 m (Fig. 4-21), and in depth from 0.45 to 0.85 m, and have strata ranging in thickness from 0.8 to 5 cm. Their orientation indicates a paleocurrent to the northwest (290 degrees).

Current ripple cross-laminations (facies Src) occur throughout the Balls Falls exposure. The units are generally laterally extensive, except at section B, where ripple cross-laminae grade laterally into a single, 0.18 m thick set of planar tabular cross-laminations (paleocurrent is 201 degrees). The ripple cross-laminae average 1 mm in thickness and form sets averaging 8 mm thick. Ripple drift and rib-and-furrow structures indicate a northwest (294 degrees) paleocurrent.

One peculiar unit (at the 3 m level) that was difficult to classify was observed in two areas of the Balls Falls exposure. Over an 8 m distance (lateral) the unit shows horizontal laminae which then begin to dip at

Figure 4-21. A large (14 m wide), symmetrical trough occurring within a trough cross-laminated unit near the base of the Whirlpool. The paleocurrent direction obtained from this trough is to the northwest (290 degrees). Scale is 1 m in length. Photo from an exposure about 100 m south of section E (see Fig. A1-3c).

17 degrees, forming planar cross-laminae with tangential bottomsets. There is some indication that the laminations may actually curve upward again. Maximum set thickness is 1 m. The cross-laminae suggest a paleoflow to the southwest (227 degrees).

One of the best exposures of facies Sc occurs at section E (see Fig. 3-6b). The unit begins as 0.31 m of low-angle cross-laminations (paleocurrent is to 345 degrees) which gradually become more and more deformed upwards in the unit. The top 0.48 m show true convolution, the intensity of which increases upwards. The laminae are all parallel to each other and form anticlines and synclines with fold axes inclined to the northwest at 320 degrees. The unit is truncated at the top by ripple cross-laminations.

The upper part of the Whirlpool is exposed at section E and consists solely of facies S/F, interbedded calcareous sandstone and shale. Because the unit is largely inaccessible and because much erosion has occurred near the top, the true thickness of this unit is unknown.

The sandstone beds have sharp bases, symmetrically rippled (straight crested and interference) tops, and variable bedding thicknesses, ranging from 5 to 40 cm. The beds have a rather atypical outcrop appearance; they are heavily pitted (10%) with elongate holes (weathered out shale clasts) ranging in size from 1 to 10 cm. The sandstone is light brown in colour, but darker (less sandy) areas with copious amounts of small (1 mm) holes concentrated along planes gives the rock a banded appearance. The small holes are weathered-out crinoid ossicles. Other fossils, although not very abundant, include gastropods, bivalves, and brachiopods. The beds are weakly bioturbated by forms which include (in order of abundance) Chondrites, Lingulichnus (or Lockeia?), Arenicolites, and possibly Phycodes and Palaeophycus. The beds are also characterized by synaeresis cracks and very large (4 mm diameter), rounded phosphatic (?) grains. Some of these beds are very similar in appearance and in paleontological and ichnological composition to those occurring in the same unit at the Lockport section. A beautiful, three-dimensional exposure of HCS can be found near the water level about 200 to 300 m upstream from section B (P. Fawcett, pers. comm., 1986).

The upper part of the Whirlpool, although incomplete in exposure, is overlain gradationally by the interbedded calcareous sandstones and shales of the Power Glen Formation (Bolton, 1953).

The Whirlpool/Whirlpool State Park

The Whirlpool section is the type section of the Whirlpool Sandstone and is part of a laterally extensive exposure of the Whirlpool that occurs on both sides of, and for the entire length of the Niagara Gorge. The Whirlpool and Whirlpool State Park (abbreviated WPSP) offer excellent vertical and bedding plane exposures. During high water levels (i.e. during the peak tourist season months of April through to the end of October) the Whirlpool's base outcrops just 0.3 m above the waterline, making it impossible to observe the lower portion of the Whirlpool along much of the exposure. Only at one area (at The Whirlpool) is the entire Whirlpool accessible during these months. During the off-season for tourists, when 75% of the water in the upper Niagara River is diverted for hydroelectric power, the water level drops 3 to 7 m, making it possible to observe the entire Whirlpool at both sites.

The exposed thickness of the Whirlpool is 7.5 m, but this is not the total thickness, for the upper part of the Whirlpool is missing. It is a thickly- to very thickly-bedded, generally noncalcareous (except in the lower 1 m) sandstone with a much coarser grain size than that which occurs in other sections west of here. The section shows a general fining upwards from about 0.5 - 1 to 3 - 3.5 phi. The Whirlpool is light grey in colour (weathers light brown), but red patches, confined within a single set or within a group of cross-strata within a set, occur at various levels throughout the section.

The Whirlpool: The Whirlpool section is a 150 m long exposure of vertical section and bedding planes located on the east side of The Whirlpool. During high water levels the entire Whirlpool is accessible only at section A (see Fig. A1-4b in Appendix 1).

About 1 m of the Queenston Shale is exposed here. As usual, it is red in colour but has a top 0.13 m thick zone of grey-green coloured shale.

The Queenston/Whirlpool contact is regionally flat and nearly horizontal, but on a smaller scale, over a lateral distance of the order of a meter, it is quite irregular, showing a maximum relief of 10 cm. The sole of the Whirlpool is very irregular with innumerable small (1 cm diameter) craggy knobs (casts of desiccation cracks?) protruding down (between 0.5 to 1 cm) into the Queenston. Shale rip-up clasts are rare on this surface, but where present, they are dark greenish-grey in colour, spherical, and average about 3 cm in diameter.

The Whirlpool section (Figs. 4-22 and 4-23a) is predominantly trough cross-laminated with minor occurrences of facies Sh, Sp, and Src. All units are tabular to irregular in shape and have erosional upper and lower unit boundaries.

The Whirlpool site is ideal for observing facies St in three dimensions. The trough cross-laminae are 0.6 cm thick and form sets averaging 0.15 m in thickness. The sets

Figure 4-22. The Whirlpool Section. The diagram is based mostly on the exposure at section A (see Fig. A1-4b for location). Note the abundance of facies St, the coarseness of the grains at the base, and the presence of three fining-upward cycles, two of which begin at scour surfaces. The interpretation of this section and the other Niagara Gorge sections is discussed in Chapter 7.

THE WHIRLPOOL

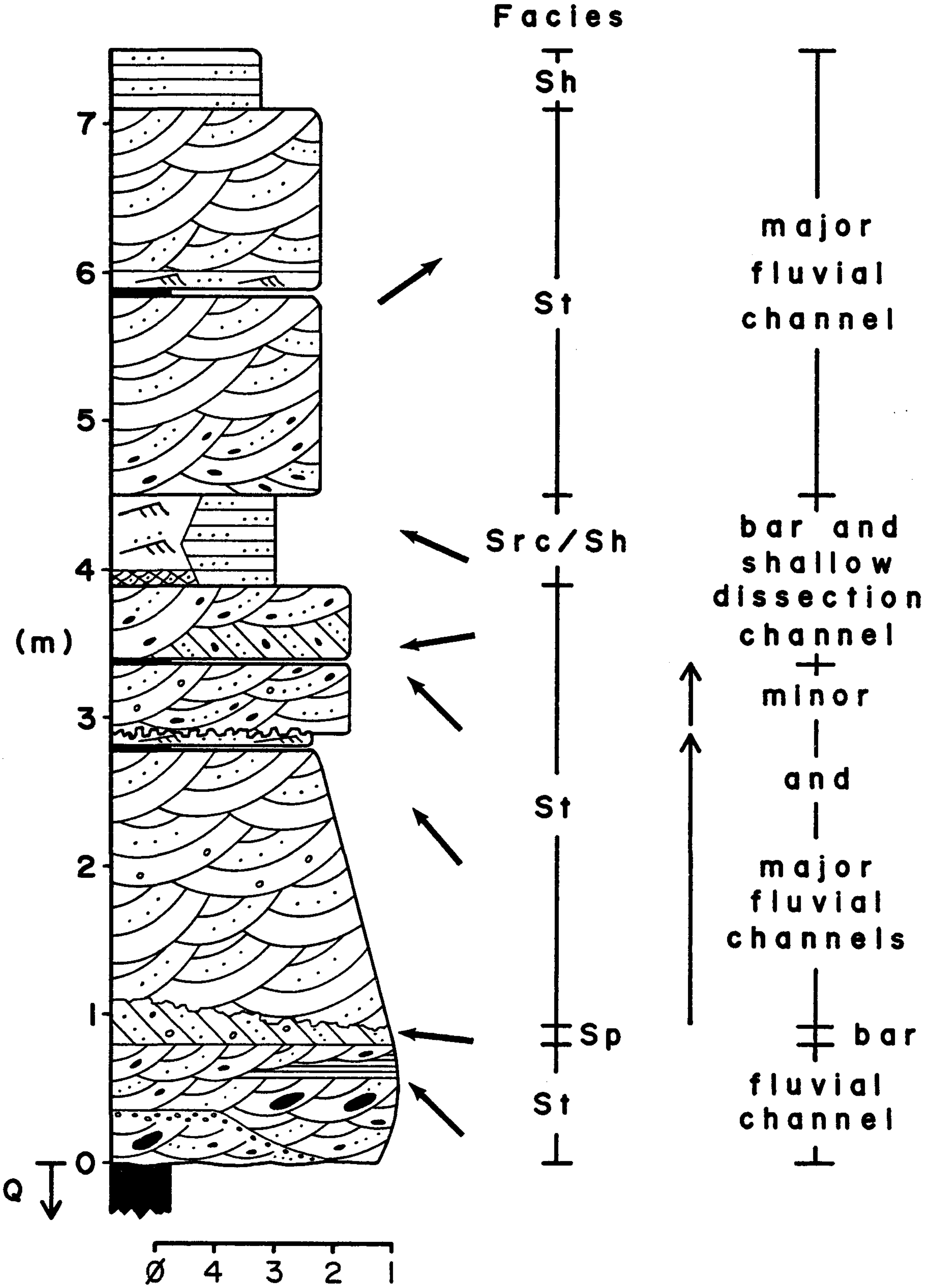
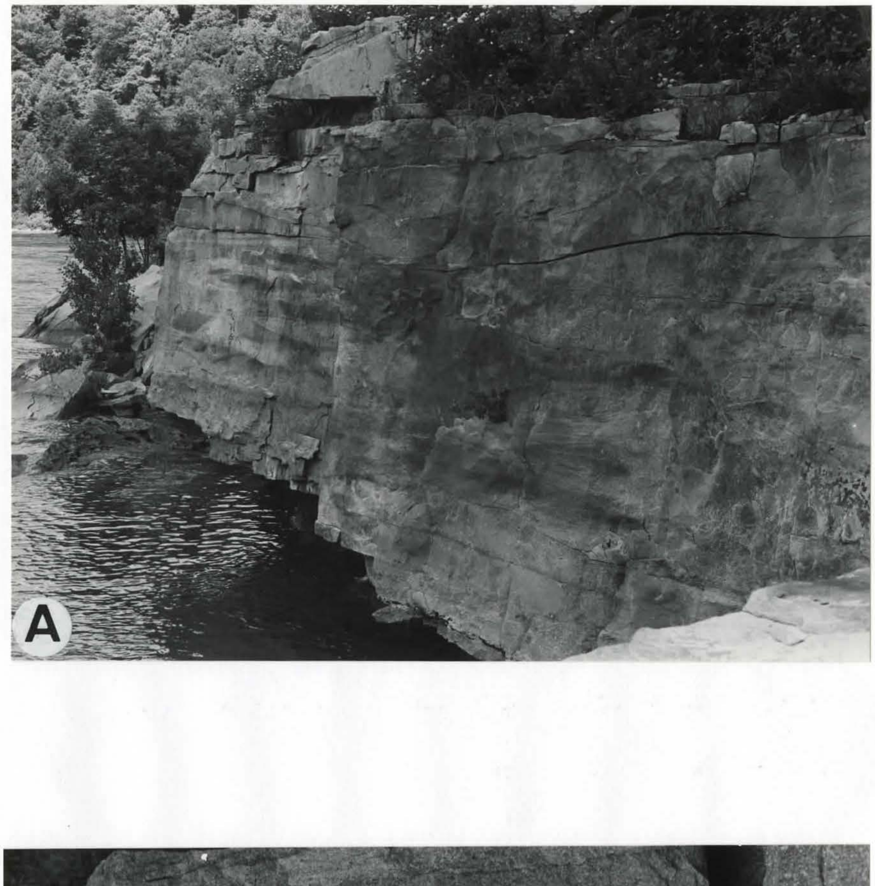


Figure 4-23. Features of The Whirlpool section.

a) Typical appearance of the Whirlpool Sandstone (lower part) at the type section (and in the Gorge). Note the massive bedding and the thick cosets (4 m in this case) of trough cross-laminations. The dark-toned areas of the rock face are areas of hematite cementation, which in some places may be confined within a single set of cross-strata. The outcrop shown here is 4 m thick. From The Whirlpool bedding plane area, 0 to 4 m above the Whirlpool's base.

b) Large shale clast moulds, in a trough cross-laminated unit at the base of the Whirlpool. The largest one is 25 cm in length. Note the high concentration of spherical weathering cavities within a 15 cm thick interval. This interval contains the coarsest grains and the highest carbonate content in the section. Book is 19 cm long. From The Whirlpool section, section A, base of Whirlpool.


A
FIELD BOOK
B

occur in cosets, which, like in all the Niagara Gorge sections, are very thick, ranging in thickness from 0.9 to 4 m. Oriented parallel to the cross-laminae are elongate-to very irregular-shaped shale rip-up clasts that average 1 cm in length. These clasts occur at various levels within the section. In a 0.4 m thick interval near the base of the Whirlpool, very large, dark greyish-green silty shale rip-up clasts are present. These shale clasts are lying subhorizontally, are elongate to irregular in shape (Fig. 4-23b), and are extremely variable in size, ranging from 4 to 25 cm and averaging 10 cm in length. These clasts occur in the coarsest interval of the section.

A common feature of the trough cross-laminated units in the Niagara Gorge is the presence of erosional, or scour, surfaces covered with irregularly shaped shale clast moulds (the shale is rarely preserved) that range in size from 2 to 9 cm and average 7 cm (see Fig. 3-1c). In cross section these shale pebble lag surfaces are very irregular (maximum relief is 4 cm), and the surface, itself, scours a maximum of 0.22 m. The Whirlpool's grain size appears to increase just above these surfaces.

Spherical cementation rosettes, ranging in size from 0.3 to 1.5 cm, are found at various levels within the trough cross-laminated units. They are most abundant, however, in the 0.4 m thick interval near the base containing the large shale clasts, coarsest grain size and the highest carbonate content (Fig. 4-23b).

The paleocurrent, primarily determined from large scale rib-and-furrow structures (facies St) on the bedding plane surfaces, is towards the northwest (305 degrees). Current crescents are superimposed on the rib-and-furrow structures and also indicate a northwest paleoflow (337 degrees).

Facies Src occurs at various levels in the section. Sets are 1 cm thick and form cosets ranging from 0.1 to 0.8 m in thickness. The surface expression of facies Src is generally as rib and furrow, but other forms, such as ripple fans, sinuous crested ripple-like structures, and climbing ripple drift (Type A), are also present. Rib-and-furrow structures indicate a northwest (313 degrees) paleoflow.

Facies Sp is a minor component of the section. The sets occur singly, and are 0.2 m thick and contain cross-laminae 0.7 cm thick. The average paleocurrent direction is towards the southwest at 272 degrees.

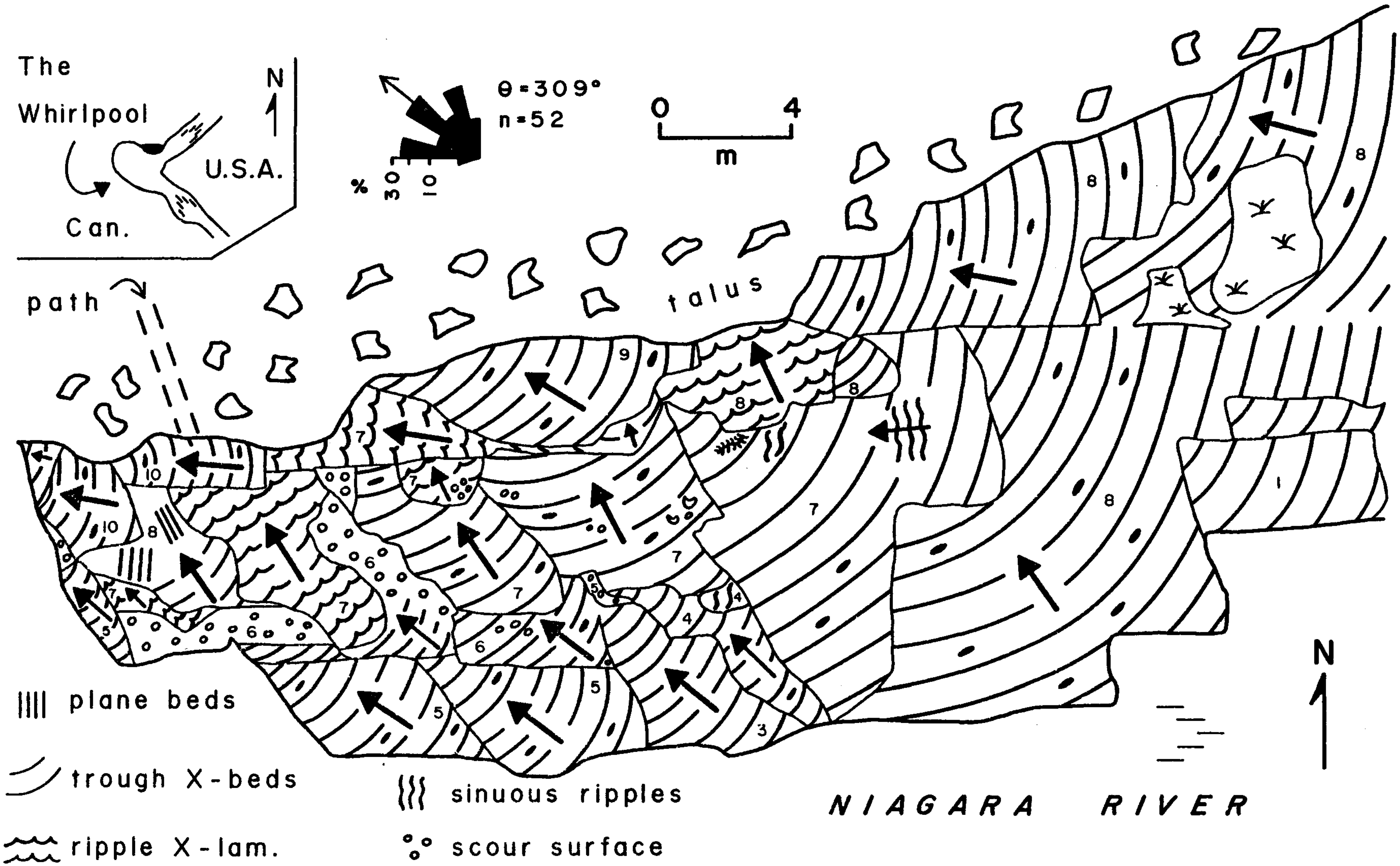
Horizontal laminations (averaging 0.5 cm thick) occur at various levels in the section. The units, which range in thickness from 0.1 to 0.9 m, are only locally present, with the exception of the occurrence at the top of the section; this unit can be traced throughout the Niagara Gorge area.

Figure 4-24 is a map of a 52 m X 16 m bedding plane that exists at The Whirlpool. The map shows the lateral

Figure 4-24. Map of The Whirlpool bedding plane showing the lateral distribution of the various facies on a series of bedding planes occurring between 2.4 and 4 m above the Whirlpool's base. The lines bounding each of the areas indicates an elevation change in the bedding plane surface. The number in each area indicates the approximate height of the bedding plane above the Whirlpool's base (see below). Arrows indicate the paleocurrent direction. Note the consistent northwest (309 degrees) paleocurrent trend. Symbols used do not indicate the true size of the features present.

Level	Height above base (m)
10	3.76 - 4.00
9	3.51 - 3.75
8	3.26 - 3.50
7	3.01 - 3.25
6	2.76 - 3.00
5	2.51 - 2.75
4	2.26 - 2.50
3	2.01 - 2.25
2	1.76 - 2.00
1	1.51 - 1.75

BEDDING PLANE MAP OF THE WHIRLPOOL (CAN.)



distribution of the various facies on a series of bedding planes occurring between the 2.4 and 4 m level. Facies St is by far the most abundant facies and is expressed on the surface as large scale rib and furrow (distance between ribs varies from 0.6 to 1.3 m). Small scale rib and furrow, a shale pebble lag, possible current lineations, and sinuous crested ripple-like structures are also present.

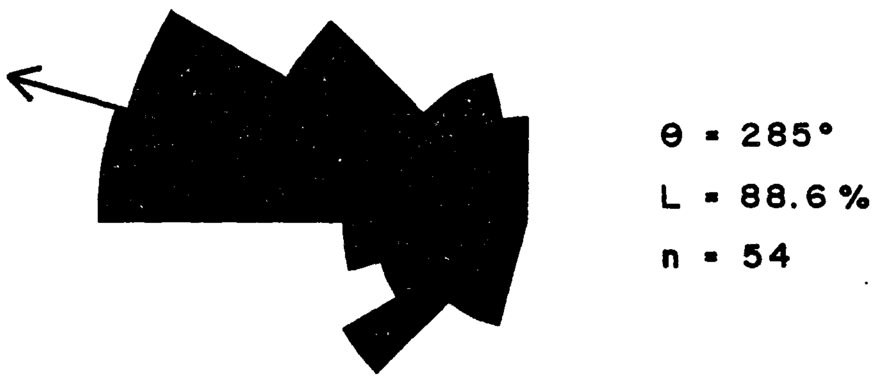
Readings obtained mainly from large and small (facies Src) scale rib-and-furrow structures show a prevalent paleocurrent to the northwest (309 degrees).

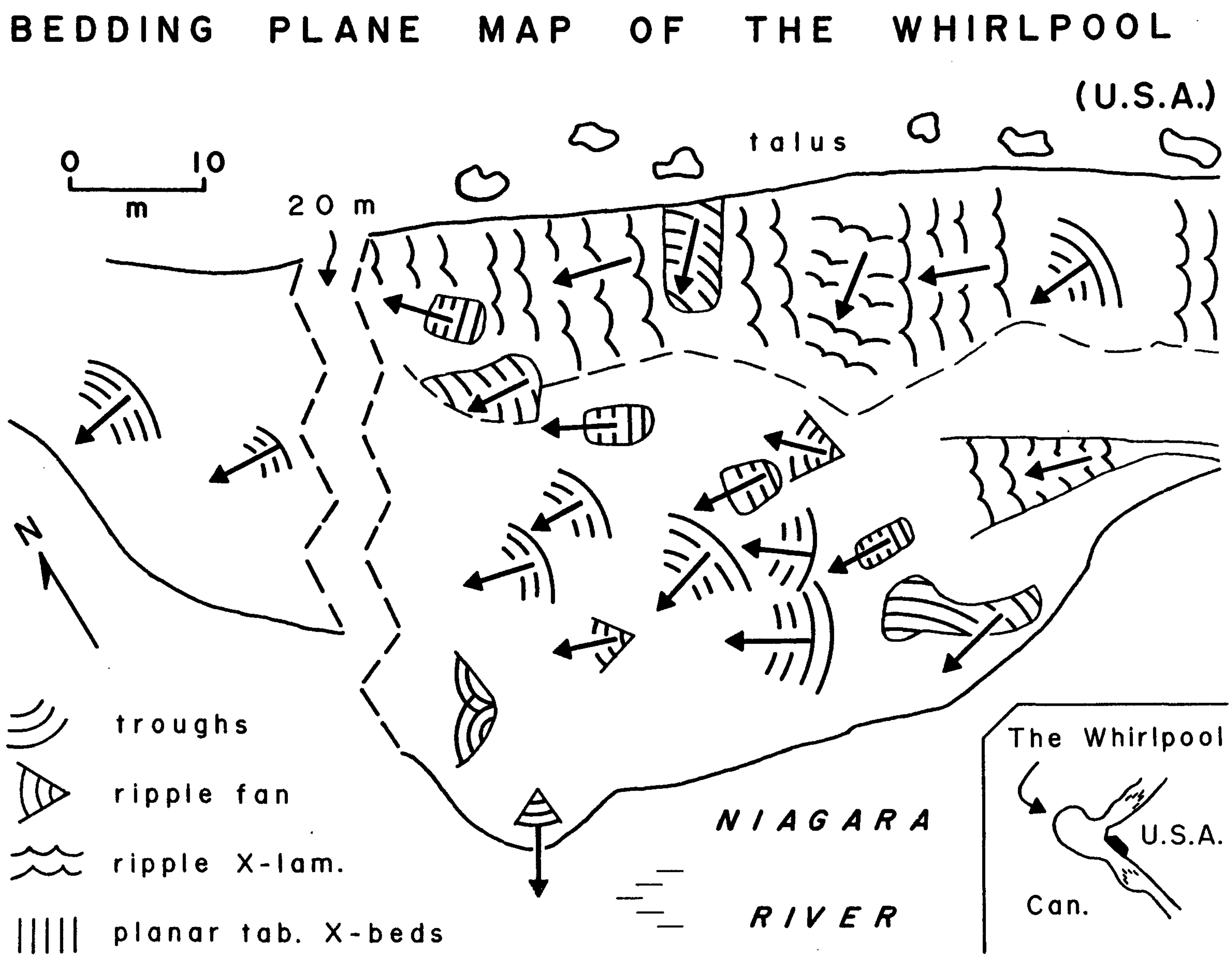
Whirlpool State Park: The Whirlpool State Park section (see Appendix 1 for location) is very similar to The Whirlpool section. The section is primarily trough cross-laminated with minor occurrences of facies Sh, Sp, and Src.

A very extensive bedding plane, 140 m X 40 m, is exposed at the 2 to 3 m level (Fig. 4-25). What makes this exposure interesting is the great number of well preserved isolated troughs. On the bedding plane these troughs are symmetrical, and vary in width from 2.5 to 7 m (Fig. 4-26a). There are many exhumed slipfaces, and on one there are rill-like structures oriented perpendicular to the trough crest. A few large scale rib-and-furrow structures (facies St) are also present. The paleocurrent trend from the trough cross-laminations is 284 degrees.

Facies Src is represented on the bedding plane by

Figure 4-25. Map of the Whirlpool State Park bedding plane. All troughs, ripple fans, and planar tabular cross-beds shown are true size. Note the consistent northwest (285 degrees) paleocurrent trend. The distribution of readings are shown in the rose diagram below.




BEDDING PLANE MAP OF THE WHIRLPOOL
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talus
0 10
m
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troughs
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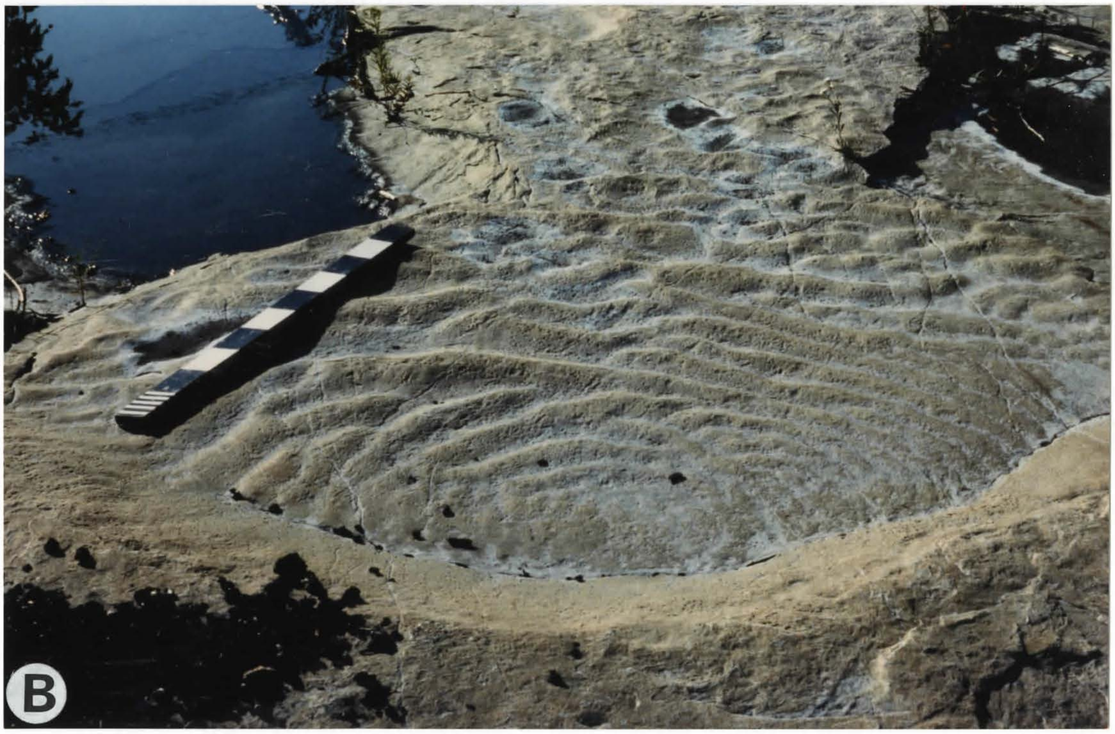
planar tab. X-beds
NIAGARA
RIVER
The Whirlpool
U.S.A.
Can.

Figure 4-26. Features of Whirlpool State Park.

a) An example of a well-preserved, isolated, large symmetrical trough exposed on the bedding plane. Note the exhumed slipfaces and the downstream concavity of the concentric foresets. Scale divisions are 10 cm in length.

b) A well-developed ripple fan showing an interference pattern. Some of these ripple fans are isolated, while others like this one, occur at the base of exhumed slipfaces. The general paleocurrent direction is towards the top of the photo. The scale is 1 m in length.


A


B

small scale rib-and-furrow structures (paleoflow trend is 283 degrees) and ripple fans. Some of these ripple fans are isolated while others occur at the base of exhumed dune slipfaces. Interference patterns are common features of these ripple fans (Fig. 4-26b).

Planar tabular cross-laminations occur locally in a few areas, and are recognized by their straight foreset traces on the bedding plane surfaces. They indicate a paleocurrent to the northwest (292 degrees).

As at The Whirlpool, the bedding plane features indicate a fairly consistent northwest (285 degrees) paleocurrent trend.

Niagara Glen/Devil's Hole

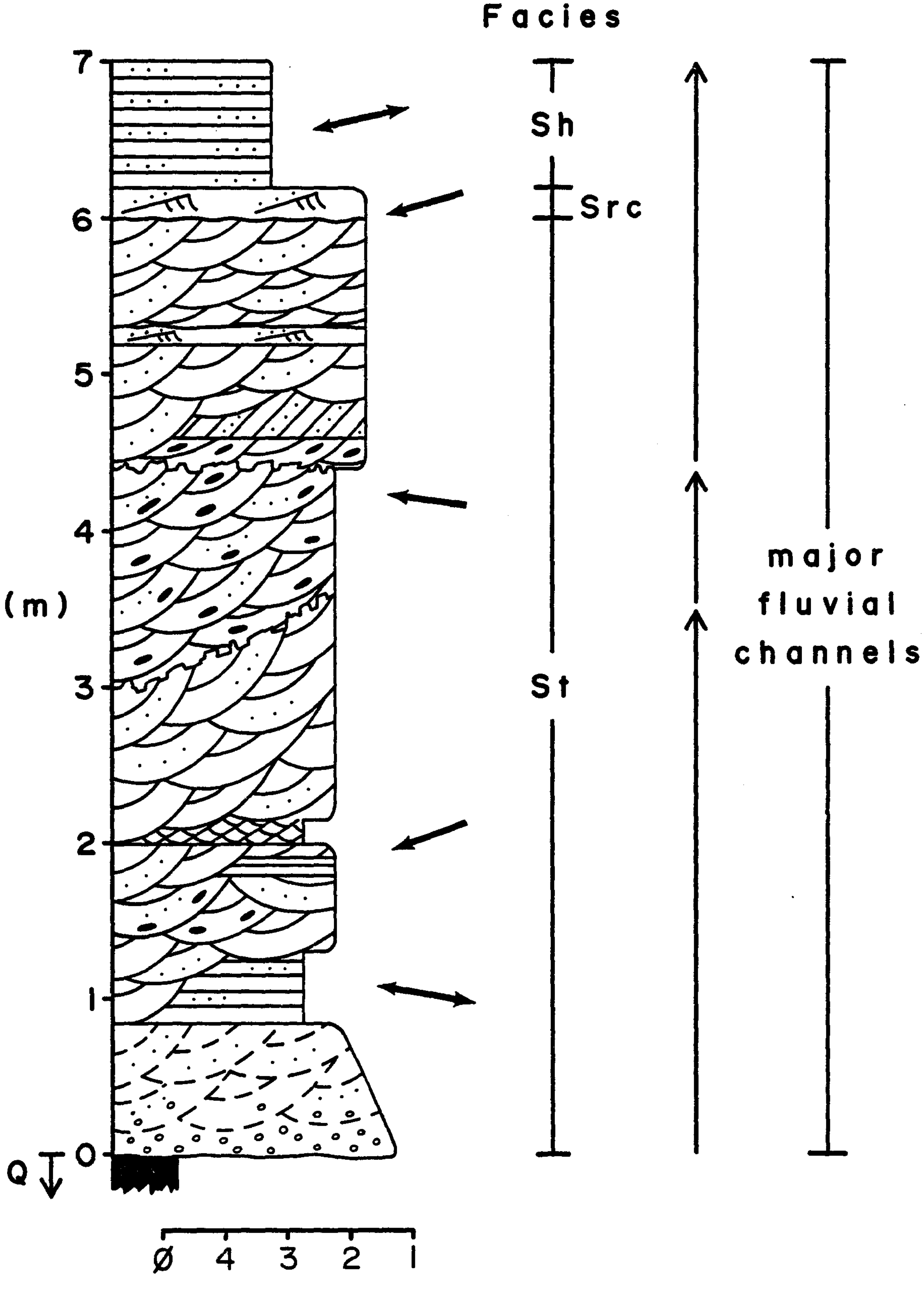
These two sections occur about 100 m apart on opposite sides of the Niagara Gorge. Because of the short distance and the similarities existing between the two exposures, the two sections are discussed here together.

At Niagara Glen, 7 m (of only the lower part) of the Whirlpool are exposed for 750 m along the base of the Glen, but access to much of this exposure is quite limited. The section diagram shown in Fig. 4-27 is based on an excellent 80 m long exposure.

On the other side of the gorge, the entire Whirlpool (8.4 m) is exposed for nearly 1 km along the Devil's Hole

Figure 4-27. The Niagara Glen section. Note the abundance of facies St and the vertical variability in grain size, with the coarsest grains generally occurring at the base and just above the scour surfaces. The section shows an overall fining-upward. The interpretation of this section is discussed more fully in Chapter 7.

NIAGARA GLEN



Trail (the abandoned line of the Upper Great Gorge Railway). Because there is very little lateral variation in the facies present along this exposure, only one section (40 m long), located almost directly across from the Niagara Glen section, was measured (Figs. 4-28 and 4-29a).

The lower part of the Whirlpool is massively bedded, contains rare shale partings (if any at all), and is noncalcareous, except at the base of the Whirlpool. Although there is an overall fining upward of the grain size, (from 1.5 - 1 to 3 - 2.5 phi) there appears to be two or three smaller fining-upward sequences (as at The Whirlpool), depending on the number of shale pebble lag surfaces; each sequence begins just above the scour surfaces and above the Whirlpool's base.

About 1 m of the Queenston is exposed. Its top 5 cm of grey-green shale is sharply overlain by the regionally flat, nearly horizontal-lying base of the Whirlpool (dips 3 degrees to 175 degrees). The Niagara Glen section provides and excellent view of the Whirlpool's base. The entire base is marked by 1.5 to 15 cm (average is 4 cm) wide ?desiccation cracks (casts) that are spaced up to 5 cm apart and protrude a maximum of 7 cm into the Queenston below. There appears to be no biogenic structures or any scour or tool markings present. Grey-green shale clasts and randomly oriented, frequently intersecting, protruding ridges (up to 5 cm wide and deep) are also present; the latter are

Figure 4-28. The Devil's Hole section. This section is very similar to the Niagara Glen section. Note the abundance of facies St and the overall fining-upward trend in the lower Whirlpool. Two fining-upward sequences, separated by the scour surface, may be present. Note the great abundance of shale clasts above the scour surface but not below, possibly indicating a high degree of channel bank erosion. The interpretation of this section is discussed more fully in Chapter 7.

DEVIL'S HOLE

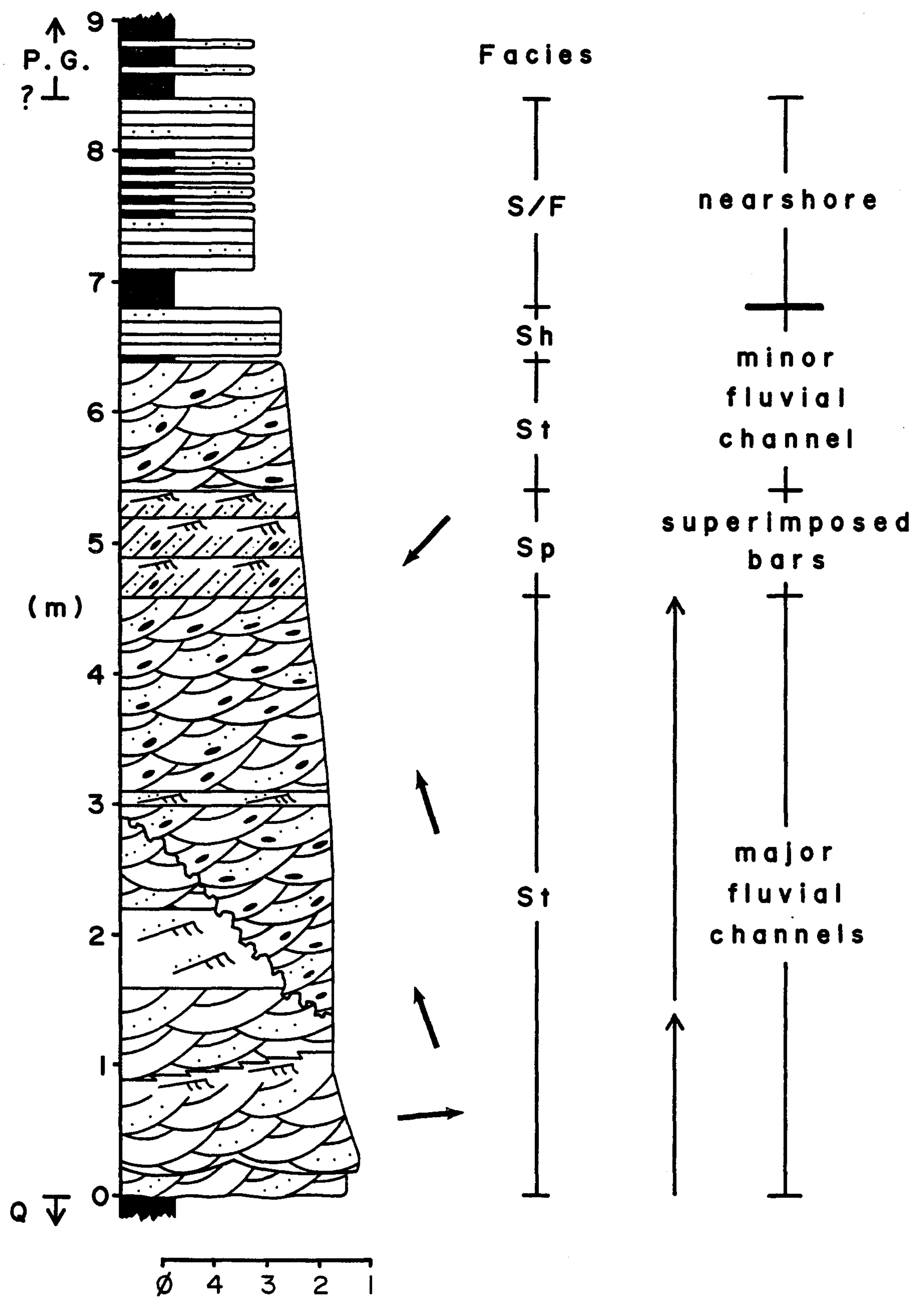

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Figure 4-29. Features of the Devil's Hole section.

a) Typical appearance of the lower Whirlpool at Devil's Hole. As at all Niagara Gorge sections, the lower Whirlpool here is massively-bedded, has a great abundance of facies St, and contains few shale interlayers. The Queenston/Whirlpool contact is at 20 cm above the base of the scale (scale is 1 m in length). The arrow points to the scour surface. Note its irregularity and how the texture of the rock changes just above it, a reflection of the sudden increase in shale clasts above this surface.

b) Bottom view of the scour surface showing well developed current crescents. The paleocurrent is towards the upper left of the photo. The largest crescent shown is about 7 cm in width. Photo from an area to the right of that shown in Figure 4-29a, 2.5 m above the Whirlpool's base.


A


B

probably desiccation cracks. Overall, the Whirlpool's base is quite flat, having only minor irregularities of up to 20 cm in relief.

The two sections are predominantly trough cross-laminated with minor occurrences of facies Src, Sh, and Sp (Fig. 4-29a). Most contacts are erosional.

The trough cross-laminations are poorly defined in a few areas near the base, but otherwise their definition is quite good. The trough cross-laminae are 0.5 cm thick and form sets averaging 0.15 m in thickness. Cosets are very thick, ranging in size from 0.5 to 4.6 m and generally averaging greater than 2.5 m.

The trough cross-laminated units contain local occurrences of horizontal and ripple cross-laminations that extend laterally for 8 m to 30 m before being truncated by the scour surfaces or the trough cross-laminations. The ripple cross-laminated cosets average 0.2 m thick and contain sets averaging 1 cm in thickness. Cross-laminae are 0.3 cm thick. Rib-and-furrow structures indicate a northwest (288 degrees) paleoflow. The horizontal laminations are 0.3 cm thick and occur in units up to 0.5 m thick. Parting lineations suggest a 277 to 97 degrees paleocurrent trend.

Two scour surfaces, similar to the ones at the Whirlpool and Whirlpool State Park, are present (see Fig. 3-1c, 4-29a). The maximum scouring by these surfaces is

1.4 m. In some areas of the surfaces, protuberances forming U-shaped patterns on the undersurface of the scour surface are present (Fig. 4-29b). These features, which are probably current crescents, are oriented with the open end of the U shapes facing to the northwest (340 degrees). Also of interest is the sudden increase or first appearance of shale clasts in the trough cross-laminations immediately above these scour surfaces (Fig. 4-29a).

Planar tabular cross-laminations occur at the same level at both of the sections. The Devil's Hole section contains the only coset (0.76 m thick) occurrence of facies Sp (Fig. 3-4b). Three sets, ranging in thickness from 9 to 25 cm, are present, and each is eroded at the top by 5 to 14 cm of ripple cross-laminations. The sets are laterally extensive (at least 80 m long) and contain 0.7 cm thick planar laminae that dip at 20 degrees to the southwest (223 degrees). The paleocurrent direction of the ripple cross-laminations is perpendicular to this, either towards 313 or 133 degrees (the ripple cross-laminae are cut transversely by the outcrop).

Horizontal laminations occur near the top at both sections. A hand specimen taken from this interval contained a few specimens of black (phosphatized ?) fossil fragments of trilobites (?) or brachiopods (?).

The unit containing facies S/F is preserved only at Devil's Hole, but unfortunately it is inaccessible. The unit has a sandstone/shale ratio of approximately 2.5:1. The sandstone beds appear to be horizontally laminated and range in thickness (with no vertical trends) from 5 to 40 cm. The shale interlayers also have this thickness range. No further details could be determined. The top of the Whirlpool actually grades upward into the Power Glen Shale, but its contact is placed at the top of the last thick sandstone bed, for above this point the amount of shale in the section greatly exceeds that of the sandstone.

Artpark

The Whirlpool exposure at Artpark, is laterally continuous and very extensive, but only a very small portion of it is accessible. Approximately 8.5 m (?) of the Whirlpool are exposed here. The sandstone is light to dark grey in colour, noncalcareous, and medium- to very thickly-, or massively-, bedded. The section shows both lateral and vertical variations in grain size, but there is an overall fining upward from 1 to 3 - 3.5 phi.

About 40 m of the Queenston Shale are exposed at Artpark. With the exception of a few silty interlayers (located in the upper half of the section) and the top 25 cm, which are greyish-green in colour, the Queenston maintains its typical brownish-red colour.

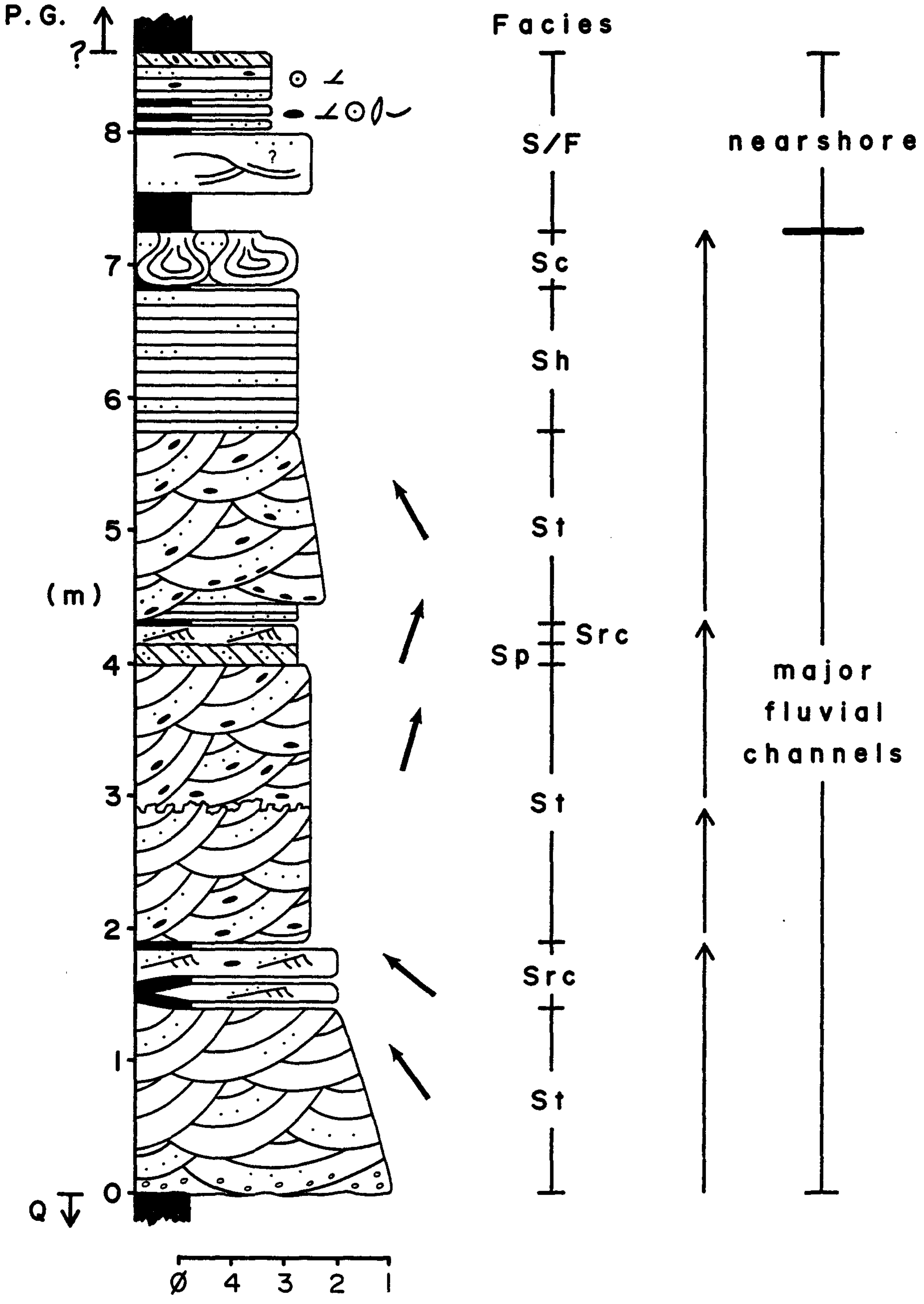
The Whirlpool's contact with the Queenston is abrupt, very gently undulating (less than 1 m in height), and subhorizontal-lying, with a dip of less than 1 degree to the south (Caley, 1940). The Whirlpool's base remains unchanged from how it appears at the other Niagara Gorge sections, and like at The Whirlpool, the 30 cm interval above the basal contact contains very large (range and average are 1 to 10 cm and 3 cm long, respectively), elongate, grey-green, shale rip-up clasts and copious amounts of 0.3 cm diameter spherical weathering cavities.

The summary section (Fig. 4-30) attempts to show the main features and the lateral variations that occur along this 1.5 km + exposure. Facies St is by far the most abundant facies, while facies Src, Sp, Sh, S/F, and Sc each make up a smaller percentage of the total section. Unit boundaries are in most cases erosional.

Cosets of trough cross-laminations are quite thick (range is from 0.6 to 2.5 m in thickness). Laminae average 7 mm in thickness, and form sets ranging in thickness from 0.1 to 0.6 m and averaging 0.15 m. Set size generally decreases upwards in the section. A scour surface, or shale pebble lag surface, was observed, but its exact vertical location could not be determined. Seyler (1981) makes reference to one such surface at the 2.9 m level; this would be consistent with the sudden increase in the abundance of shale rip-up clasts at and above this level (see Fig 4-30). These clasts are elongate, 1 cm long (average), and are

Figure 4-30. The Artpark section. This diagram attempts to summarize the main features and lateral variations that occur along this 1.5 km long exposure. Note the abundance of facies St, the overall fining-upward, and the presence of at least two fining-upward sequences in the lower part of the Whirlpool. The interpretation of this section is discussed in Chapter 7.

ARTPARK



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greyish-green and brownish-yellow in colour. They are imbricated parallel to the foresets, and are evenly dispersed throughout the units. Readings from the trough cross-laminae indicate a northwest (340 degree) paleocurrent. Horizontal laminations and ripple cross-laminations occur as minor elements within the trough cross-laminated units.

Facies Src occurs at various levels in the section. The units, or cosets, range in size from 0.13 to 0.67 m, and sets and laminae average 5 mm and 1 mm in thickness, respectively. Rib-and-furrow structures indicate a paleocurrent to the north at 357 degrees. At the 3.3 m level a ripple-like structure (Fig. 4-31) looking very much like truncated, straight-crested symmetrical ripples occurs on a bedding plane that also displays rib-and-furrow structures. The 'ripple crests' are slightly sinuous, and have a wavelength of 10 cm. Crest orientation is 282 to 102 degrees. The origin of this structure is not known.

One, single set occurrence of facies Sp is present at the 4 m level. The set is 0.15 m thick, and contains 0.6 cm thick laminae dipping 23 degrees (apparent) to the southwest (approximately 240 degrees).

The top 3 m or so of the section is inaccessible, with the exception of a 1.2 m thick interval, which is shown on the diagram beginning at about the 7.6 m level. The features depicted within the top 3 m of the section diagram

Figure 4-31. Photo of a bedding plane displaying a structure resembling truncated, straight-crested symmetrical ripples. Note the tuning fork bifurcation at the lower right. These are interpreted as low stage bar modification features (see Chapter 7 and 8 for more discussion). Pencil is 13 cm long. From 3.3 m above the Whirlpool's base, near the observation deck structure.

are not meant to represent any one location at the Artpark exposure, but is instead a compilation of features observed at various sites along the exposure. Stratigraphic locations are only approximate.

A 1.5 m thick unit containing facies Sh occurs at the 6 m level. The sets, or beds, vary in thickness from 8 to 28 cm.

Above this unit is a 0.3 m thick interval containing what appears to be ball-and-pillow structures (Fig. 3-6a). The pillows are interconnected, and are ellipsoidal in shape, averaging 0.4 m in diameter.

The remainder of the section consists of interbedded sandstone and shale (facies S/F). The sandstone layers are of variable thickness (ranging from 0.5 to 45 cm) and content. The lowermost bed contains low-angle cross-laminations, and may possibly be an HCS bed. The beds above are calcareous and contain numerous 1 cm long, curved shale rip-up clasts. Internally, the beds are horizontally laminated (averaging 0.5 cm thick), and on the planes between each lamination there is a concentration of crinoidal stems and ossicles. A few specimens of ostracods and brachiopods are present, as well. Because the contact with the Power Glen is not exposed, it is difficult to know whether these crinoidal beds really belong to the Whirlpool or the Power Glen. Such beds also occur at Balls Falls (Section E), where they are considered to be part of the

Whirlpool; therefore, the same will apply here at Artpark.

The top of the Whirlpool is placed approximately at the 8.5 m level, above which there is a significant increase (greater than 50%) in the amount of shale in the section.

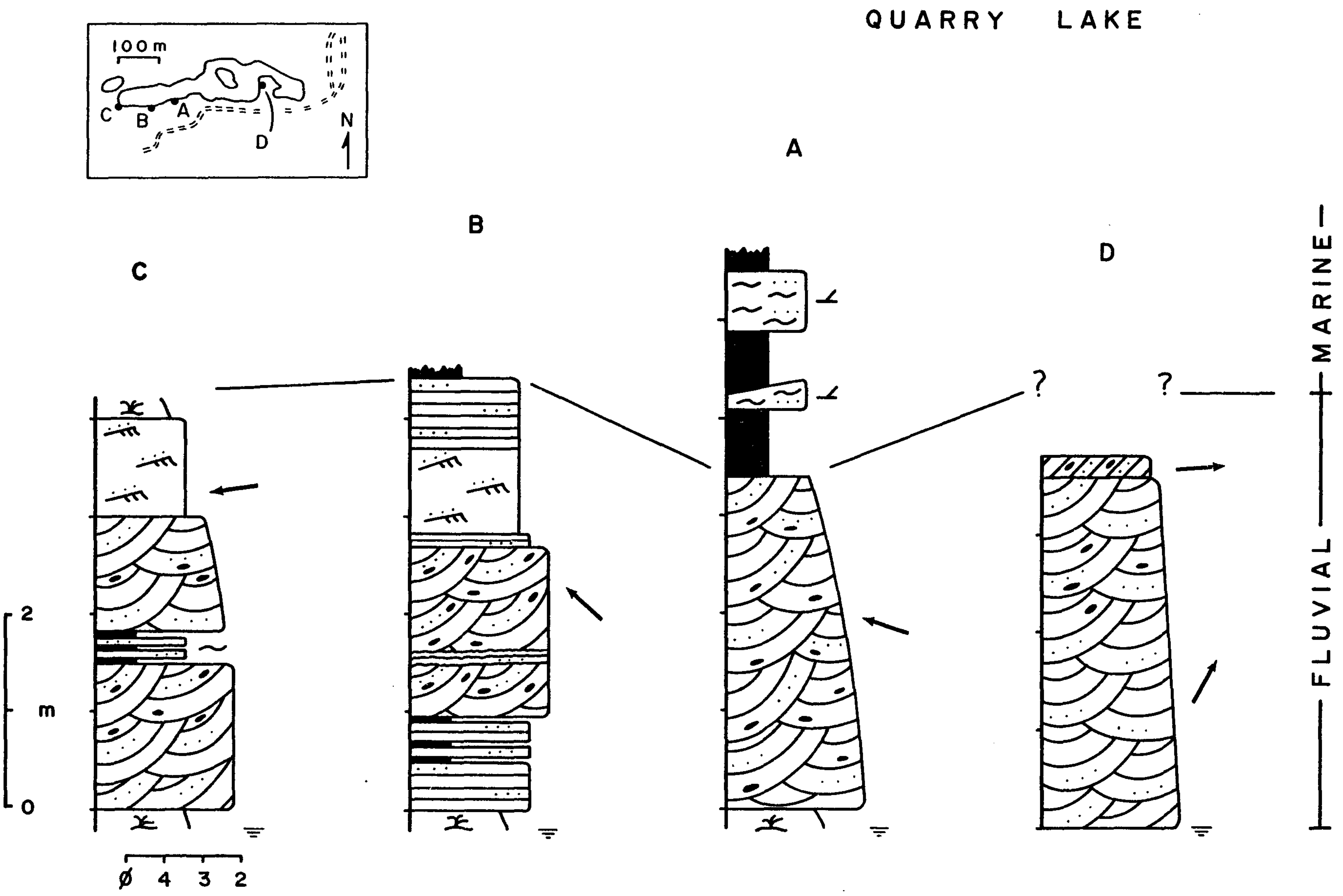
Quarry Lake

Quarry Lake is a 500 m X 70 m, abandoned, water-filled quarry situated at the base of a secondary escarpment, 2.5 km northwest of Pekin, New York. The Whirlpool is only partially exposed in this quarry. Because of this incompleteness of the section (the Queenston/Whirlpool contact lies under water, and only a portion of the upper unit of the Whirlpool is exposed) and the disturbance of the walls by the quarrying and subsequent weathering, it is difficult to obtain a detailed measured section of the Whirlpool here. The exposure offers abundant paleocurrent information, but because of the instability of the walls, the data may not be very reliable.

Four sections on the south wall of the quarry were measured to illustrate the features of the Whirlpool at this locality. They are shown in Fig. 4-32.

The Whirlpool has a maximum exposed thickness of 5.5 m. The sandstone is light grey in colour, noncalcareous (except in the upper part), and medium- to thickly-bedded. The grain size generally fines upward from 2 - 2.5 to

Figure 4-32. Diagram showing the four sections measured at Quarry Lake. The locations of these sections on the south wall of the quarry are shown on the inset. Facies interpretations are discussed in Chapters 7 and 8. Note the predominance of facies St in the lower Whirlpool, suggesting that this section is probably a record of in-channel deposition. The presence of shale interlayers may indicate that some channels were shallower than others, undergoing quiet water sedimentation during low stages. The upper Whirlpool represents deposition in a quiet nearshore environment.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3.5 - 4 phi.

The predominant facies is facies St; however, facies Src and Sh and S/F also constitute a significant portion of the exposure in some areas. Facies Sp, Sw, and shale interlayers also occur but are of minor importance. The upper and lower bounding surfaces of most of the units are erosional. The lateral facies relationships and the lateral extent of the units could not be documented because of the limited lateral accessibility to the quarry walls.

Trough cross-laminated sets range in thickness from 5 to 35 cm (generally becoming thinner upwards in the section) and form cosets ranging from 0.4 to 3.4 m. No single sets or large troughs are present at this section. The cross-laminations average 7 mm in thickness and often have 5 mm long shale rip-up clasts lying parallel to their boundaries. The average paleocurrent direction is towards the northwest at 337 degrees.

Units containing facies Src occur only at sections B and C. Sets are 3 cm thick, and they form cosets ranging in thickness from 0.08 to 1.3 m. The ripple cross-laminations average 2 mm in thickness. At section C, thin (2 cm thick) shale layers are interbedded with the lower ripple cross-laminated unit. Readings obtained from rib-and-furrow structures indicate a westward paleocurrent (262 degrees).

The only occurrence of facies Sh is at section B, where it constitutes 36% percent of the exposed section.

Laminations average 4 mm in thickness, and they form beds, or sets, ranging in thickness from 8 to 36 cm. The two units containing this facies are both about 0.8 m thick. In the upper half of the lower unit a few thin shale interlayers (0.5 cm thick) occur. No paleocurrent data could be obtained.

Section D contains the only occurrence of planar tabular cross-laminations. The unit is 0.2 m thick and consists of only one set of the cross-laminations. The laminations are planar, 0.5 cm thick, and dip (26 degrees) to the east (86 degrees). The lateral extent of this unit could not be determined, but it is at least 6 m in length.

Facies Sw occurs only as a minor element within a trough cross-laminated unit at section B. The wavy laminations are horizontal, nonparallel, and continuous (0.5 cm thick), and eventually grade into poorly defined ripple cross-laminations near the top of the interval.

The upper part of the Whirlpool, exposed only at section A, is at least 2.1 m thick and consists only of facies S/F. The two sandstone beds that are in this unit are 0.1 m and 0.5 m thick, wedge to tabular in shape, calcareous, and internally wavy-laminated. The top and bottom of the sandstone beds are flat and sharp with the shale, and there are no signs of symmetrical ripples on the bed tops. The dark grey shale is more abundant than the sandstone interlayers, producing a sandstone/shale ratio of

1:2. The Power Glen, which overlies the Whirlpool in this area, is not exposed at the quarry.

<u>Lockport</u>

At Lockport, New York, the Whirlpool is exposed in its entirety (about 5.5 m) at a road cut and a railway cut. The following section description is based only on the road cut exposure; however, the railway exposure will be discussed briefly later. Blasting to create the road cut has exposed the Whirlpool on two walls, a SE - NW-striking wall (70 m long) and a SW - NE wall (40 m long), producing an excellent three dimensional exposure (Fig. 4-33).

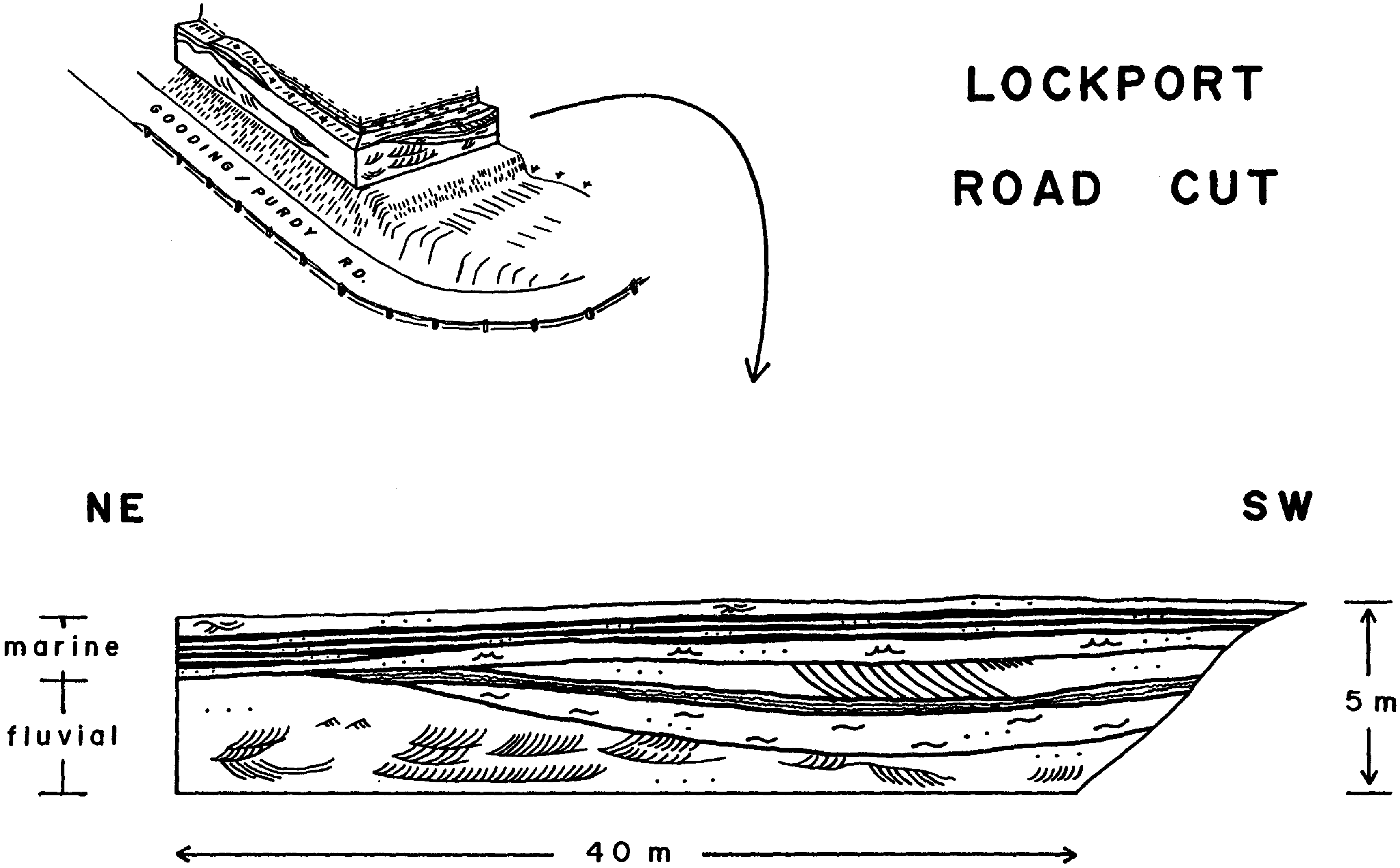
<u>Lockport Road Cut</u>: About 6 m of the Queenston are exposed here. It is, as usual, red in colour, but it has a grey-green coloured, 15 cm thick interval at the top. The Queenston/Whirlpool contact is sharp, very flat, and subhorizontal-lying, with a dip of 1 degree to the south (265 degrees).

The Whirlpool is medium- to very thickly-bedded, and shows an overall fining upward in grain size, from 2 - 1.5 to 4 - 3.5 phi. The sandstone is only calcareous at the base and in the upper part of the Whirlpool.

Two very large channels, one nested inside the other, are the most salient features of the Lockport section

Figure 4-33. Diagram showing the exposure of the Whirlpool at the Lockport road cut. Note the presence of two channels, one (on the NE - SW wall) nested inside the other (on the SE - NW wall). Figure 4-34 is based on the features exposed on the NE - SW wall.

LOCKPORT ROAD CUT



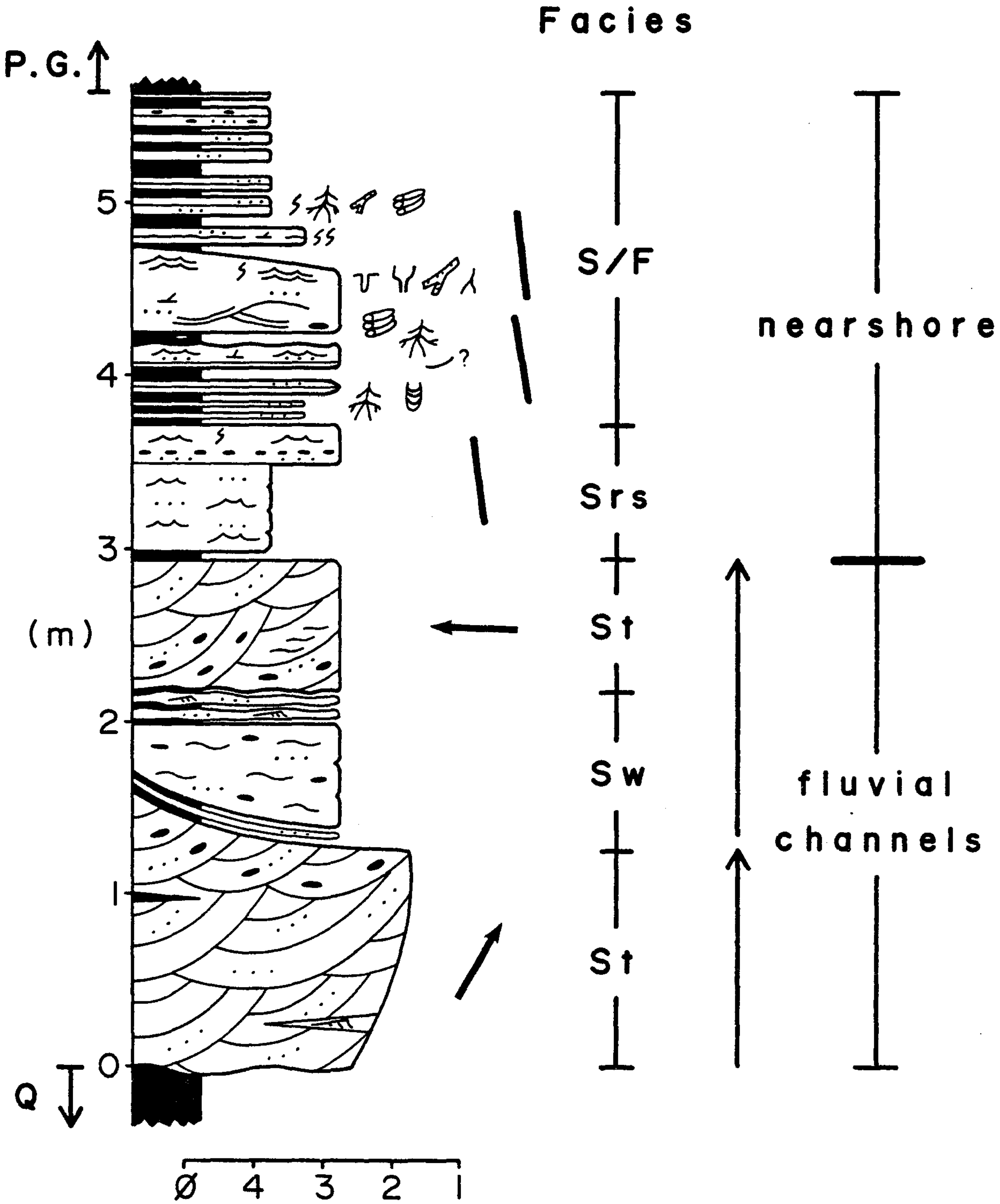
(Fig. 4-33). They are both only partially exposed, and are at least 21 m and 42 m wide. No lateral accretion surfaces are associated with these channels.

Facies St is the most abundant facies in the section. Its abundance is not, however, fully represented in the section diagram of Fig. 4-34, which represents a site located near the southwestern end of the SW - NE-striking wall, where one of the channels cuts down into the trough cross-laminations of unit #1. Both facies Srs (unit #4) and S/F (unit #5) are significant components of the section, extending laterally throughout the exposure, while facies Sw (unit #2), being more limited in extent, is of lesser importance.

Unit #1 is a thick, tabular, laterally extensive body containing trough cross-laminations. The unit generally is 3 m thick, but on the SW - NE wall, where it is scoured into by one of the channels, it reaches a minimum thickness of 1.3 m. Cross-laminations are 7 mm thick, and form sets ranging in thickness from 0.2 to 0.7 m. One symmetrical trough is present and is 5 m wide and 0.6 m high. Shale rip-up clasts (1 cm long) are ubiquitous in the upper half of the unit, and they are imbricated parallel to or at a slight angle (18 degrees) to the foresets. A few cosets of ripple cross-laminations (maximum thickness is 25 cm) occur at various levels within unit #1. The paleocurrent trend (from 34 readings) is to the northeast

Figure 4-34. Section diagram summarizing the features exposed on the NE - SW-striking wall of the Lockport road cut. Note the overall fining-upward in the lower Whirlpool and the sharp contact separating the upper and lower parts of the Whirlpool. Take note that the absence of trace fossils above 5 m is a reflection of the sampling procedure and not of the true distribution of the trace fauna. The interpretation of this section is discussed in Chapter 7.

LOCKPORT ROAD CUT



(30 degrees), but this value is not really indicative of the true paleocurrent because the readings could only be obtained from the SW - NE wall, which is a longitudinal section through the cross-strata. The SE - NW-striking wall, too, is a longitudinal section with cross-strata dipping towards the northwest. Therefore, the true paleocurrent trend is probably towards the northwest.

The SE - NW wall shows a channel surface within unit #1 (Fig. 4-33). This suggests, perhaps, that unit #1 may have been formed by the vertical accretion of several channel deposits.

Units #2 and #3, both lenticular in shape, occur only within the channel that is exposed on the SW - NE wall. Unit #2 is 0.79 m thick (maximum) and contains facies Sw. The wavy wisps of shale are discontinuous, nonparallel, less than 1 mm thick, and are spaced about 1 cm apart (vertically). Shale rip-up clasts are present; they are 1 cm long, 0.2 cm wide, and are horizontal-lying. The unit becomes interlayered with thin (less than 1 cm) shale layers in the upper 0.1 to 0.4 m of the unit. The sandstone/shale ratio varies from 10:1 to 4:1 in this interval. Some ripple cross-laminated sets are present, and indicate a paleoflow the the southwest.

Unit #3 is 0.45 to 0.8 m thick and contains one set of trough cross-laminations (facies St). Foresets average 8 mm in thickness. Elongate, 1 cm long, 3 mm wide shale rip-up clasts imbricated parallel to the foresets occur in the lower half of the unit. Also present, but rare, are backflow ripples occurring in the bottomsets of the cross-strata. The paleocurrent for unit #3 is towards the west (272 degrees).

Erosionally overlying unit #3 and parts of unit #2 (see Fig. 4-33) is unit #4, which contains facies Srs. This unit is 0.7 m thick and slightly undulatory in shape, and extends throughout the entire exposure. The symmetrical ripples are rounded, straight-crested, occasionally bifurcating, and have a ripple index of 8. The strike of the ripple crests average 353 to 173 degrees. The laminations, which are 1 mm thick, are complete rippleforms (Hunter, 1977), showing drifting both to the east and west directions. *Lingulichnus* is quite abundant on the top surface of unit #4.

The top unit, unit #5, consists of 1.9 m of facies S/F. The unit is tabular in shape, and extends throughout the entire exposure. The sandstone beds are sharp-based, tabular to undulatory in shape, and range in thickness from 0.5 to 48 cm (average is 10 cm but thins upward). Shale layers range from 1 to 9 cm in thickness, and on average thicken upward. The sandstone/shale ratio is about 2:1. Internally, the sandstone beds show horizontal laminations, HCS, and horizontal and symmetrical ripple cross-laminations. Ripple crest orientations average 353 to

173 degrees.

The best example in the study area of facies S/Fhcs occurs here at the Lockport section (Fig. 3-11a,b,c). The HCS bed is undulatory in shape (with a wavelength of 10 to 15 m), ranging in thickness from 13 to 48 cm. The base of the bed is sharp and erosional, and is lined with small shale clasts. Divisions H, F, X, and M are present. Division M is thoroughly bioturbated, while divisions X and F are sporadically to thoroughly bioturbated (with Lingulichnus and Skolithos) in some places. Division X, symmetrical ripples (orientation of crests is 173 to 353 degrees), shows aggradation with slight preferential drift to the northeast (70 degrees). The HCS bed also contains a very large cavity (50 cm long, 7 cm thick) which may be a weathered-out shale rip-up clast (Fig. 3-11c).

Bioturbation in the sandstone beds ranges from weak to thorough (see Fig. 3-15a) (increases upward, overall), and includes the following forms: Chondrites, Palaeophycus, Lingulichnus (or Lockeia?), Teichichnus, nondescript burrows, and possibly Diplocraterion and Skolithos. The shale layers are also moderately to completely bioturbated with horizontal, sand-filled exichnia (Chondrites?; see Fig. 3-15b). Fossils were not observed, but one sample taken near the base of the unit contains trilobite (?) or brachiopod (?) fragments similar to those found at Devil's Hole.

The lower contact of the Power Glen is gradational with the Whirlpool; the top of unit #5, or the top of the Whirlpool, is placed at the 5.5 m level where the shale content in the section begins to exceed 50%.

The Lockport Railroad Cut: The Whirlpool is exposed for 500 m on both sides of a railroad cut about 0.5 km northeast of the road cut. Unfortunately, the existence of this (new) outcrop was not realized until after the field season, by which time it was too late to attempt a proper measurement of this exposure; therefore, its main features will be described only briefly here.

The railroad cut exposes the Queenston, the Power Glen, and the entire Whirlpool (both upper and lower parts). What makes this section so interesting is the presence of numerous, large (up to 20 m wide) troughs, or channels. Some of these channels are present within the lower part of the Whirlpool while others, clearly belonging to the upper part, scour (up to 1.5 m) into the top of the lower part of the Whirlpool (Fig. 4-35a,b). Some channels display minor lateral accretion surfaces.

The lower unit is predominantly trough cross-laminated (paleocurrent trend is towards the northwest at about 287 degrees) and contains rare, thin shale interlayers. Contrasting greatly with this is the interbedded sandstones and shales of the upper unit, which

Figure 4-35. Features of the Lockport railroad cut.

a) Large channel-like feature displaying minor lateral accretion towards the left (north). The channel lies entirely within a trough cross-laminated unit in the lower Whirlpool. The Queenston/Whirlpool contact lies just above the tracks. Note the sharp contact between the upper and lower parts of the Whirlpool, about (1 m above the scale). The Power Glen and Grimsby Formations can be seen overlying the Whirlpool. Scale is 1 m in length. Photo is from the east wall of the cut.

b) Photo showing pronounced scouring into the lower Whirlpool. Top of scale (1 m in length) rests at the contact between the upper and lower parts of the Whirlpool. Notice that as much as 1 m of the trough cross-laminated unit (lower Whirlpool) has been scoured down into on the left side of the scale. The thick sandstone bed in the upper Whirlpool may be the same HCS bed that is exposed at the road cut (see Figs. 3-11 and 4-34). The upper Whirlpool grades into the Power Glen above. Photo is from the west wall of the cut.

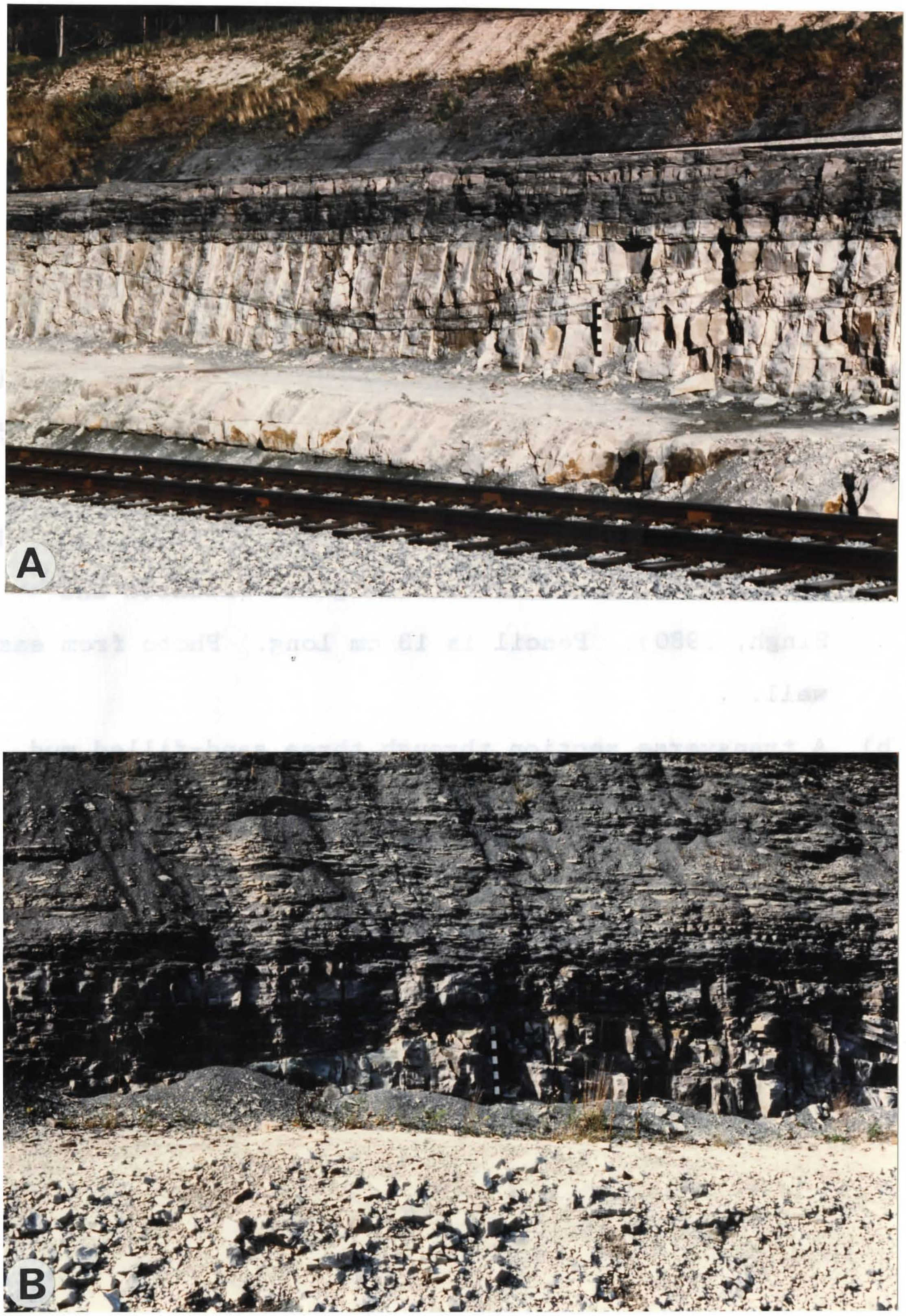

A
B

Figure 4-36. Shallow water indicators at the Lockport railroad cut.

a) A structure resembling wrinkle marks on a bedding plane surface in the upper Whirlpool. Wrinkle marks can form in partly cohesive sediments under a very thin film of water, as thin as 1 cm. As such, they can be a good indicator of intermittent emergence (Reineck and Singh, 1980). Pencil is 13 cm long. Photo from east wall.

b) A transverse section through three sand-filled mud cracks in the upper Whirlpool. Note the V-shaped profiles. These features, like the wrinkle marks, are very good indicators of intermittent subaerial exposure. Pencil is 13 cm long. Photo from east wall.

is similar in appearance to unit #5 at the road cut. Straight-crested and interference ripples (both symmetrical) and synaeresis cracks characterize the top surface of the sandstone beds. The ripple crests strike 301 to 121 degrees. A structure resembling wrinkle marks is also present (Fig 4-36a), and may be an indicator of very shallow water conditions. All trace fauna found at the road cut occur here with the addition of Arenicolites and possibly Cruziana. Crinoids, minor gastropods, and possible Lingula shell fragments are present in the upper beds. The shale interlayers are thoroughly bioturbated, and towards the bottom of the upper unit, where bioturbation is considerably less, numerous, 5 cm deep, sand-filled desiccation cracks (?) occur within one silty-shale layer (Fig. 4-36b).

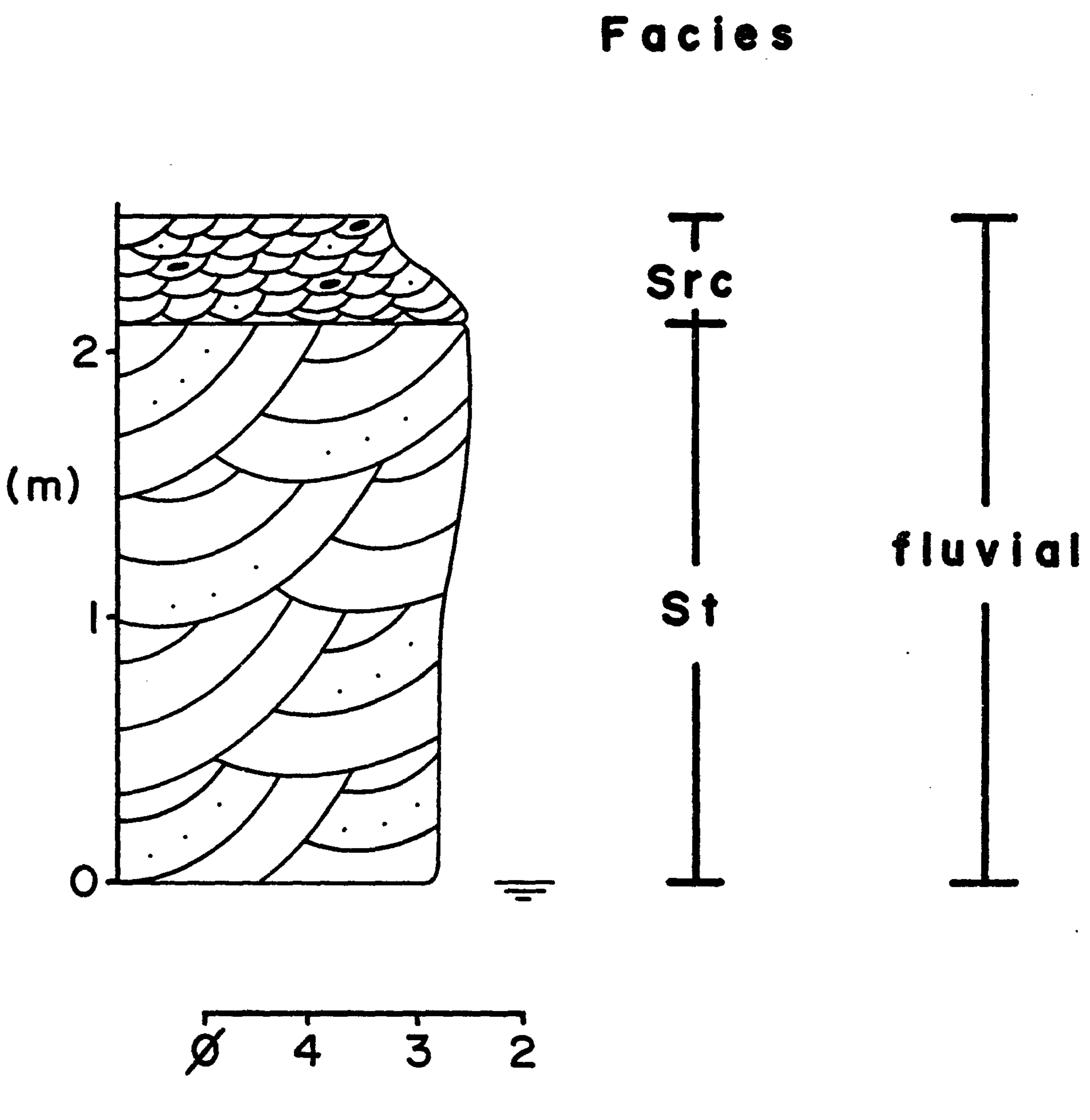
In the northern part of the exposure, a shale layer marking the bottom of the upper unit is truncated by what may possibly be a very large (300 (?) m + wide) channel. Readings from trough cross-laminations and channels within this larger 'channel' indicate a paleocurrent to the west (277 degrees).

Gasport

The Whirlpool is exposed at a small waterfall on the east branch of Eighteen Mile Creek, 1.6 km northeast of Gasport. Like most waterfalls it is a poor exposure, and

Figure 4-37. The Gasport section. The diagram and the interpretation are based on very limited vertical and lateral exposure, mostly from the right (west) side of the falls.

GASPORT



only 2.4 m (of the lower part) of the Whirlpool are exposed. The Queenston and Power Glen Formations are not present. The grain size is variable vertically (no trends) and ranges from 2 - 1.5 to 3.5 - 3 phi. The sandstone is noncalcareous.

Unit #1 (Fig. 4-37) is 2.1 m thick and consists of facies St. The foresets are approximately 2 cm thick and form sets ranging in thickness from 0.3 to 0.4 m. The outcrop is a transverse section showing symmetrical troughs, and from the crosscutting relationships, it appears that the troughs are migrating towards the west. The lateral extent, shape, paleocurrent, and relationship of this unit with other units could not be determined.

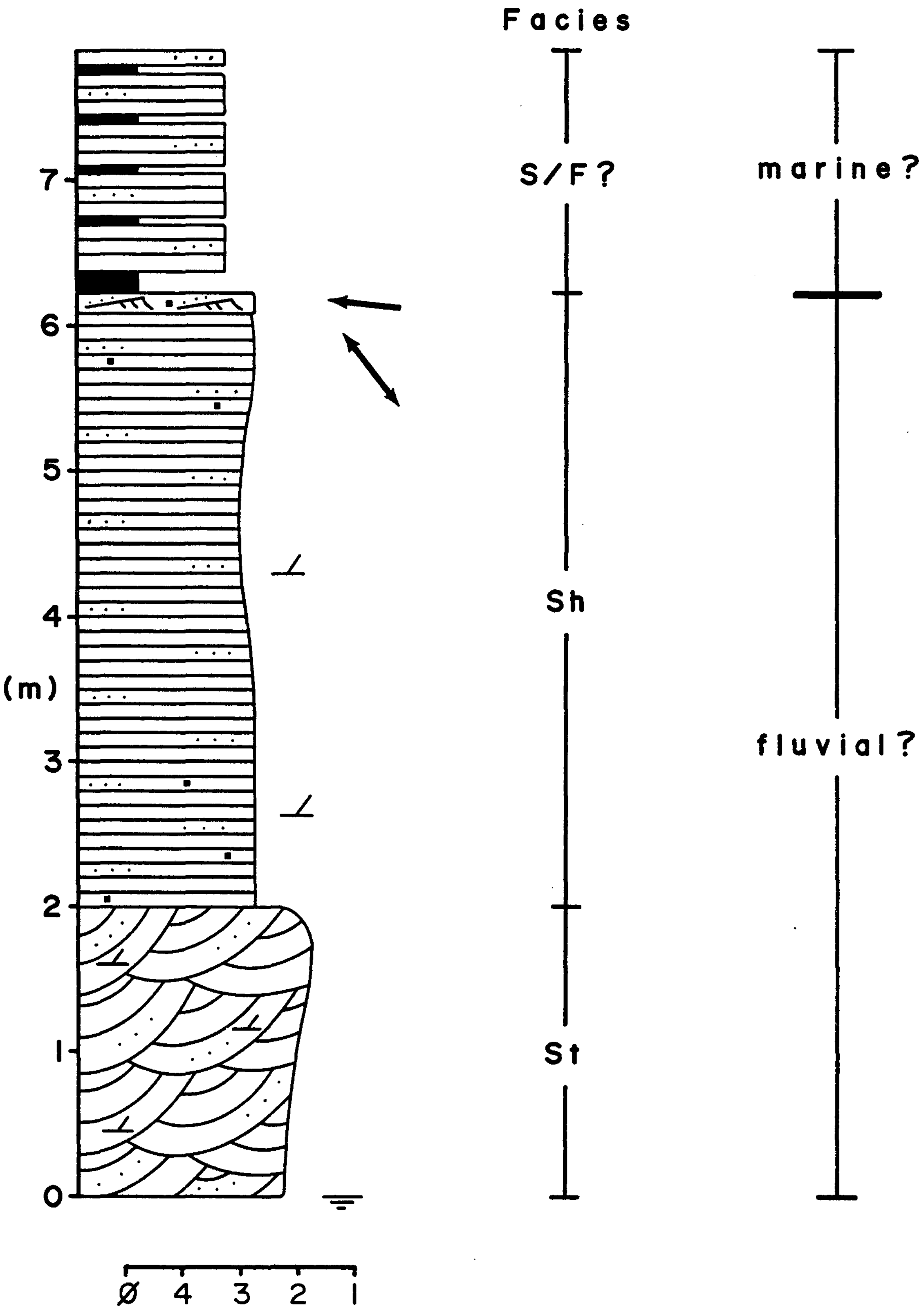
The top 0.3 m of this exposure, forming unit #2, is ripple cross-laminated (facies Src). The laminations average 2 mm in thickness. Elongate, greenish-grey, silty shale rip-up clasts are present, and average 0.5 to 1 cm in length. Other details concerning this unit could not be determined.

Medina

The Whirlpool is exposed at an 8 m high waterfall in Medina, New York. Most of the Whirlpool is present here (approximately 8 m), but because the Queenston and Power Glen are not exposed, its total thickness cannot be

Figure 4-38. The Medina section.

MEDINA



determined. Because much of the exposure is inaccessible, details concerning the facies present are primarily based on visual and hand sample examination; needless to say, the section diagram (Fig. 4-38) only crudely represents the features of this exposure.

The Whirlpool is medium-bedded and has a variable grain size that shows an overall fining upward from 2 - 1.5 to 3 - 2.5 phi. The sandstone in the lower 2 m of the section is quite calcareous (petrographic analysis shows that the sandstone contains 6% rounded carbonate lithoclasts; see Chapter 6).

Unit #1 is 2 m thick and consists of facies St. Sets appear to be quite thick, reaching a maximum of 0.5 m in thickness. No paleocurrent readings could be obtained.

Unit #2 consists of approximately 4.2 m of horizontal laminations (facies Sh). The laminations range in thickness from 1 to 5 mm. Readings from parting lineations indicate a paleocurrent trend of 322 to 142 degrees. At the 6.1 m level there is a minor occurrence of ripple cross-laminations (10 cm thick). The laminations average 1 to 2 mm in thickness. Readings from rib-and-furrow structures indicate a paleoflow to the west (277 degrees). The top 1.5 m of the section is also horizontally-laminated but appears to contain shale interlayers; therefore, unit #3 probably consists of facies S/F.

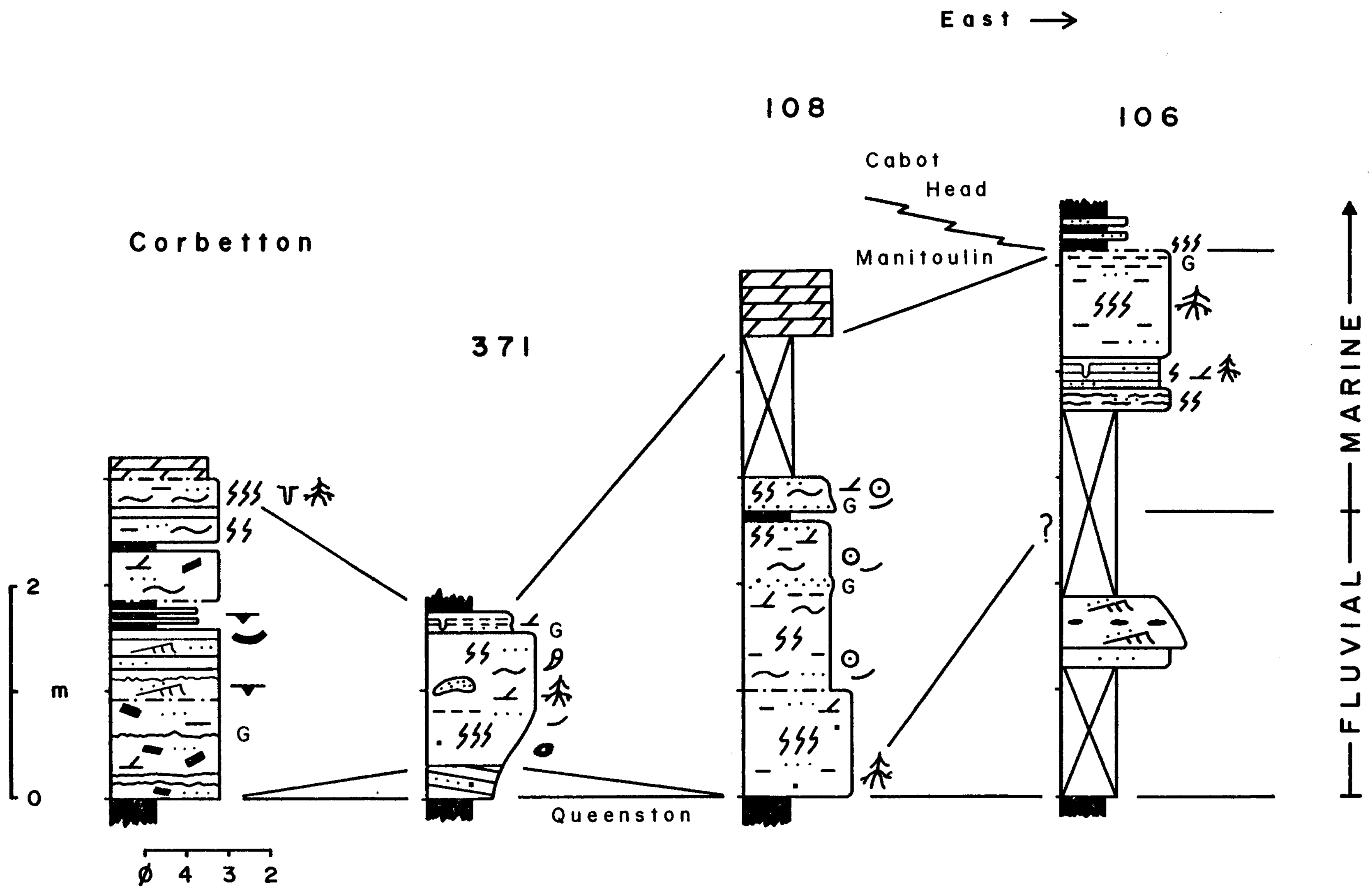
Cores

To complement the surface study of the Whirlpool's facies and to provide data in the pinch-out areas, ten cores from the Lake Erie region and one from near Primrose were examined in considerable detail. The section diagrams are shown in Figures 4-39 to 4-41. Rather than discussing each core separately, this section will instead focus mainly on interesting and unusual features and regional trends. Details concerning the facies comprising each section can be obtained from the section diagrams.

In the cored area, the Whirlpool is everywhere underlain by the red Queenston Shale and overlain by the Cabot Head Shale except in the areas of cores 371, 108, and Corbetton (O.G.S. core), where the Cabot Head is replaced by the Manitoulin Dolomite. The Whirlpool's thickness is quite variable in the Lake Erie region, and ranges in thickness from 1.6 to 7 m (see Chapter 2, Fig. 2-4). The grain size, too, shows regional as well as vertical variability, ranging from 2 - 1.5 to 4 - 4.5 phi and generally averaging about 3.5 - 3 phi. Depending on the sandstone's shale, or mud, content, the Whirlpool is very light grey to olive-grey in colour. But brownish-to greyish-red sandstone also occurs (cores 240 and 146), and is most abundant in core 240, where it constitutes approximately 2.1 m of the section.

The nature of the Whirlpool in the Lake Erie area is

Figure 4-39. Diagram showing four of the cores (Corbetton, which is an O.G.S. core, 371, 108, and 106) measured, three of which are in the Lake Erie region. See Figure 1-1 for their location. As in most of the cores west of core 552, the lower Whirlpool is quite thin and may even be absent in some of these sections. Regionally, the upper Whirlpool is quite variable in thickness and may constitute as much as 100% of the Whirlpool at some sections. Unlike in the Whirlpool outcrops, the upper Whirlpool in the cores shown on this diagram consists predominantly of facies Sb.



East →
Corbetton
371
108
106
Cabot
Head
Manitoulin
Queenston
FLUVIAL
MARINE
m
2
0
ø 4 3 2

Figure 4-40. Diagram of cores 146, 678, and 676. See Figure 1-1 for the locations of these cores. Compare with Figure 4-39 and note that the lower Whirlpool is still quite thin to non-existent in the area of Lake Erie. Notice that east of core 146, the upper Whirlpool begins to look like the outcrops, consisting primarily of facies S/F.

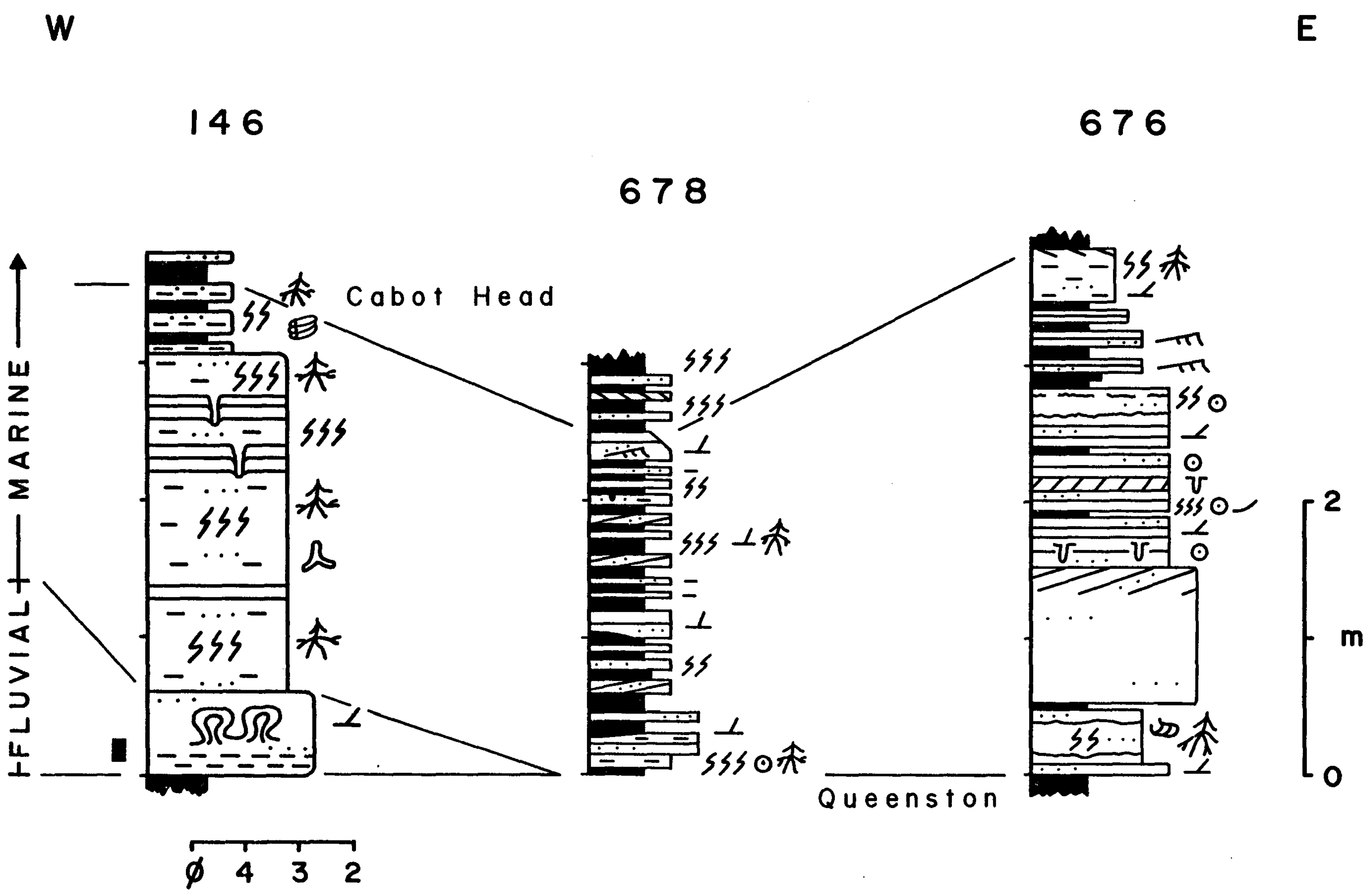
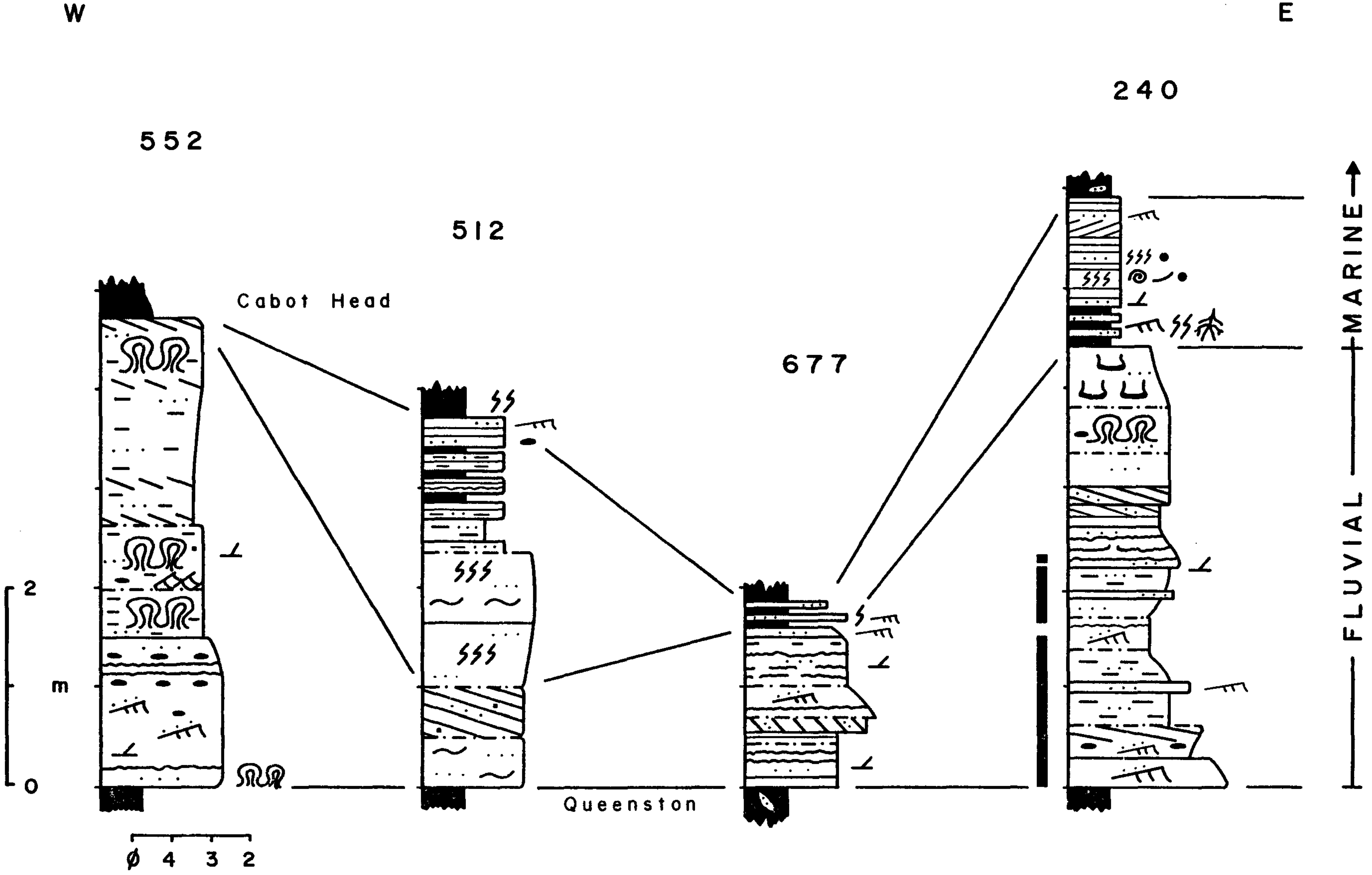

W
E
146
678
676
Cabot Head
Queenston
FLUVIAL
MARINE
ø 4 3 2
2
m
0

Figure 4-41. Diagram of cores 552, 512, 677, and 240. Even though these cores are closely-spaced (see Figure 1-1), there is considerable lateral variation in facies and in the thickness of the Whirlpool and its two units. An interpretation of the Whirlpool in the Lake Erie region is included in Chapter 7.


W
E
552
512
677
240
Cabot Head
Queenston
MARINE
FLUVIAL
2
m
0
ø 4 3 2

quite different from that in the outcrop areas of the Niagara Escarpment. Bioturbated sandstone, generally restricted to the upper one-third of the Whirlpool in the outcrop sections, is unusually abundant in the cored areas, and may constitute as much as 100% of the Whirlpool section. Facies Sb and S/F are both major constituents of the upper unit of the Whirlpool, and, unlike in the outcrop sections, where the upper unit comprises generally less than one-third of the entire section, the percentage of the upper unit in certain areas of Lake Erie, namely those cores west of and including 676, is very high, reaching a minimum of 61% of the entire section.

With respect to vertical or regional trends in the Lake Erie region, there is definitely more bioturbation (and also a greater percentage of the upper unit) present in the cores west of and including core 676, but the transition from the less or nonbioturbated areas to those with much bioturbation does not appear to be a gradual one; instead, it is quite a rapid, or sharp, transition. As well, each core varies with respect to vertical trends in the degree of bioturbation: cores 240 and 512 show an upward increase in the intensity, while cores 108 and 371 show an upward decrease; others, like cores 676, 678, 146, and 106, show no trends at all.

Most of the facies recognized in the outcrop areas are present in the cores. Certain facies, however, like facies Shcs and St, are much more difficult to recognize. The only occurrence of HCS (possibly facies Shcs.Ah-b) is in core 240; however, possible storm layers containing abundant crinoid and brachiopod fragments (much like the horizontal laminated, crinoid beds present at Artpark and Balls Falls, section E) occur in core 676. Cores 240 and 677 are really the only cores showing evidence of continuous current activity (i.e. they contain abundant horizontal, low-angle and ripple cross-laminations), and therefore bear the closest resemblance to the surface sections.

As previously mentioned, the Whirlpool's grain size shows both vertical and regional variability. There is no well developed westward fining trend in the grain size (taken to be the modal size at the Whirlpool's base) as was expected; however, the easternmost core is much coarser (2 - 1.5 phi) than the westernmost (4 - 4.5 phi). Vertically, most cores show an overall fining upward.

Fossil fragments occur in cores 240, 676, 678, 108 and 371, and are the same forms--crinoids, brachiopods, corals, and gastropods--as those present in the outcrop sections. Identification of trace faunal forms is made difficult by the moderate to thorough bioturbation that exists in most of the cores, but those that are recognizable include: Chondrites, Teichichnus, and possibly Rhizocorallium, Asterosoma, Scoyena, Scalarituba missouriensis, and Skolithos.

Shale rip-up clasts, which are so abundant in outcrop sections, are rare in the cores, and this may be because facies St, which, more than any other facies, commonly contains the rip-ups, does not appear to be present in the Lake Erie area. The clasts present in cores 512, 552, and 106, are greyish-green in colour, horizontal-lying, and are confined to thin intervals (less than 4 cm). Lengths range from 0.1 to 2 cm, and widths, from 1 to 2 mm. Unusual rip-ups occur in the Corbetton (O.G.S.) core. Some are rectangular in shape (10mm long, 2 mm wide) while others are very elongate and irregular in shape and conform to the lower depositional surface. A ripping up of semi-indurated shale layers and little subsequent transport of the material is suggested by these non-rounded shale fragments.

Glauconite occurs in small amounts in the Corbetton core and cores 106, 108, and 371, and appears to be associated with coarse sandstone intervals.

Synaeresis cracks, which are quite common in the upper part of the Whirlpool in the outcrops, do no appear to be present in the cores. The Corbetton core may contain the only occurrence.

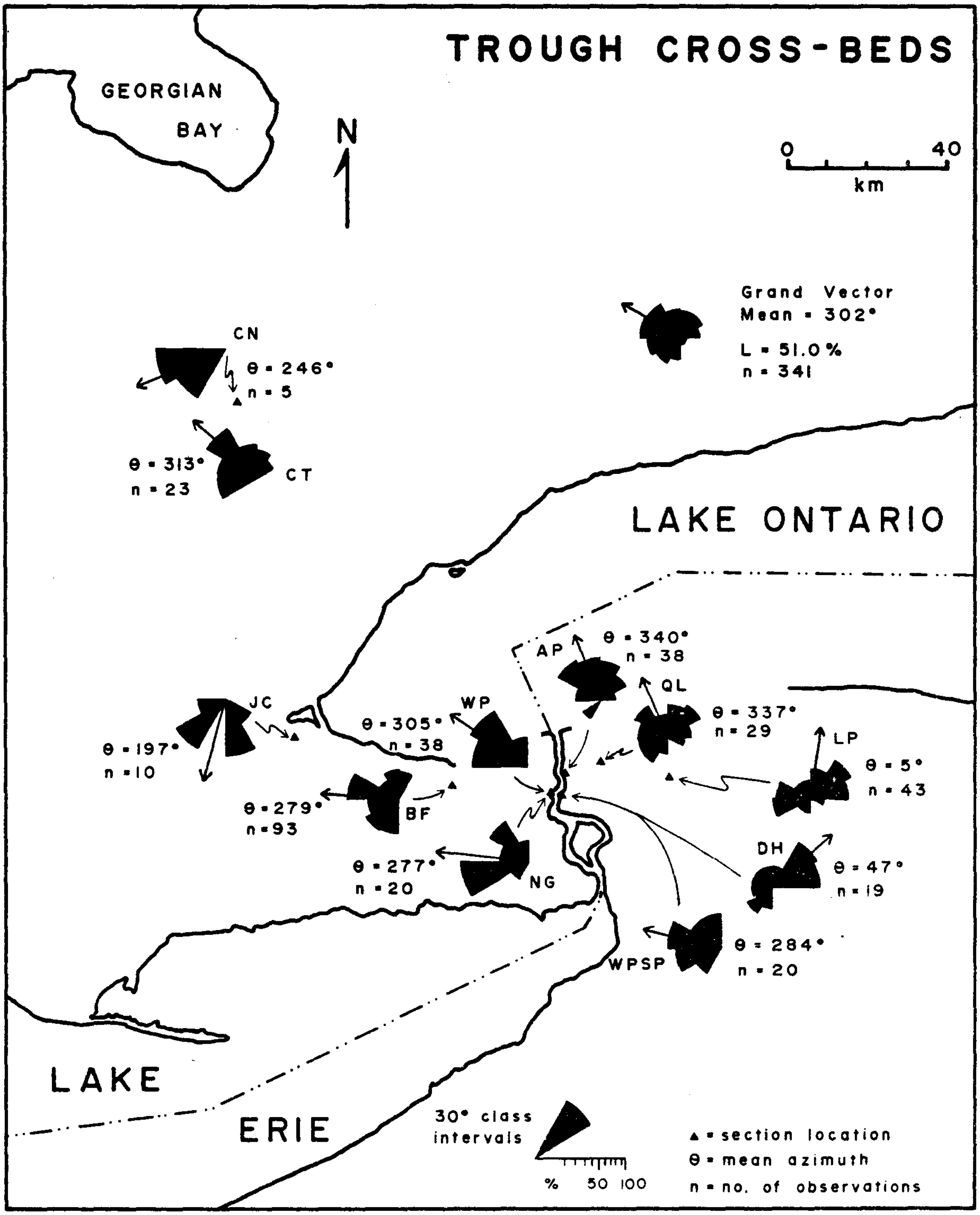
What is most interesting about the Whirlpool in the Lake Erie area is the great variability that occurs in the thickness and facies content over very short distances (for example, compare cores 240 and 677, 512 and 552, and 676 and 678).

REGIONAL PALEOCURRENT PATTERNS

Regional paleocurrent patterns for trough cross-laminations, all directional features, and symmetrical ripples are shown in Figures 4-42, 4-43, and 4-44, respectively. Details concerning the types of directional features used, the paleocurrent analysis, and the problems encountered in obtaining readings from facies St have been discussed already in Chapter 1 and therefore will not be repeated here. Statistical values for each of the rose diagrams on the maps are limited to the vector mean (theta) and the number of readings (n); however, additional statistics--vector magnitude (R), consistency (L), and Chi-square and Rayleigh tests--for each of the rose diagrams can be found in Appendix 3. Take note, as well, that the rose diagrams are scaled areally rather than linearly, and that the rose diagrams for some of the sections (e.g. Medina and sections up north) are based on very limited paleocurrent data.

Figure 4-42 shows the regional paleocurrent pattern for the trough cross-laminations and large troughs. Unfortunately, the rose diagrams on this map are somewhat misleading, for the high degree of variability they indicate is really a reflection of the way in which the readings were obtained rather than of the true paleocurrent trend (see

Figure 4-42. Regional paleocurrent pattern for the trough cross-laminations and large troughs, or channels. See text for discussion. Note that the rose diagrams are scaled areally. Curved arrows show the location of the rose diagrams; those without these arrows are positioned properly over the appropriate section.


TROUGH CROSS-BEDS
GEORGIAN BAY
N
0 40
km
Grand Vector Mean = 302°
L = 51.0%
n = 341
CN
θ = 246°
n = 5
θ = 313°
n = 23
CT
LAKE ONTARIO
AP
θ = 340°
n = 38
QL
θ = 337°
n = 29
JC
θ = 197°
n = 10
θ = 305°
n = 38
WP
LP
θ = 5°
n = 43
θ = 279°
n = 93
BF
DH
θ = 47°
n = 19
θ = 277°
n = 20
NG
θ = 284°
n = 20
WPSP
LAKE
ERIE
30° class intervals
% 50 100
▲ = section location
θ = mean azimuth
n = no. of observations

Chapter 1). Had all the readings been obtained from trough axes on bedding plane surfaces, it is likely that the variability would have been considerably reduced. Nevertheless, the calculated vector mean values shown should be accurate representations of the true paleocurrent trend at each of the localities. Minor deviations occur, but the main paleocurrent trend appears to be towards the northwest, with a grand vector mean value of 302 degrees.

Figure 4-43 is a regional paleocurrent map based on readings from trough cross-laminations, small-scale rib-and-furrow structures, parting lineations, current crescents, and isolated large troughs. Readings from low-angle and planar tabular cross-laminations are not included. Although the paleocurrent distribution for each of the directional features is not depicted on the rose diagrams, a breakdown of the readings used for each rose diagram is included with the statistics in Appendix 3 (also see Appendix 2). The majority of the readings, however, are from trough cross-laminations (compare n values with those in Fig.4-42), which would also, as in Fig. 4-42, account for the rose diagrams' high degree of variability. Some deviations occur, but the overall paleocurrent trend appears to be to the northwest, at 301 degrees, which is consistent with Salas' (1983) results for the Georgetown area.

Figure 4-44 shows the regional pattern for the orientation of symmetrical ripple crests in the upper part

Figure 4-43. Regional paleocurrent map based on readings from trough cross-laminations, small-scale rib-and-furrow structures, parting lineations, current crescents, and large troughs. Note that the rose diagrams are scaled areally. The number of readings obtained from each of the structures at each section is given in Appendix 3.

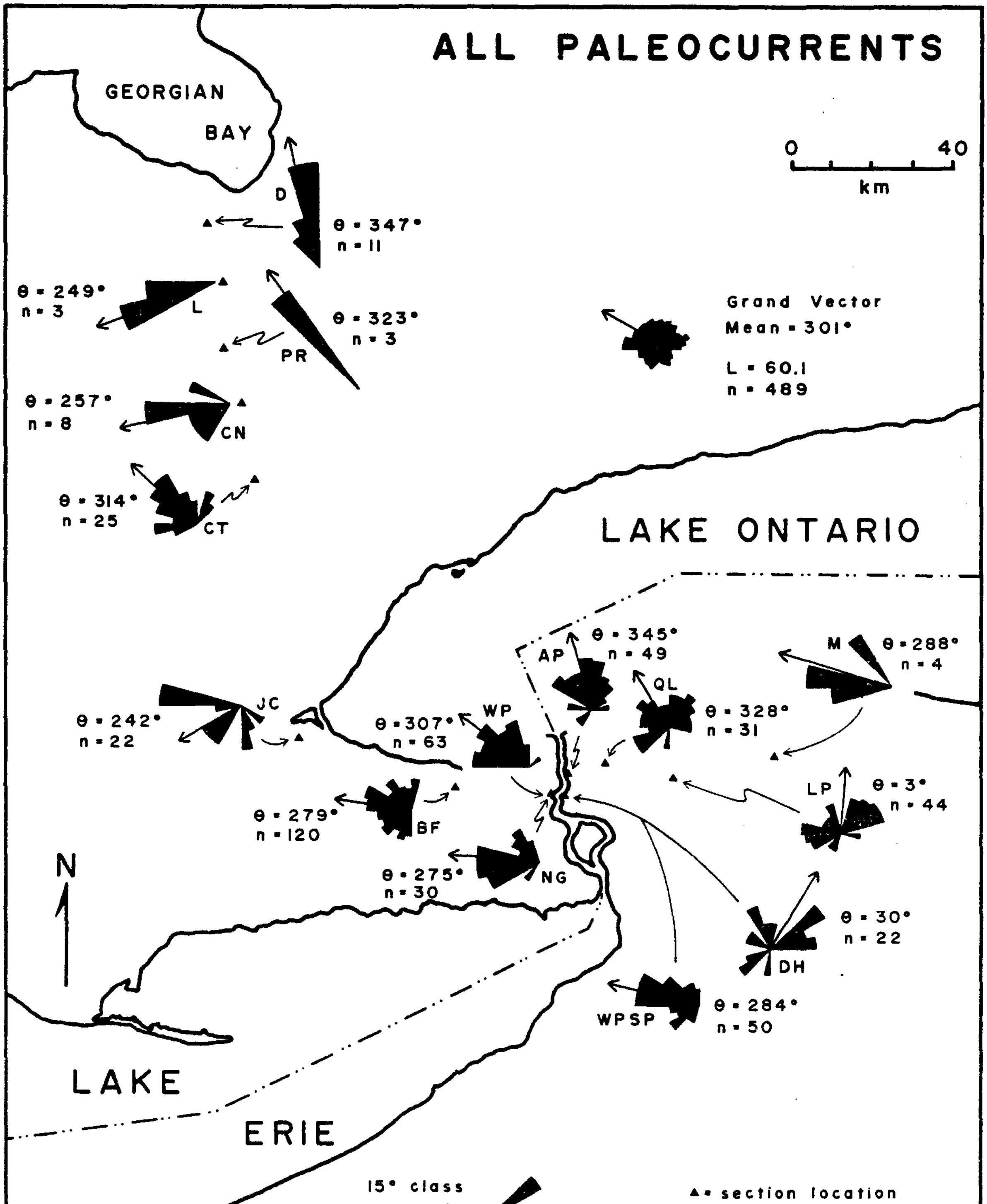
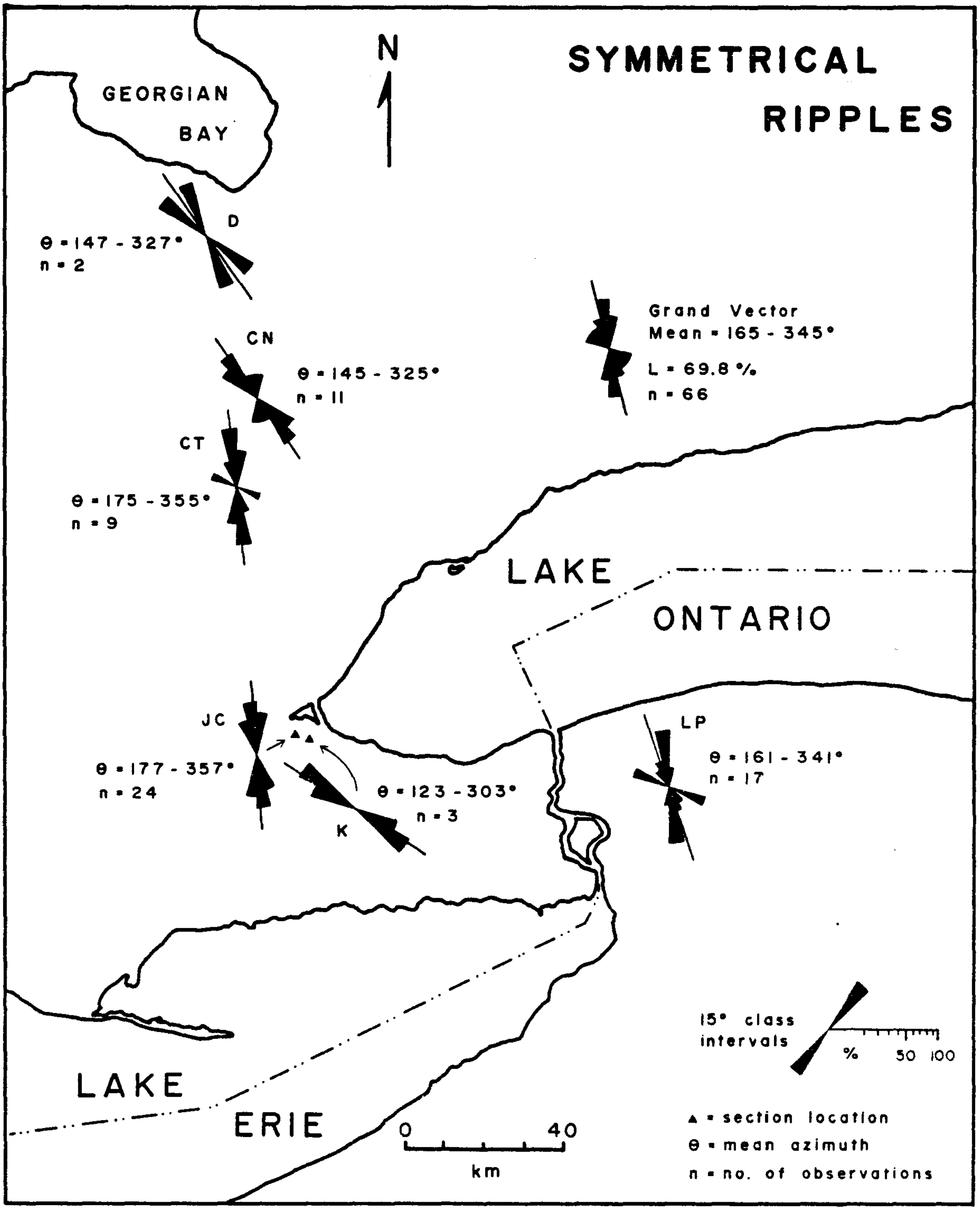

ALL PALEOCURRENTS
GEORGIAN BAY
0 40
km
D
θ = 347°
n = 11
θ = 249°
n = 3
L
θ = 323°
n = 3
PR
Grand Vector
Mean = 301°
L = 60.1
n = 489
θ = 257°
n = 8
CN
θ = 314°
n = 25
CT
LAKE ONTARIO
AP
θ = 345°
n = 49
M
θ = 288°
n = 4
QL
θ = 328°
n = 31
JC
θ = 242°
n = 22
θ = 307°
n = 63
WP
LP
θ = 3°
n = 44
θ = 279°
n = 120
BF
N
θ = 275°
n = 30
NG
θ = 30°
n = 22
DH
WPSP
θ = 284°
n = 50
LAKE
ERIE
15° class
intervals
% 50 100
▲= section location
θ = mean azimuth
n = no. of observations

Figure 4-44. Map showing the regional pattern for the orientation of symmetrical ripples. Note that the rose diagrams are scaled areally. The center of each rose diagram is positioned over the appropriate section unless otherwise indicated.


SYMMETRICAL RIPPLES
N
GEORGIAN BAY
D
θ = 147 - 327°
n = 2
CN
θ = 145 - 325°
n = 11
CT
θ = 175 - 355°
n = 9
Grand Vector Mean = 165 - 345°
L = 69.8 %
n = 66
LAKE ONTARIO
JC
θ = 177 - 357°
n = 24
θ = 123 - 303°
n = 3
K
LP
θ = 161 - 341°
n = 17
15° class intervals
%
50 100
LAKE ERIE
0
40
km
▲ = section location
θ = mean azimuth
n = no. of observations

of the Whirlpool. The ripple crests display a consistent northwest-southeast orientation, with a grand vector mean of 165 to 345 degrees, which is in accordance with the 145 to 325 degree orientation obtained by Salas (1983).

CHAPTER 5

PALEONTOLOGY AND ICHNOLOGY

INTRODUCTION

This chapter presents a brief description of the trace fossils, macrofossils, and microfossils that were observed in the Whirlpool, and discusses the possible depositional environments implied by their presence. It is by no means a thorough study of the paleontology and ichnology of the Whirlpool. Other fossils and trace fossils than those listed here are surely present and were likely overlooked due to time considerations. With respect to the trace fossils and macrofossils (more specifically the trace fossils), the absence of certain traces or fossils in the cores or in the outcrops may be real, reflecting regional differences in their distribution, or it may simply reflect the greater difficulty involved in recognizing certain traces and fossils in the cores than in the outcrops, or vice versa.

TRACE FOSSILS

Trace fossils are totally absent from the lower part of the Whirlpool, but are abundant and diverse in the upper part. Seyler (1981) attributed the spherical cavities situated at the base of the Whirlpool to the burrowing of worms, but evidence suggests that these holes are really weathering, or dissolution, cavities (Calow, 1983; Salas, 1983). Salas (1983) noted the presence in the upper part of the formation of Monocraterion, Teichichnus, Diplocraterion yoyo, and Phycodes. The last three (and possibly the first) were observed to be present in this study, and these along with the others recognized are shown in Table 5-1, which also indicates at which localities (of those sections that had the upper unit exposed) and where in the vertical section (of the upper unit) these traces occur. The outcrop sections are listed first, from Osler Bluff southeastward to Lockport, New York, and then the cores, from core 371 eastward to core 240. Figures 5-1, 5-2, and 5-3 show some of the traces present in the Whirlpool. (See also Figs. 3-7b, 3-10b, 3-11c, 3-13b, and 3-15b.)

The trace fossils present and the degree of bioturbation are indicated on all the section diagrams in Chapter 4. The symbols used for the degree of bioturbation are explained in the legend for the diagrams (Fig. 4-1), and are based on the classification scheme suggested by Reineck (1963; cited in Reineck and Singh, 1980), which is shown below:

Table 5-1. List of all the traces recognized in the upper Whirlpool. Table shows the regional distribution of the trace fauna and the approximate location of the traces within the upper unit at each location. See text for discussion of trends. See Figure 1-1 for the explanation of the abbreviations used for the sections.

SECTION

TRACE	O.B. B	O.B. M	O.B. T	D B	D M	D T	OGS CORE B	OGS CORE M	OGS CORE T	CN B	CN M	CN T	CT B	CT M	CT T	J.C. B	J.C. M	J.C. T	K B	K M	K T	B.F. B	B.F. M	B.F. T	LP B	LP M	LP T	LP.R.C. -- ? --
Arenicolites											X										X			X				X
Asterosoma																												
Chondrites									X*					X			X*							X*	X*		X*	X
Conichnus														?													?	
Conostichnus														X														
Cruziana																												?
Diplocraterion													X												X			X
Lingulichnus																						X*		X		X		X
Lockeia																						?		?		?		?
Palaeophycus						X*					X*			X*			X*			X*	X*	?				?	?	X
Phycodes																						?						
Rhabdoglyphus caliciformis											X																	
Rhizocorallium																												
Rusophycus																	?											
Scalarituba missouriensis																												
Scoyena																												
Skolithos									X					X			X				X					X		?
Teichichnus									X		X			X						X						X	X	
Tylichnus														X														
Unknown					X						X			X										X				
Nondescript		?				X			X*			X		X			X			X	X	X				X		X

TRACE	CORE 371 B	CORE 371 M	CORE 371 T	CORE 188 B	CORE 188 M	CORE 188 T	CORE 186 B	CORE 186 M	CORE 186 T	CORE 146 B	CORE 146 M	CORE 146 T	CORE 678 B	CORE 678 M	CORE 678 T	CORE 676 B	CORE 676 M	CORE 676 T	CORE 512 B	CORE 512 M	CORE 512 T	CORE 677 B	CORE 677 M	CORE 677 T	CORE 240 B	CORE 240 M	CORE 240 T
Arenicolites																											
Asterosoma	X																										
Chondrites	X*	X	X	X			X*	X		X	X	X	X	X	X	X		X							X		
Conichnus																											
Conostichnus																											
Cruziana																											
Diplocraterion																											
Lingulichnus																											
Lockeia																											
Palaeophycus																											
Phycodes																											
Rhabdoglyphus caliciformis																											
Rhizocorallium																X											
Rusophycus																											
Scalarituba missouriensis																									?	?	
Scoyena										?	?	?															
Skolithos			X				?										?	?									
Teichichnus												X				?									?		
Tylichnus																											
Unknown			X				X			X	X	X	X	X	X		X								X		
Nondescript	X*	X	X	X*	X	X	X*	X		X	X	X	X*	X	X	X	X	X	X	X	X	X	X		X	X	

X, present; ?, classification questionable; *, most abundant trace at locality; B,M,T - bottom, middle, and top portions of the upper Whirlpool

Figure 5-1. Trace fossils of the Whirlpool.

a) *Palaeophycus* burrows on the base of a sandstone interbed. Burrows are 0.5 cm wide. Photo is from Cataract (far left of Fig. 4-13) 5.1 m above the base of the Whirlpool.

b) *Conostichnus* (or possibly *Monocraterion*) protruding from the base of a sandstone interbed. Sample is from same location as above.

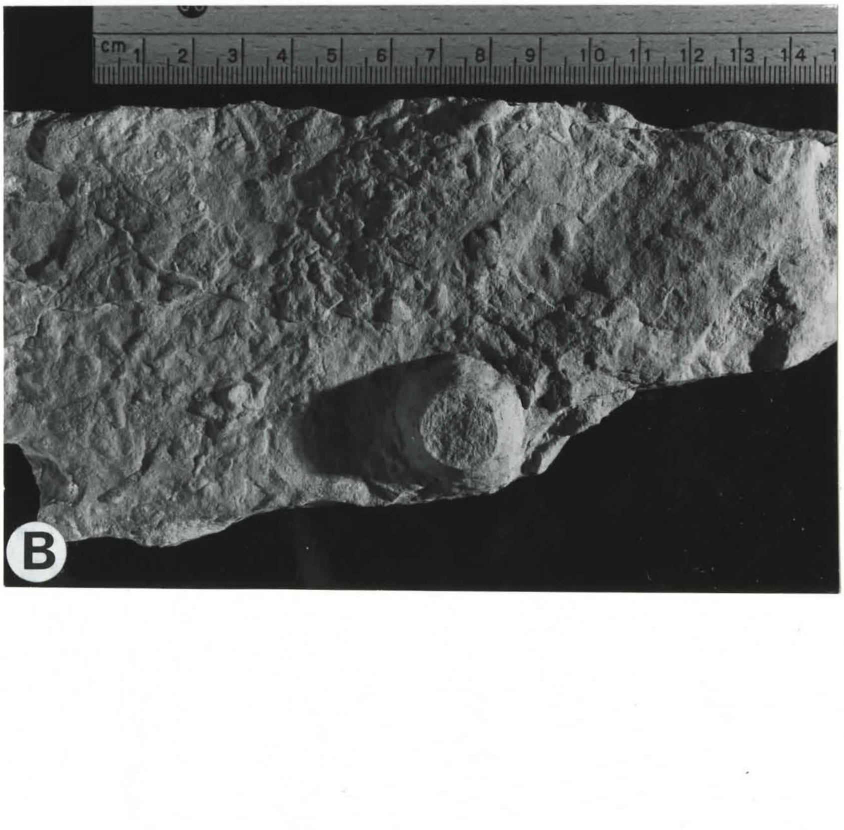

cm 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Figure 5-2. Trace fossils of the Whirlpool.

a) Cruziana or collapsed Palaeophycus burrows (Dr. G. Narbonne, pers. comm., 1986) on top of a sandstone interbed. Photo also shows a Lingulichnus burrow (just right of lens cap) and abundant crinoid ossicles. Lens cap is 58 cm in diameter. Photo is from the Lockport railway cut, east wall, on the bedding plane near upper set of tracks.

b) Top view of a rather large Diplocraterion (?) burrow (protrusive type) in a muddy sandstone bed. Sample is from the Lockport road cut, 3.8 m above the Whirlpool's base.


A


cm 1 2 3 4 5 6 7 8 9 10 11
B

Figure 5-3. Side view of two Teichichnus burrows that were found on the base of an HCS bed. The largest burrow is 6 cm long. Samples are from the Lockport road cut, 4.3 m above the Whirlpool's base.

Grade	Degree of Bioturbation (%)	Classification of Bioturbation
0	0%	no bioturbation
1	1- 5%	sporadic bioturbation traces
2	5-30%	weakly bioturbated
3	30-60%	medium bioturbated
4	60-90%	strongly bioturbated
5	90-99%	very strongly bioturbated
6	100%	completely bioturbated.

At most localities the degree of bioturbation was observed to increase upward in intensity, from grade 0 to grade 6.

The trace fossils range from being well defined (figurative) to nondescript (deformative) in form, depending on the degree of bioturbation (Schafer, 1972). The modes of preservation are variable and include all the four forms--exichnia, endichnia, epichnia (both ridges and grooves), and hypichnia (ridges)--present in Martinsson's (1970) classification scheme.

Table 5-1 indicates that there are no observable trends in the regional distribution of the various trace fauna. The one exception to this, perhaps, is _Lingulichnus_ sp., whose presence is confined to only those sections east of Stoney Creek, Ontario (i.e. wherever the Whirlpool is overlain by the Power Glen).

The Whirlpool's assemblage consists of trace fossils that are generally associated with the Skolithos and Cruziana ichnofacies; however, for reasons outlined below, the assemblage is more indicative of the Cruziana ichnofacies. The evidence supporting this includes: 1) the high abundance and diversity of the traces; 2) the dominance of horizontal to inclined feeding (e.g. Chondrites sp., Rhizocorallium sp., Phycodes sp., Teichichnus sp., Scalarituba missouriensis, Asterosoma sp., Rhabdoglyphus? sp.) and crawling (e.g. Cruziana sp., Tylichnus sp., Palaeophycus sp.) traces; and 3) the high abundance of traces that are diagnostic of the Cruziana ichnofacies (Chondrites sp., Palaeophycus sp., Teichichnus sp., Rhizocorallium sp., and Arenicolites sp.) (Frey and Pemberton, 1984). A possible fourth, although indirect, reason involves the facies characteristics of the upper part of the Whirlpool. The Skolithos ichnofacies is generally indicative of the foreshore and shoreface environments, where the high energy levels result in abrupt changes in rates of erosion, deposition, and physical reworking of the sediments (Frey and Pemberton, 1985). The resulting sediments are therefore slightly muddy to clean and well-sorted, with physical sedimentary structures (horizontal lamination, low-angle cross-lamination, and large- and small-scale trough cross-laminations) predominating over biogenic (mostly dwelling structures) ones (Frey and Pemberton, 1985). This type of environment is clearly not that in which the most commonly occurring facies (S/F and Sb) in the Whirlpool was deposited; instead, these facies are better explained, as will be indicated below, by the processes operating in the Cruziana ichnofacies environment.

The Cruziana ichnofacies is most characteristic of moderate to low energy level environments. Sediment textures and bedding styles vary but generally include well sorted silts and sands, interbedded muddy and clean silts and sands, and moderately to intensely bioturbated sediments, which produce a thoroughly homogeneous mixture of muds, sands, and silts (Frey and Pemberton, 1984, 1985). These energy levels and sediments are characteristic of estuaries, bays, lagoons, tidal flats, and continental shelves (Frey and Pemberton, 1984, 1985). In shallow waters, say, for example, between fairweather wave base and storm wave base, the ongoing quiet water sedimentation may be periodically interrupted by the rapid emplacement of storm-derived sands and silts, producing an interbedded sandstone and shale sequence. The low energy levels common to this environment are most favourable to deposit-feeding organisms; therefore, horizontal to inclined feeding and crawling traces are very abundant (Pemberton and Risk, 1982; Frey and Pemberton, 1984, 1985; Pemberton and Frey, 1984). During, and for some time after, storms, however, when energy levels are increased and silts and sands are emplaced, conditions become suitable to support the suspension feeders, or tube-builders, comprising the *Skolithos* ichnofacies. With the passing of the storms, and the return to more normal, quieter conditions, these opportunistic fauna eventually give way to the resident community, the traces of which comprise the *Cruziana* ichnofacies. In this way, alternations of the *Skolithos* and *Cruziana* ichnofacies may occur in the same sedimentary facies (facies S/F) (Pemberton and Risk, 1982; Frey and Pemberton, 1984, 1985; Pemberton and Frey, 1984).

The above description of the processes and sediment styles characteristic of the shallow, quiet, storm-influenced environment commonly associated with the *Cruziana* ichnofacies fits well with what is present in the upper part of the Whirlpool. The upper unit consists primarily of facies S/F and Sb. The abundant traces of the *Cruziana* ichnofacies are preserved as exichnia within the shale layers and as hypichnial ridges on the bases of the sandstone beds. The traces of the *Skolithos* ichnofacies (e.g. *Skolithos* and *Diplocraterion*) occur only on the tops of the sandstone beds (in varying degrees of bioturbation), which, with the presence of HCS and parallel lamination with symmetrical ripples, are most likely storm-derived. The fact that the degree of bioturbation in the upper unit increases upward is best explained by a deepening of the water (and therefore an increase in the distance from shore), which would result in quieter waters and greater lengths of time between sand emplacements, during which time the sediment has a greater chance of becoming bioturbated more thoroughly by the resident fauna. But this situation could also be produced by a gradual decrease in the number of storms, which would, in turn, affect the length of time between storm emplacements of sand.

MICROFOSSILS

Introduction

Palynomorphs in the Whirlpool and the other Medina formations have been found and described by Gray and Boucot (1971), Miller and Eames (1982), and Salas (1983). The palynomorphs obtained from the Whirlpool itself include a diverse assemblage of acritarchs, chitinozoans, and spore-like microfossils. Gray and Boucot (1971) have also noted the presence of scolecodonts, the dental remains of annelids.

The acritarchs, chitinozoans, and scolecodonts are considered to be marine in origin. The environment indicated by the Early Silurian spore-like microfossils, on the other hand, is not so obvious, and has been the subject of much debate over the past 20 years (Volkava, 1965, cited in Schopf, 1969; Gray and Boucot, 1971, 1977, 1980; Gray et al., 1974; Banks, 1975; Smith, 1981). The presence of spores in tetrad groups, the presence of a triradiate scar on isolated spores, and the presence of a cutinized cell wall (an anti-desiccation device), all of which are morphological features that correlate completely with the reproductive structures of present day land plants (hence the name 'spore-like'), have led some workers to interpret the occurrence of spore-like microfossils as evidence of vascular land or semiaquatic plants (Gray and Boucot, 1971, 1977; Gray et al., 1974; Strother and Traverse, 1979). But the question of origin of these Lower Silurian spore-like microfossils remains largely unresolved due to the lack of vegetative remains of possible source plants in rocks of this age (Schopf, 1969; Banks, 1975; Gray and Boucot, 1980; Smith, 1981).

A micropaleontological study (primarily palynological) of the Whirlpool was conducted to obtain additional information that would lend support to or contradict the view, based on ichnological, paleontological, and facies evidence, that the Whirlpool was deposited under two very different depositional environments (see Chapter 7). Although the origin of the spore-like microfossils is somewhat uncertain, Strother and Traverse's (1979) view that the spore-like microfossils probably belonged to "extinct plant groups which were demonstrating pre-vascular adaptations to terrestrial habitats" is accepted here.

A total of 20 samples, taken from both the upper and lower portions of the Whirlpool and covering a total of nine sections ranging from Duntroon to Lockport, were selected for this study. Because spores are rarely found in sand-sized rocks (Gray et al., 1974), the sampling was limited to shaly intervals only.

The microfossils were extracted and mounted (see Appendix 4) using a combination of procedures outlined by Barss and Williams (1973) and that used by Dr. J. Legault (pers. comm., 1985). A 24 micron mesh was used to recover the microfossils. The procedure, on the whole, yielded very good results. Microfossils were recovered from 18 of the 20 samples, but five of these (D-10, FR-7, FR-17, FR-24, C-9) yielded very few (less than 5) microfossils per slide (the range was roughly 15 to 150 microfossils per slide). The absence or paucity of microfossils in some of the slides may be real or may be the result of a laboratory error. Identification, using a polarized microscope, of the various palynomorphs was accomplished with the aid of the diagrams and photographs of the known Whirlpool palynomorphs included in the papers by Miller and Eames (1982), Strother and Traverse (1979), and Richardson and Ioannides (1973).

Whirlpool Microfossils

Table 5-2 lists the various palynomorphs found, their abundance, and the location (upper or lower part of the Whirlpool) of the samples at each of the sections. All of the spore-like microfossils recovered from the Whirlpool

Table 5-2. List of the microfossils in the Whirlpool. The table shows the regional distribution of the microfossils and shows the location of each sample at the section from which it came. See text for a discussion of the trends present in this table. Asterisks indicate samples taken from the lower Whirlpool. See Figure 1-1 for an explanation of the abbreviations used for the sections. The letters 'r', 'o', 'c', 'f' and 'a' indicate the relative abundance of each microfossil per slide.

SECTION	D	CN	<----------CT			-------->	J.C.	<-------K		------->	B.F.	WP	<----QL	-->	<---------LP			---------->
HEIGHT ABOVE BASE (m)	3.1	5.8	2.75	3.4	4.1	4.75	2.8	0.7	1.5	2.3	4.7	0.2	1.6	3.7	1.0	1.4	3.0	3.8
SAMPLE	D-10*	CAN-11	C-9*	C-16*	C-18	C-23	JC-D-22	FR-7	FR-17	FR-24	BF-E-1	WP-A*	BSC-Sh-c*	BSC-1-A (Sh)	LP-1*	LP-2*	LP-3*	LP-20
SPECIES NAME																		
SPORE-LIKE MICROFOSSILS																		
Dyadospora murusattenuata		o		c	c	o	o				c	c	c	o	f	f	f	c
Dyadospora murusdensa		c		o	c	c	c							o	f	c	c	o
Nodospora burnhamensis		o		o	c	c	o				o					c	o	o
Nodospora oyleri						r									o	?r	o	r
Nodospora sp.		c		c	f	f	c				c		c	c	c	f	f	c
Rugosphaera tuscarorensis		r		o	o	?c	o				o				o		o	r
Tetraletes sp.							?r								o	o	o	r
Tetrahedraletes medinensis		o		c	c	o	o				o		c	c		c	f	c
Strophomorpha ovata											o							
Nodospora cf. N. rugosa		o			o	r	r				r				o			o
?Tasmanites sp.		o		c		o	r				o	c				o	o	o
?Retusotriletes cf. warringtonii												a						
?Retusotriletes cf. goensis			c				r				c		f	c				
?Retusotriletes sp.	o	o	c	f	o	r	o			c	c		c	c				c
ACRITARCHS																		
Leiosphaeridia? Sp. A																		o
Leiosphaeridia sp.		?r					?r											
Moyeria cabotti																		?r
Leiofusa sp.									f		r			o				
Leiofusa sp. A										c								
Micrhystridium? polorum							r		f					o				
Micrhystridium sp. B		o																
Micrhystridium sp.						r			f									
Veryhachium trispinosum					r													
Retisphaeridium? fragile							?r											
CHITINOZOANS																		
Cyathochitina cf. C. campanuloeformis		?o					o											
OTHER																		
tube-like fragments	r	c		r		r	o	c	f	f	o							
cuticle-like fragments					o	r	r											
Scolecodonts		f			o	c	f				f			f				c

a = abundant (50%)
f = frequent (>20% to 50%)
c = common (> 7% to 20%)
o = occasional (> 2% to 7%)
r = rare (0% to 2%)

* fluvial Whirlpool
? possibly present

by Miller and Eames (1982; also noted by Salas, 1983) were observed in the samples except Nodospora retimembrana, Vermiculatisphaera obscura, and Rugosphaera? cerebra. Three additional taxa, ?Tasmanites sp., ?Retusotriletes sp., and ?Nodospora rugosa, were also observed. The acritarchs and chitinozoans recovered include most of those reported by Miller and Eames (1982) plus one additional species, Retisphaeridium? fragile. Other microfossils, either not mentioned or noted by Miller and Eames (1982), but which were observed in this study, include scolecodonts, and tube-like and cuticle-like fragments.

The Whirlpool's spore-like microfossils are medium brown to opaque in colour and occur primarily as tetrads and dyads, although monads are also present. Sizes of the spore-like microfossils vary, but generally range from 24 to 65 microns. Clusters of spore tetrads, dyads, and/or monads were common features in some of the samples. Some of the spore-like microfossils are shown in Fig. 5-4, 5-5, and 5-6. For additional pictures and detailed descriptions of each of the taxa, see Miller and Eames (1982), Strother and Traverse (1979), and Salas (1983).

Table 5-2 reveals a number of interesting trends concerning the palynological content and distribution within the Whirlpool: 1) spore-like microfossils are abundant and fairly diverse within the lower part of the Whirlpool; 2) no acritarchs, chitinozoans, or scolecondonts are present in

Figure 5-4. Spore-like microfossils of the Whirlpool.

a)	<u>Nodospora</u> sp.	Sample JC-D-22.	400 X.
b)	<u>Nodospora</u> <u>oyleri</u>.	Sample JC-D-22.	400 X.
c)	<u>Nodospora</u> <u>burnhamensis</u>.	Sample JC-D-22.	400 X.
d)	<u>Nodospora</u> ?<u>rugosa</u>.	Sample JC-D-22.	256 X.

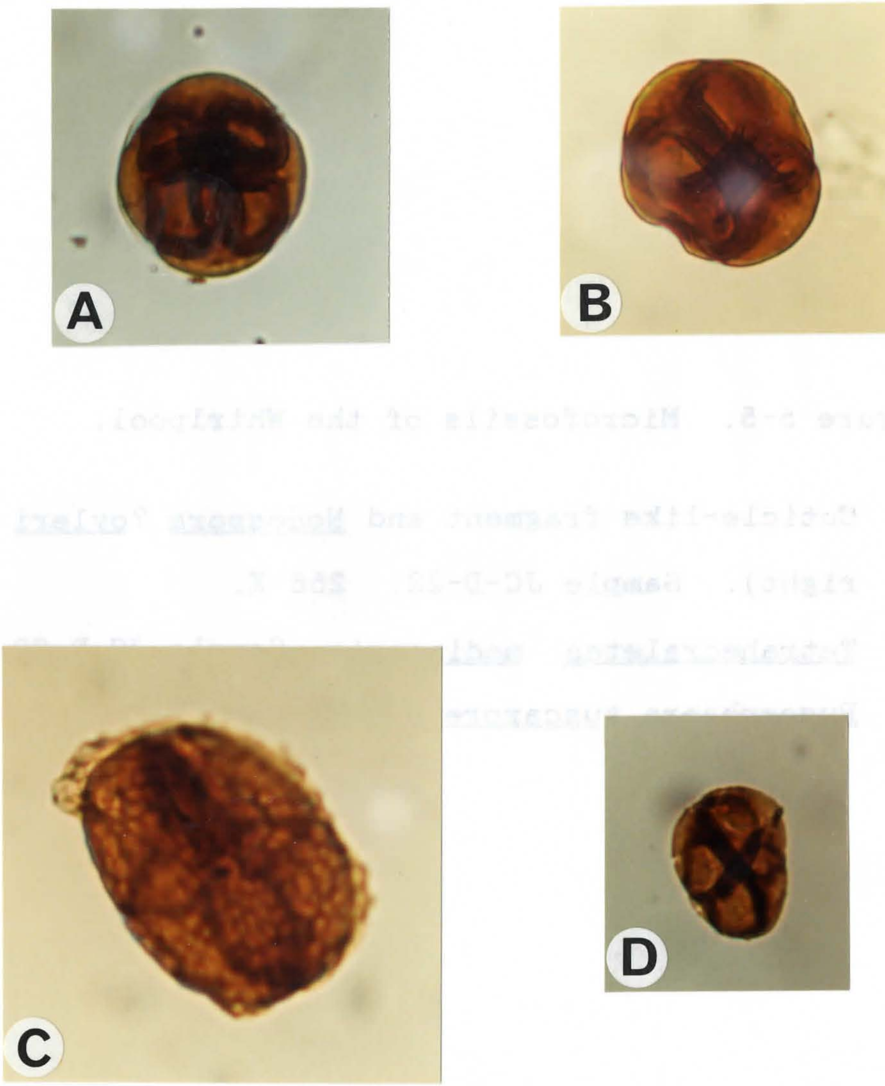

A
B
C
D

Figure 5-5. Microfossils of the Whirlpool.

a) Cuticle-like fragment and Nodospora ?oyleri (upper right). Sample JC-D-22. 256 X.

b) Tetrahedraletes medinensis. Sample JC-D-22. 256 X.

c) Rugosphaera tuscarorensis. Sample C-23. 400 X.

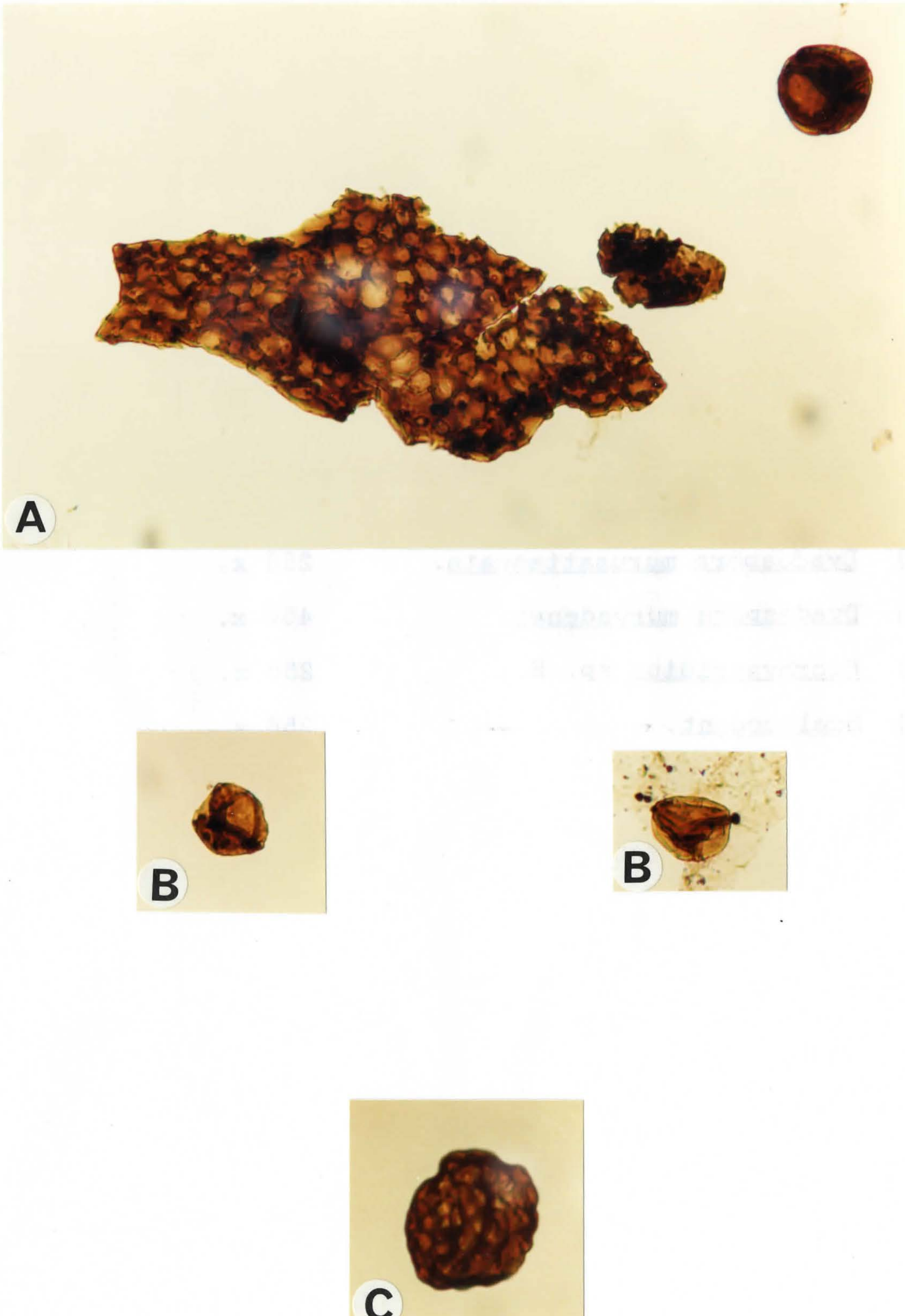

A
B
B
C

Figure 5-6. Microfossils of the Whirlpool.

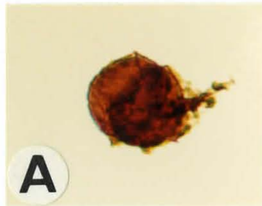
a) *Dyadospora murusattenuata*. 256 x.

b) *Dyadospora murusdensa*. 400 x.

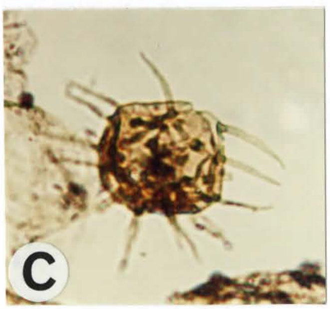
c) *Micrhystridium* sp. B. 256 x.

d) *Scolecodont*. 256 x.


A


A


B


C


D

the lower part; 3) spore-like microfossils, acritarchs, chitinozoans, and scolecodonts comprise the microfossil assemblage of the upper unit; 4) the diversity of spore-like microfossils in the upper unit is equal to, if not greater than, that of the lower unit; and 5) the abundance (not necessarily the frequency of occurrence, however) of the various spore-like microfossil taxa in the upper unit is somewhat less than that in the lower unit.

Environmental Significance

It appears that two very different environments are suggested by the microfossil content and distribution within the Whirlpool. The lower unit, with its high abundance and moderate diversity of spore-like microfossils and lack of marine organic microfossils (acritarchs, chitinozoans, and scolecodonts), is displaying a strong terrestrial influence, which is consistent with the absence of trace fossils and body fossils in this part of the Whirlpool. The upper unit, on the other hand, despite the presence of spore-like microfossils, is clearly marine because of the presence of acritarchs, chitinozoans, and scolecodonts.

Gray and Boucot (1971, 1972, 1974) have demonstrated that spore tetrad and acritarch distribution and abundance is related to water depth and shoreline proximity: spore diversity and abundance is greatest in a quiet nearshore environment, and drops off drastically seaward of the proximal offshore environment, while acritarch diversity and abundance is greatest offshore and decreases drastically landward. Because of the low abundance of marine microfossils and the scarcity of marine body fossils, Gray and Boucot (1971) have suggested a nearshore environment of deposition for the Medina. Salas (1983) considered the presence of desiccation cracks (possibly synaeresis cracks?) and the abundance of spore-like microfossils in the upper unit to be indicative of a intertidal mudflat environment. But this latter interpretation, although consistent with Gray and Boucot's (1972) microfossil distribution findings, is inconsistent with the environment the facies and trace fossils signify.

Because spores have the hydraulic equivalent of medium silt to clay-sized particles, they are most likely to occur where fine-grained sediments accumulate (Stanley, 1965). Such quiet water environments occur in both nearshore and offshore settings. Stanley (1965), working along the eastern coast of the United States, found that the abundance of spores increases seaward from a position 32 km from the shoreline (the high energy levels prevent abundant spore deposition closer to shore) and reaches a maximum 296 km from shore before dropping off again seaward of this point. But the location of the maximum abundance can be greatly affected by riverine influences (increasing the distance from shore) and to a lesser extent by wind dispersal patterns.

From Stanley's (1965) work on spore abundance, it is not unreasonable to suggest that part of the upper Whirlpool may represent an offshore environment, between fairweather wave base and storm wave base (as is possibly indicated by the trace fossil evidence). The lower abundance of spore-like microfossils in the marine (upper) part of the Whirlpool than in the terrestrial (lower) part is expected, but the greater diversity is not, and may be due to operator error. The low abundance of marine microfossils in the upper unit places the depositional environment relatively close to shore, but an estimate of distance is not possible due to a lack of data and the fact that spore-like microfossil abundance in the upper Whirlpool probably reflects a combination of three different sources: 1) normal, everyday sedimentation from suspension along with silts and clays (sediments introduced by currents and wind): 2) spores derived from more shoreward environments but introduced, along with other sediments, into a more seaward environment by storm-induced currents; and 3) spore-like microfossils from older terrestrial deposits (lower Whirlpool) reworked during the transgression (see Chapters 7 and 8) and introduced, along with younger forms, into more distal depositional environments.

MACROFOSSILS

Macrofossils have been found only in the upper unit of the Whirlpool. Their sparse occurrence and their presence in a part of the Whirlpool that may be considered by some as belonging to the Manitoulin, Power Glen, or Cabot Head probably explain why the Whirlpool's fossils have never been the subject of serious study.

The number of different species present in the Whirlpool, as noted by previous workers, is few in number. Williams (1914, 1919) noted the presence of *Pleurotomaria* cf. sp. *littorea*, *Lingula cuneata*, *Modiolopsis*? *orthonota*, *Cornulites distans*, ?*Cornulites* sp., *Euconia* cf. *littorea*, and *Hormotoma subulata* (Conrad)?, and Schuchert (1943) reported the occurrence of *Conularia cataractensis* (Ruedemann). Col. C. C. Grant (1900) noted the presence of an *Orthoceras* in an exposure of the Medina Sandstone (probably the Whirlpool Sandstone) in an abandoned quarry in Hamilton, Ontario, and Salas (1983) reported the occurrence of *Blothrophyllum* sp. and *Synaptophyllum* sp.

The fossils found in this study, some of which are the same as those mentioned above, and the locations of their occurrence are shown in Table 5-3. The table does not reveal any major patterns or trends, but does indicate that brachiopods and crinoids are the most regionally widespread of all the fossils and that the corals are restricted

Table 5-3. This table lists the fossils found in the Whirlpool during this study. See text for a list of species found by previous workers. There is a minor omission in the table; it should show the presence of gastropods at Cannings Falls.

Section Species	Duntroon	Cataract	Jolley Cut	Kenilworth Ave.	Balls Falls	Devil's Hole	Artpark	Lockport	371	108	678	676	240
ANTHOZOA													
?Enterolasma sp.	x												
Streptelasma sp.			x	x									
undeterminable									x				
BIVALVIA													
cf. Modiolopsis sp.		x											
cf. Actinodonta sp.		x											
undeterminable				x	x								
BRACHIOPODA													
cf. Eoplectodonta sp.	x												
cf. Strophonella sp.					x								
Strophonella striata (Hall)	x												
Lingula? sp.								x					
Leptaena sp.	x												
undeterminable	x		x	x	x	x	x			x		x	x
CRINOIDEA													
undeterminable	x	x		x	x		x	x		x	x	x	
GASTROPODA													
Hormotoma sp.	x												
Hormotoma subulata (Conrad)?		x	x		x								
cf. Holopea sp.								x					
undeterminable													
planospiral	x												
conospiral	x	x											x
OSTRACODA													
Leperditia cylindrica (Hall)	x						x						

regionally to areas where the Whirlpool is overlain by the Manitoulin Dolomite.

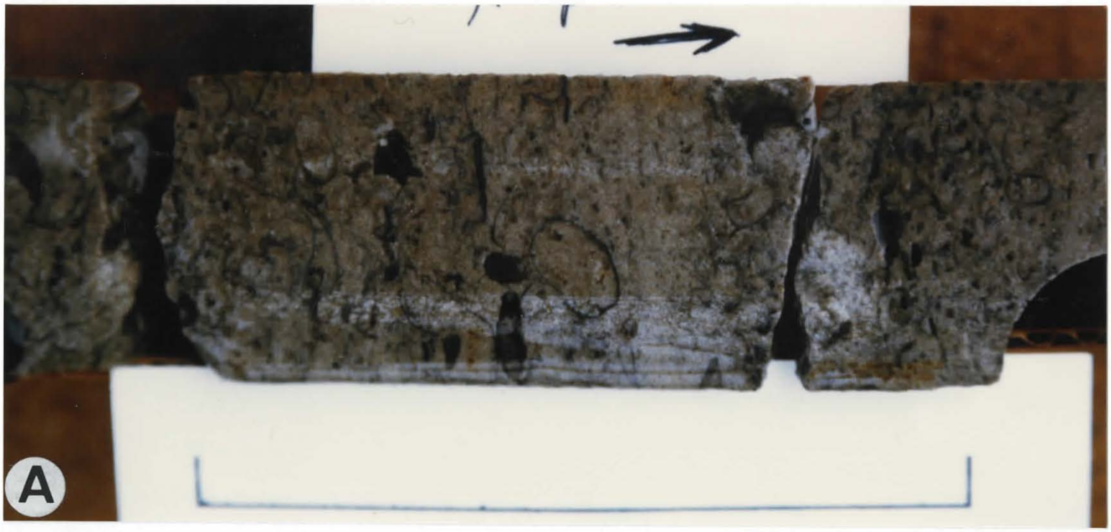
The fossils are randomly oriented (that is, not in life position), disarticulated, and partially fragmented (Fig. 5-7a). They are preserved as moulds or imprints within the sandstone beds (Fig. 5-7b) as well as on the bases and tops of the sandstone beds. Their fragmented nature and lack of preservation of fine details makes the classification of the fossils difficult or impossible at times.

It is uncertain how much environmental information can be obtained from the Whirlpool's fossils. Their random orientation, their fragmented or disarticulated nature, and their occurrence only in the sandstone beds suggest that some degree of transport and/or reworking of the fossils may have taken place. During initial stages of storms, large storm waves uproot benthonic organisms and winnow away all fine sediment, leaving behind a lag of disarticulate shells, onto which a layer of sand may be deposited during more advanced stages of the storm. In this way, the fossils are preserved 'in situ' (Dott, 1983). It seems unlikely that the above mechanism of fossil preservation could have been responsible for the Whirlpool's fossil distribution. The fossils are not concentrated as lags on the bases of the sandstone beds, and some of the fossils, for example, the crinoids (at Balls Falls, Artpark, core 676), occur

Figure 5-7. Two of the fossils found in the Whirlpool.

a) Photo showing abundant gastropod fragments within a sandstone bed. Arrow indicates up and scale is 10 cm long. Photo is of core 240, 5.2 m above the Whirlpool's base.

b) An excellent preservation of a crinoid stem within a thin sandstone bed displaying drifting and vertically aggrading symmetrical ripples. Stem is 7.5 cm long. From Duntroon, 3.8 m above the base of the Whirlpool.


A


B

throughout the entire thickness of the sandstone beds and are, in many cases, concentrated in layers between the sandstone laminations. Such a distribution seems to suggest that some transportation has occurred, but because the fossils have not been greatly abraded, large distances of transport may not be involved.

CHAPTER 6

PETROGRAPHY

A petrographic study of the Whirlpool was undertaken primarily to determine: 1) the Whirlpool's composition; 2) the percentage of feldspar in the sandstone; 3) the percentage and type of porosity; and 4) whether or not any regional and vertical trends exist in the above three as well as in the grain size.

To provide a good regional and vertical coverage of the Whirlpool, 48 thin sections were made from hand samples obtained from 24 of the 30 core and outcrop sections. For the regional analysis, samples were chosen from within one meter (if possible) of the Whirlpool's base at each of the 24 sections, and for the vertical analysis, six very good exposures were selected, and from each of these, samples were taken at approximately one meter intervals (vertically).

Each thin section was cut perpendicular to bedding, impregnated with blue dye epoxy for porosity determinations, and stained (half of the slide) for plagioclase and alkali feldspars and calcite according to techniques suggested by Houghton (1980) and Friedman (1971), respectively. The stained portion of each thin section was point counted (traverses of 25 points) under a petrographic microscope until 300 grains were counted. The results of the point counting are shown in Table 6-1. The essential constituents, recalculated to 100%, are shown in Table 6-2 along with the vertical locations, facies, textures, and sandstone classifications. Estimates of grain sphericity were made by comparison with a chart published by Rittenhouse (in Beard and Weyl, 1973). The degree of rounding and sorting was estimated by using charts published by Powers (1953) and Beard and Weyl (1973), respectively. The sandstone classification and grain size (the grain size is the modal grain size of the thin section) classes are from Folk (1974). Opaques were identified using reflected light.

GENERAL DESCRIPTION

In general, the Whirlpool is a moderately spherical, rounded, well sorted, very fine- to fine-grained subarkose. Framework grains are primarily composed of quartz, feldspar, and rock fragments, but minor amounts of heavy minerals (opaques, ultrastables, and phosphatic grains) also occur. Quartz, occurring as syntaxial overgrowths, is the dominant cement, but calcite and dolomite, generally subordinate in abundance to the quartz, may show high abundances locally. Porosity is secondary in nature and generally constitutes

Table 6-1. Table showing the results of the point counting. The abbreviations used in the thin section name that are not the same as those used in Figure 1-1 are as follows: CAN, Cannings Falls; C, Cataract; FR, Kenilworth Avenue; BSC, Quarry Lake; GAS, Gasport; and MED, Medina. In the table, 't' indicates trace amounts.

Thin Section	Quartz (%)	Kspar (%)	Plag (%)	SRF (%)	MRF (%)	Phosphatic Grains (%)	Ultrastable Heavy Minerals (%)	Opaques (%)	Clay (%)	CEMENT: Quartz (%)	CEMENT: Calcite (%)	CEMENT: Dolomite (%)	CEMENT: Other (%)	Porosity (%)
MM-2	37.7	4.6	0.5	0.9	0.3	-	0.2	0.3	-	9.1	-	44.6	0.9	0.9
OB-6	61.7	9.2	1.0	1.0	0.5	t	0.2	0.5	-	14.2	3.7	6.2	1.0	0.2
D-5	48.1	5.8	0.8	2.5	0.4	0.2	0.2	0.4	2.5	16.9	15.2	4.5	2.5	-
D-11	56.4	5.5	0.2	1.5	-	0.9	1.1	-	0.4	18.0	3.3	-	0.9	9.5
D-12	67.6	4.2	-	1.0	0.7	0.5	t	0.2	-	8.2	12.9	-	0.2	4.5
L-3	59.4	3.5	0.2	2.1	1.2	0.5	0.7	1.6	-	9.2	15.0	5.1	1.2	0.5
PR-7	62.0	5.1	0.2	1.2	-	0.9	0.5	t	0.2	17.5	2.6	-	0.2	6.1
PR-5	79.0	1.6	-	0.3	0.3	0.3	0.3	-	-	9.8	0.5	-	-	7.9
PR-3	66.7	4.3	-	0.5	-	0.2	t	0.2	-	11.3	15.3	-	1.4	-
CAN-1	74.1	4.3	0.3	1.3	0.3	0.3	t	0.3	-	10.5	-	-	-	8.6
C-24	62.3	5.6	-	2.7	1.5	0.2	0.2	0.2	t	18.6	1.7	5.9	0.2	0.2
C-20	43.5	3.4	0.5	1.5	0.2	0.3	0.2	0.7	18.0	12.3	-	18.0	1.3	-
C-17	72.4	4.8	0.3	0.5	0.5	1.9	t	-	t	8.0	3.2	0.3	-	8.0
C-12	71.8	4.2	-	1.1	0.5	0.5	0.3	0.3	2.6	12.9	1.8	0.5	0.3	2.9
C-5	69.0	9.0	-	1.6	0.8	0.3	0.3	0.3	-	12.9	0.5	-	-	4.4
C-1	61.0	2.0	-	1.1	-	1.5	-	t	-	5.5	12.1	0.4	12.9	3.3
JC-B-9	65.6	3.1	0.2	1.2	-	t	0.2	1.7	-	9.9	13.7	3.8	0.2	0.2
JC-12-A	71.3	3.3	0.5	0.3	-	0.3	-	-	-	17.4	0.8	-	-	6.3
JC-10-A	65.1	4.9	0.2	1.5	t	1.0	t	0.5	1.0	22.2	-	0.5	0.2	2.9
JC-8-A	75.0	3.5	0.5	0.5	t	0.5	0.3	0.3	-	12.1	0.5	0.3	0.3	6.2
JC-6-A	71.3	1.2	-	0.2	t	0.2	t	-	-	15.8	2.9	1.0	7.1	0.2
FR-20	65.4	1.8	-	0.2	-	0.8	0.2	-	-	19.0	4.7	4.1	1.6	2.2
FR-1	72.3	2.3	-	0.8	0.3	0.5	0.3	1.8	t	20.4	0.5	t	-	0.8
BF-E-11	65.0	1.7	3.2	3.0	0.7	0.2	0.5	-	2.5	21.1	-	-	0.2	1.7
BF-E-8	73.2	6.4	0.6	5.0	1.5	0.3	0.3	t	1.5	10.5	-	0.6	-	-
NG-24	66.4	6.2	0.2	1.2	0.2	t	t	t	t	19.9	2.0	2.2	0.5	0.7
NG-21	73.8	2.9	0.3	0.8	0.3	0.3	t	-	-	20.2	t	-	-	1.3
NG-19	73.3	1.3	0.5	0.8	-	0.8	0.3	t	1.8	20.5	-	-	-	0.8
NG-18	76.0	1.9	1.1	1.4	1.1	0.6	0.6	-	t	16.9	t	-	-	0.3
NG-15	74.0	2.1	-	1.0	t	t	0.3	0.3	-	14.3	6.8	-	0.3	0.8
WP-3-A	75.8	3.5	0.3	0.8	0.3	0.5	-	-	t	15.5	0.5	1.4	-	1.1
AP-1-A	79.0	0.5	0.3	1.9	-	-	0.3	-	-	11.5	0.5	-	0.5	5.5
BSC-1-C	62.6	7.6	2.3	1.5	0.8	0.5	0.5	0.5	t	17.3	0.5	5.1	0.5	0.3
LP-24	71.5	3.6	1.3	-	0.3	0.5	t	t	-	13.9	2.8	6.2	-	-
LP-15-A	61.1	2.7	0.2	1.8	0.4	0.4	t	-	7.8	23.6	1.8	0.2	-	-
LP-7-A	71.0	1.7	0.2	1.2	-	t	0.2	-	t	24.3	0.5	0.7	-	t
LP-5-A	78.4	1.4	2.0	1.7	-	0.3	0.6	-	-	14.0	0.3	0.3	0.3	0.8
LP-1-A(D)	67.5	2.1	0.5	0.5	0.7	t	0.2	t	-	9.8	17.7	-	1.0	-
GAS-1	72.3	7.0	0.8	1.4	1.1	0.6	t	t	-	14.2	0.8	-	-	1.1
MED-2	67.6	1.5	-	5.1	-	2.0	-	0.3	t	8.7	14.0	-	0.3	0.5
371-1	53.6	9.3	2.9	0.7	-	t	0.2	1.1	-	7.0	5.4	14.0	5.7	-
108-1	53.8	1.5	-	0.2	0.2	0.2	0.4	0.6	-	4.0	-	38.6	0.6	-
106-1	70.2	3.1	-	0.8	0.3	1.8	-	0.5	-	16.1	3.1	1.0	-	3.3
146-1	68.3	1.2	-	0.2	-	t	0.2	t	-	17.0	0.5	3.3	9.1	0.2
676-2	78.7	3.0	-	0.8	-	0.3	-	-	-	11.9	0.3	1.1	0.8	3.0
552-1	76.7	2.7	-	0.8	0.3	1.1	0.3	-	t	12.1	3.3	-	0.3	2.2
240-1	73.1	4.0	0.5	1.9	1.1	-	t	t	7.8	9.9	-	0.5	0.5	0.5
240-2	79.5	1.4	-	0.6	0.6	0.6	-	0.3	2.3	6.3	-	0.3	4.8	1.1

Table 6-2. Table showing the recalculations of the essential constituents to 100%. Also shown are the facies, textural characteristics, sandstone classifications and vertical location of all the thin sections. The abbreviations used for the degree of roundness and sorting are explained below:

ms - moderated sorted	sa - subangular
ws - well sorted	sr - subrounded
vws - very well sorted	r - rounded
ews - extremely well sorted	wr - well rounded

Thin Section	Height From Base(m)	Facies	Quartz (%)	Feldspar (%)	Rock Fragments (%)	Sphericity	Roundness	Sorting	Grain Size (mm)	SANDSTONE CLASSIFICATION
MM-2	1.2	Sw	85.6	11.7	2.7	0.77	r	ews	0.049	med. cryst. silty dol.
OB-6	0.8	Sw	84.1	13.9	2.0	0.81 - 0.83	r to wr	vw	0.075	dol. subarkosic arenite
D-5	2.0	Srs	83.4	11.5	5.1	0.75 - 0.77	sr	vws	0.069	cal. subarkosic arenite
D-11	1.15	Src	88.6	9.0	2.4	0.77	r	vws	0.089	subarkosic arenite
D-12	0.5	Sh	91.9	5.7	2.4	0.77	r	vws	0.12	cal. subarkosic arenite
L-3	0.0	Sm	89.6	5.6	4.9	0.77	wr	ws	0.086	cal. subarkosic arenite
PR-7	2.0	Src	90.5	7.8	1.7	0.77 - 0.79	r	vws	0.093	subarkosic arenite
PR-5	1.15	Src	97.3	2.0	0.7	0.77	r	vws	0.150	quartz arenite
PR-3	0.3	Sm	93.2	6.0	0.7	0.75	r to wr	vws	0.2	cal. subarkosic arenite
CAN-1	3.8	Sh	92.3	5.7	2.0	0.75	r to wr	vws	0.1	subarkosic arenite
C-24	5.0	S/F	86.4	7.8	5.8	0.79	wr	vws	0.104	subarkosic arenite
C-20	4.55	S/F	88.7	7.9	3.4	0.75	sr	ws	0.062	dol. shaley siltstone
C-17	3.6	Src	92.2	6.5	1.4	0.77 - 0.79	r	ews	0.111	subarkosic arenite
C-12	3.2	Srs	92.5	5.4	2.0	0.81	r	ws	0.143	subarkosic arenite
C-5	1.7	Src	85.4	11.2	3.4	0.73	wr	ws	0.11	subarkosic arenite
C-1	0.0	Sm	95.2	3.1	1.7	0.77	r	ws	0.25	cal. quartz arenite
JC-B-9	3.65	S/Fhcs	93.5	4.8	1.7	0.81	wr	ws	0.115	cal. subarkosic arenite
JC-12-A	2.5	Src	94.6	5.0	0.3	0.77	r	vws	0.134	subarkosic arenite
JC-10-A	1.8	Src	90.8	7.1	2.0	0.77	sr to r	ws	0.105	subarkosic arenite
JC-8-A	1.1	St	94.3	5.1	0.7	0.79	wr	vws	0.130	subarkosic arenite
JC-6-A	0.0	St	98.0	1.7	0.3	0.77	r to wr	ws	0.23	quartz arenite
FR-20	1.55	Shcs.A	97.1	2.6	0.3	0.77	r	ws	0.122	quartz arenite
FR-1	0.0	Sl	95.5	3.1	1.4	0.77	r to wr	vws	0.147	quartz arenite
BF-E-11	2.75	Sh	88.2	6.7	5.1	0.75	r	ws	0.113	subarkosic arenite
BF-E-8	1.3	Src	84.5	8.1	7.4	0.83	r	ews	0.114	subarkosic arenite
NG-24	6.8	Sh	89.3	8.7	2.0	0.77	r	ws	0.12	subarkosic arenite
NG-21	4.5	St	94.6	4.0	1.3	0.75	r	ws	0.23	subarkosic arenite
NG-19	2.0	Src	96.6	2.4	1.0	0.77	r	vws	0.098	quartz arenite
NG-18	1.0	Sh	93.2	3.7	3.1	0.73 - 0.75	wr	ws	0.15	subarkosic arenite
NG-15	0.0	St	96.0	2.7	1.3	0.77	sr to r	ws	0.38	quartz arenite
WP-3-A	0.7	St	93.9	4.7	1.3	0.77	wr	ws	0.503	subarkosic arenite
AP-1-A	0.0	St	96.7	1.0	2.3	0.77	r to wr	ws	0.5	quartz arenite
BSC-1-C	1.6	Src	83.7	13.3	3.1	0.71 - 0.75	r	vws	0.1	subarkosic arenite
LP-24	4.5	S/Fhcs	93.3	6.4	0.3	0.81	r	ews	0.116	subarkosic arenite
LP-15-A	3.5	Srs	92.3	4.4	3.4	0.79	r	ws	0.087	subarkosic arenite
LP-7-A	2.8	St	95.7	2.7	1.7	0.77	r	vws	0.13	quartz arenite
LP-5-A	1.6	Sw	93.9	4.0	2.0	0.77	r to wr	vws	0.15	subarkosic arenite
LP-1-A(D)	0.0	St	94.6	3.7	1.7	0.73 - 0.75	r	vws	0.15	cal. subarkosic arenite
GAS-1	0.9	St	86.9	9.4	3.7	0.77	r	ms	0.171	subarkosic arenite
MED-2	1.7	St	91.1	2.1	6.9	0.77	sr to r	ws	0.268	cal. sub(calc)litharenite
371-1	0.2	Sl	80.6	18.4	1.0	0.79	r	vws	0.06	dol. siltstone
108-1	0.9	Sb	96.6	2.7	0.7	0.77	wr	ws	0.120	dol. quartz arenite
106-1	0.3	Src	94.5	4.1	1.4	0.77 - 0.79	r to wr	ws	0.183	subarkosic arenite
146-1	0.1	Sc	98.0	1.7	0.3	0.79	r	vws	0.142	quartz arenite
676-2	0.9	Sm	95.3	3.7	1.0	0.75	wr	vws	0.177	quartz arenite
552-1	1.2	Sm	95.2	3.4	1.4	0.75	r	ws	0.137	quartz arenite
240-1	1.4	Src	90.7	5.7	3.7	0.75	sa to sr	ews	0.066	(red)subarkosic arenite
240-2	0.1	Src	96.9	1.7	1.4	0.75	wr	ws	0.304	(red)quartz arenite

less than 4% of the Whirlpool (Fig. 6-1).

COMPOSITION

Figure 6-3 shows the composition of the sandstone samples plotted on Folk's (1974) QFR diagram. The majority of the samples (67%) fall within the field designated as subarkose, while 31% lie within the quartzarenite field, and 2%, within the sublitharenite field.

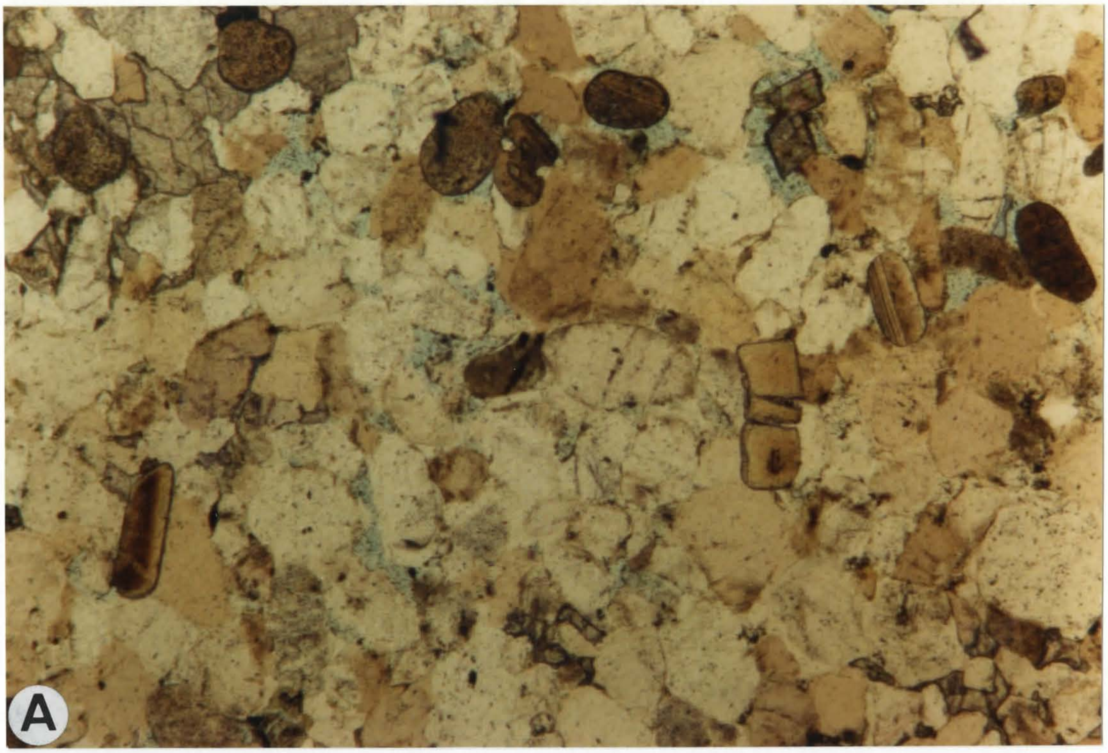
The vertical variability of the sandstone composition at the Lockport, Niagara Glen, The Jolley Cut, Cataract, Primrose, and Duntroon sections is shown in Figures 6-4 and 6-5. Variability in composition is minor and occurs randomly, showing no significant vertical trends; however, regionally it would appear that the percentage of feldspar is slightly higher in sections to the northwest. Note, too, that there are no major differences in compositions between the lower and upper units of the Whirlpool. The regional variability in sandstone composition is shown in Figure 6-6. Again, there appears to be no well developed regional compositional trends.

FRAMEWORK

Results from the point counting show that the framework comprises anywhere from 51% to 88% (average is

Figure 6-1 Photo showing the typical appearance of the Whirlpool's sandstone. The Whirlpool is very highly cemented by silica cement. In this photo, notice the abundance of syntaxial quartz overgrowths (look for dust rims), the point to point grain contacts, the minor calcite cementation, and the small percentage of feldspar, rock fragments, heavy minerals, and porosity (blue). The thin section has been stained for feldspar and calcite. Thin section FR-1 (Kenilworth Ave.), cross-polarized light, 40 X.

Figure 6-2. Photo of thin section MED-2 showing numerous very well rounded, highly spherical, medium-grained, micritized ooids and minor echinoderm fragments. These carbonate, lithoclasts were observed only at the Medina section. The thin section has been stained for calcite and feldspar. Cross-polarized light, 40 X.



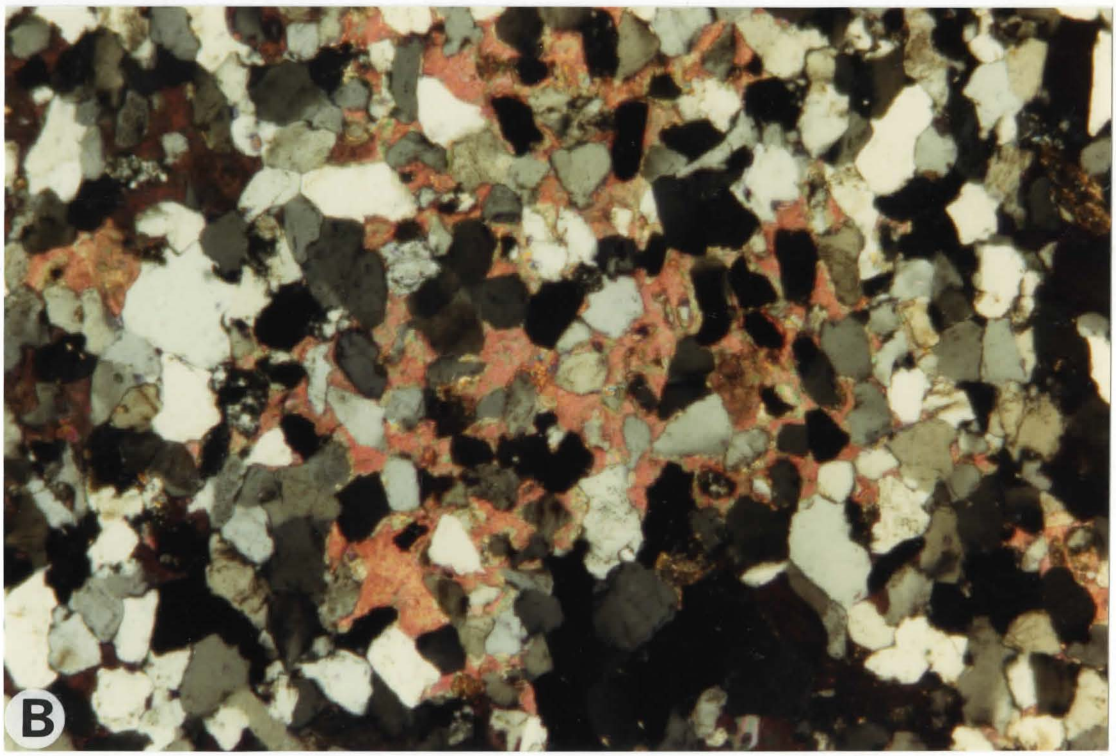
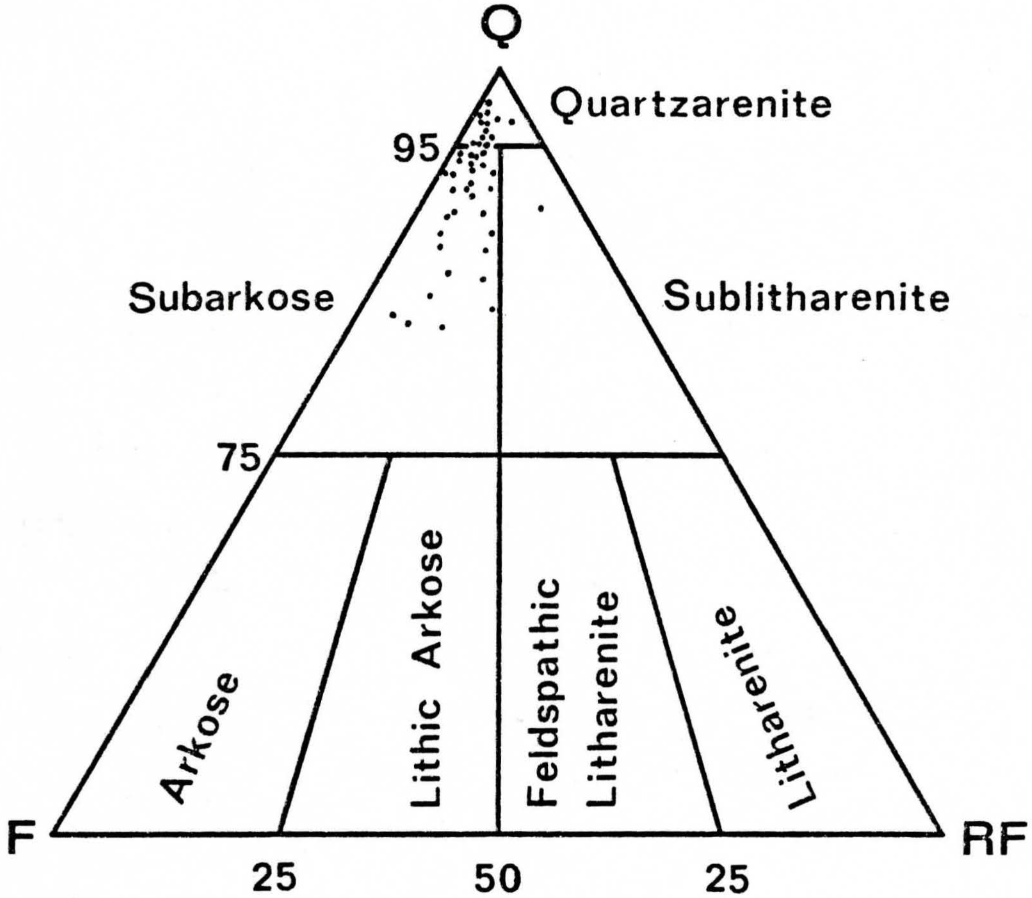
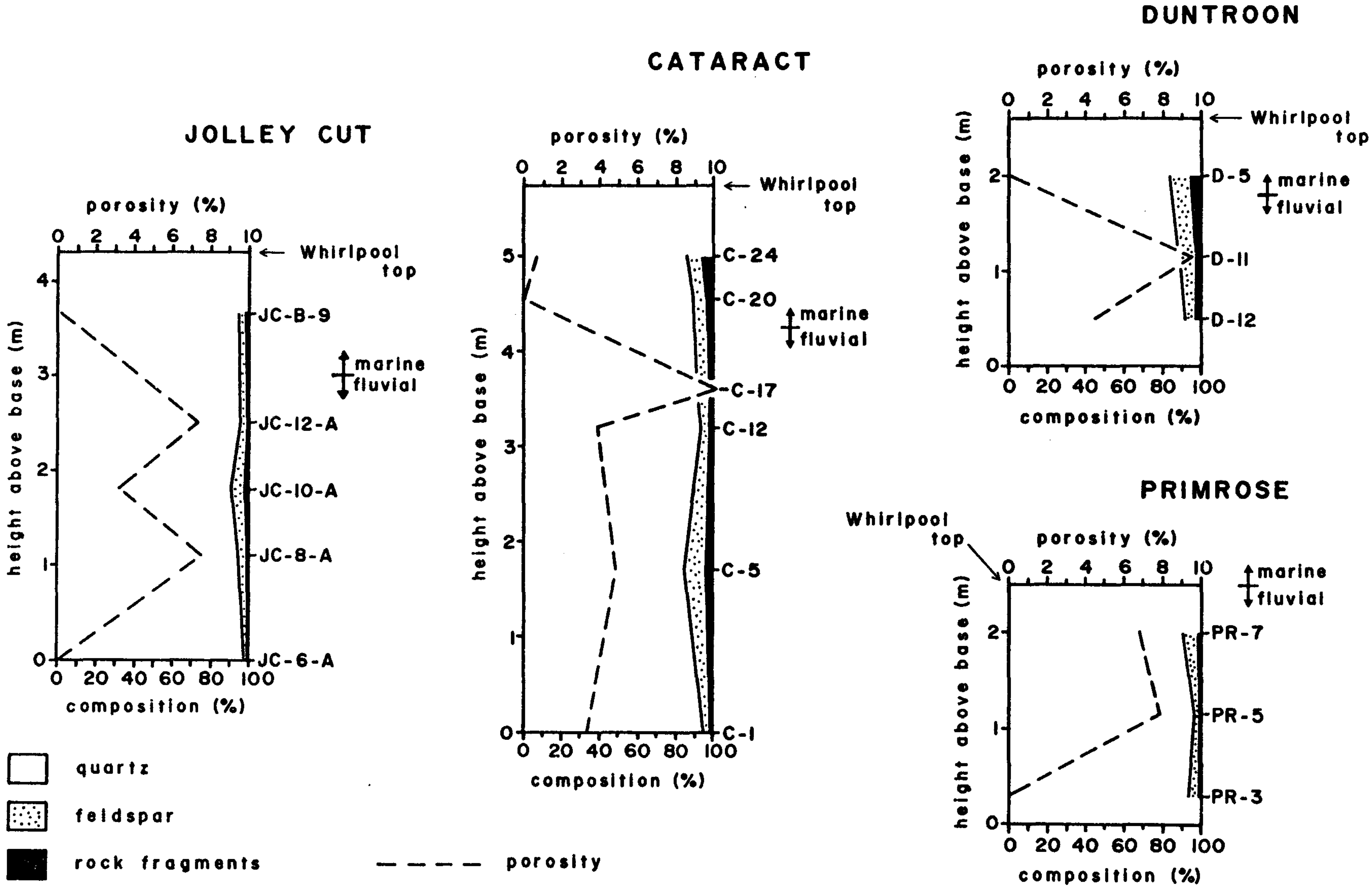

B

Figure 6-3. Diagram showing the composition of the Whirlpool's sandstone samples (the two siltstone samples have not been plotted). The majority of the samples fall within the area designated as subarkose. Q = quartz plus polycrystalline quartz, F = feldspar, and RF = rock fragments plus chert. Classification scheme is from Folk (1974).



Q
Quartzarenite
95
Subarkose
Sublitharenite
75
Arkose
Lithic Arkose
Feldspathic Litharenite
Litharenite
F
RF
25
50
25

Figure 6-4. Variability of the sandstone composition and porosity at The Jolley Cut, Cataract, Primrose, and Duntroon sections. See text for discussion. The height of the samples at Duntroon are relative to the base of the exposure, not to the base of the Whirlpool.



JOLLEY CUT
porosity (%)
Whirlpool top
JC-B-9
JC-12-A
JC-10-A
JC-8-A
JC-6-A
marine
fluvial
height above base (m)
composition (%)
CATARACT
porosity (%)
Whirlpool top
C-24
C-20
C-17
C-12
C-5
C-1
marine
fluvial
height above base (m)
composition (%)
DUNTROON
porosity (%)
Whirlpool top
D-5
D-11
D-12
marine
fluvial
height above base (m)
composition (%)
PRIMROSE
Whirlpool top
porosity (%)
PR-7
PR-5
PR-3
marine
fluvial
height above base (m)
composition (%)
quartz
feldspar
rock fragments
porosity

Figure 6-5. Variability of the sandstone composition and porosity at the Lockport road cut and Niagara Glen sections. See text for discussion.

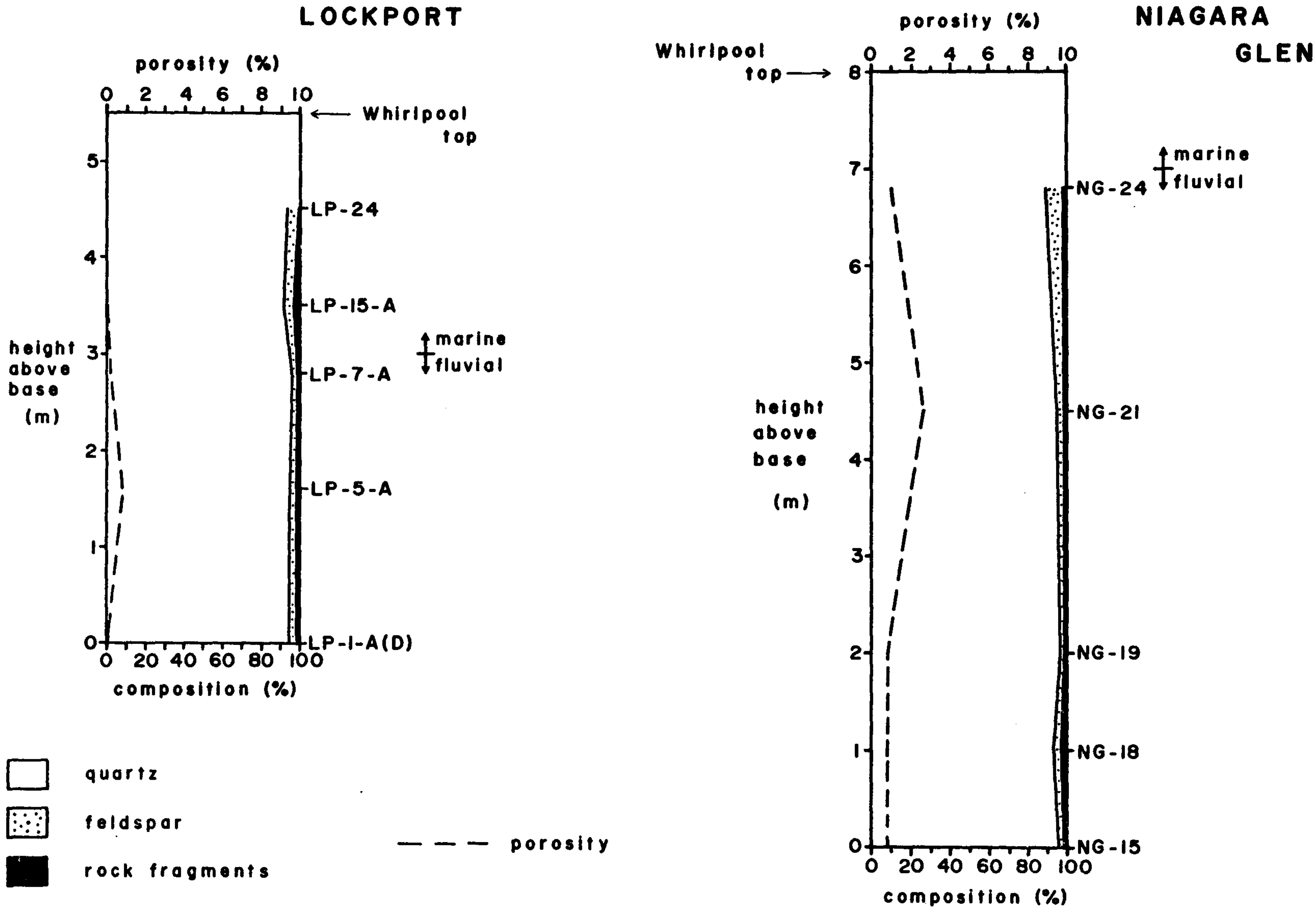
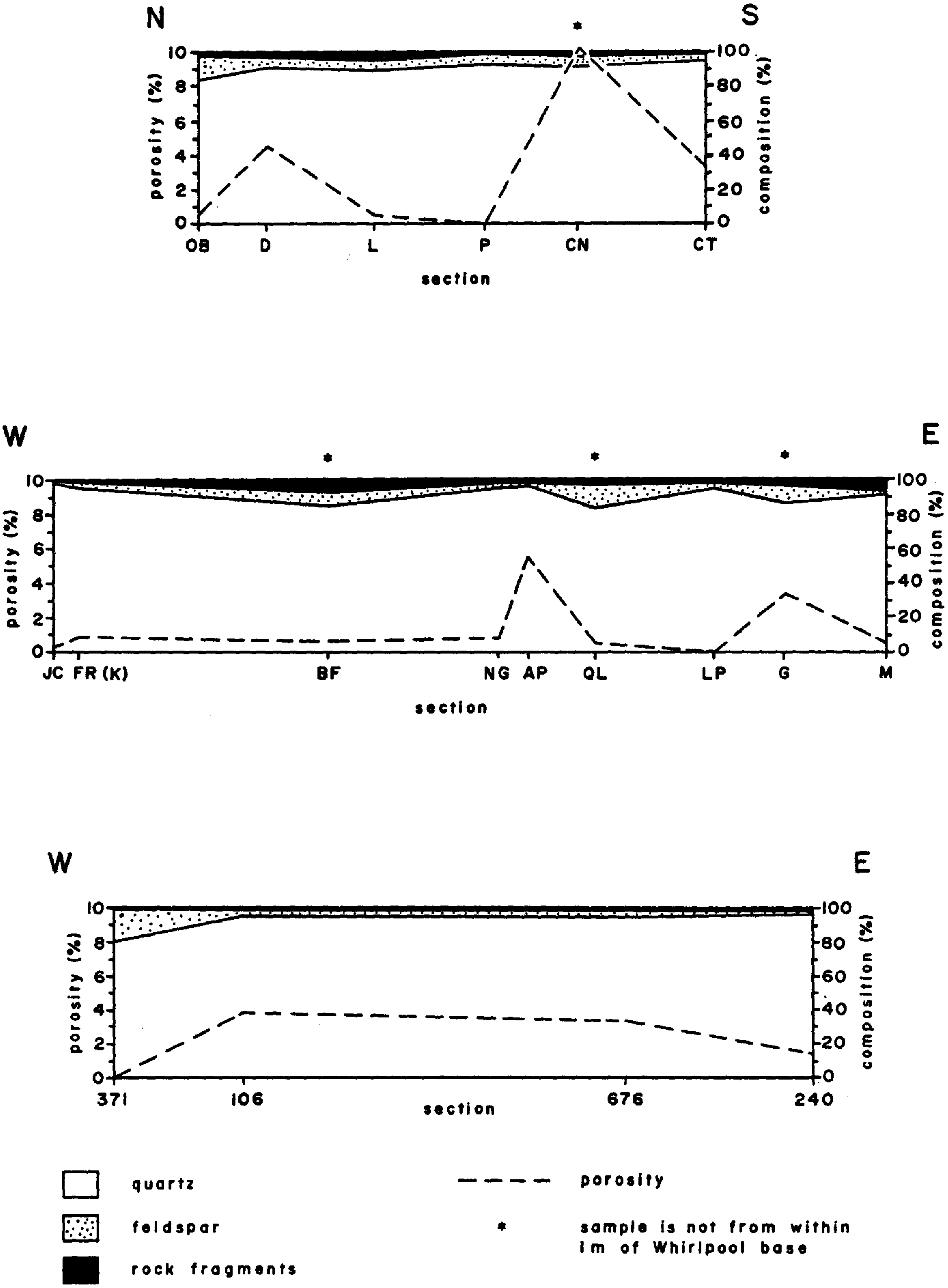

LOCKPORT
porosity (%)
0 2 4 6 8 10
Whirlpool top
height above base (m)
0 1 2 3 4 5
LP-24
LP-15-A
LP-7-A
LP-5-A
LP-1-A(D)
marine
fluvial
0 20 40 60 80 100
composition (%)
NIAGARA GLEN
porosity (%)
0 2 4 6 8 10
Whirlpool top
height above base (m)
0 1 2 3 4 5 6 7 8
NG-24
NG-21
NG-19
NG-18
NG-15
marine
fluvial
0 20 40 60 80 100
composition (%)
quartz
feldspar
rock fragments
porosity

Figure 6-6. Regional variability in the sandstone composition and porosity. The thin section data used for these graphs are from samples taken from within one meter of the Whirlpool's base. Asterisks indicate those sections where the thin section is from a sample located just above or as close as possible to the 1 m level. The horizontal scale shows the relative distance between sections. See Figure 1-1 for an explanation of the abbreviations used. FR = Kenilworth Avenue.



N
S
*
porosity (%)
composition (%)
OB
D
L
P
CN
CT
section
W
E
*
*
*
porosity (%)
composition (%)
JC
FR (K)
BF
NG
AP
QL
LP
G
M
section
W
E
porosity (%)
composition (%)
371
106
676
240
section
quartz
feldspar
rock fragments
porosity
sample is not from within 1m of Whirlpool base

75%) of the sandstone, and that the average percent framework is 11% higher in the lower unit (78%) than in the upper (67%). The essential constituents, quartz, feldspar, and rock fragments, make up approximately 98% of the framework, while phosphatic grains, opaques, and other heavy minerals constitute the remaining 2%.

Quartz

Quartz is by far the most important component of the Whirlpool, constituting between 81% and 98% (average is 92%) of the framework. The quartz grains appear to be rounded and moderately to highly spherical, but because of the high degree of authigenic syntaxial quartz overgrowth cementation and the frequent lack of grain inclusions and dust rims (which are used to distinguish grain from overgrowth), it is difficult to make a definite statement about the roundness and sphericity of the quartz grains. Some grains even show evidence of having rounded, or worn, overgrowths, indicating a second cycle or multicycle origin.

The quartz grains are predominantly single-crystals, showing straight and sometimes slightly undulose extinctions. Semi-composite (Folk, 1974) quartz grains, showing slightly undulose extinction, and polycrystalline quartz (chert not included) grains, displaying a variable number of subcrystals with straight to crenulated boundaries and straight to slightly undulose extinctions, constitute less than 2% (on average) of the total quartz present.

Inclusions, such as vacuoles and microlites, occur in a small percentage of the quartz grains. Their abundance within a single grain ranges from very low (one or a few crystals) to very high. The microlites are anhedral to euhedral (needle-like) in form and consist primarily of zircon, tourmaline, biotite, and sillimanite. Vermicular chlorite inclusions also occur.

The original grain boundaries of the quartz are usually protected by the quartz overgrowths, but where the grains float in carbonate or sulfate cements, quartz overgrowths are absent and the original grain boundaries are embayed and often corroded by these other cements (see Fig. 6-8).

Feldspar

The percentage of feldspar grains in the framework ranges from 1% to 18%, but generally averages less than 8%. Alkali feldspars (mostly orthoclase and some microcline) are the most abundant, making up 35% to 100% and generally averaging greater than 85% of the total feldspars, while the percentage of plagioclase (mostly untwinned) ranges from 0% to 65% and averages less than 15%.

The feldspar grains generally appear to be rounded and moderately to highly spherical, despite the fact that their original outlines are often obscured by syntaxial overgrowths, corrosion by other pore-filling cements, and dissolution, forming porosity. Syntaxial overgrowths of K-spar are sometimes well developed, forming rhombohedral crystals.

Clay alteration (sericitization, kaolinization, and vacuolization) of the feldspars is neither common nor well developed where present; however, many of the feldspars do show some form of replacement (ranging from corroded borders to total replacements) by calcite and/or dolomite. Dissolution, ranging from minor to total, is present in some of the feldspars and is generally responsible for up to 20% of the porosity present in the samples.

The percentage of feldspar in the Whirlpool is variable and shows no well developed trends either regionally or vertically (Figs. 6-4 to 6-6); however, it appears that the feldspar content is slightly higher at the northwesternmost (Osler Bluff, Duntroon) and westernmost (core 371) sections.

Rock Fragments

Rock fragments, ranging from 0.3% to 7% and averaging 2% of the total framework, include mainly sedimentary rock fragments (SRF) and metamorphic rock fragments (MRF). SRF are the most abundant (ranging from 50% to 100% of the rock fragments) and include primarily chert (generally comprising greater than 40% of the SRF) and minor amounts of siltstone and silty shale fragments. The MRF consist of both high and low grade types; the latter may often be confused with some SRF. All the rock fragments are well rounded and moderately to highly spherical in shape. Some of the softer grains show evidence of being squashed between or molded around other, more competent grains.

One sample (MED-2), from Medina, is a sub(calc)litharenite and contains the only occurrence of carbonate lithoclasts in the study area (Fig. 6-2). These carbonate grains, which comprise 7% of the framework, are very well rounded, highly spherical, medium-grained, micritized ooids and minor echinoderm fragments. Such carbonate lithoclasts are present in the lower part of the Queenston shale, as well (Dr. G.V. Middleton, pers. comm., 1986).

Heavy Minerals

Four groups of heavy minerals (Folk, 1974)--opaques, micas, ultrastables, and metastables--are present in the Whirlpool, and together they constitute, on average, less than 2% of the total framework.

Hematite, magnetite, chalcopyrite, pyrite, limonite, and trace amounts of chromite (?), and leuxocene (?) all constitute the opaque heavy mineral suite. Some of these minerals (pyrite, hematite), however, also occur as replacement cements. In general, if the mineral has an irregular or rounded, grain-like form, it is assumed to be detrital in origin and therefore counted as part of the framework. Some of these 'questionable' detrital opaques are found concentrated along the tops of laminations, further lending credibility to their detrital origin. Hematite, apart from occurring as detrital grains, also occurs as coatings around other detrital grains. These coatings may also be detrital or partially detrital in origin (Seyler, 1981).

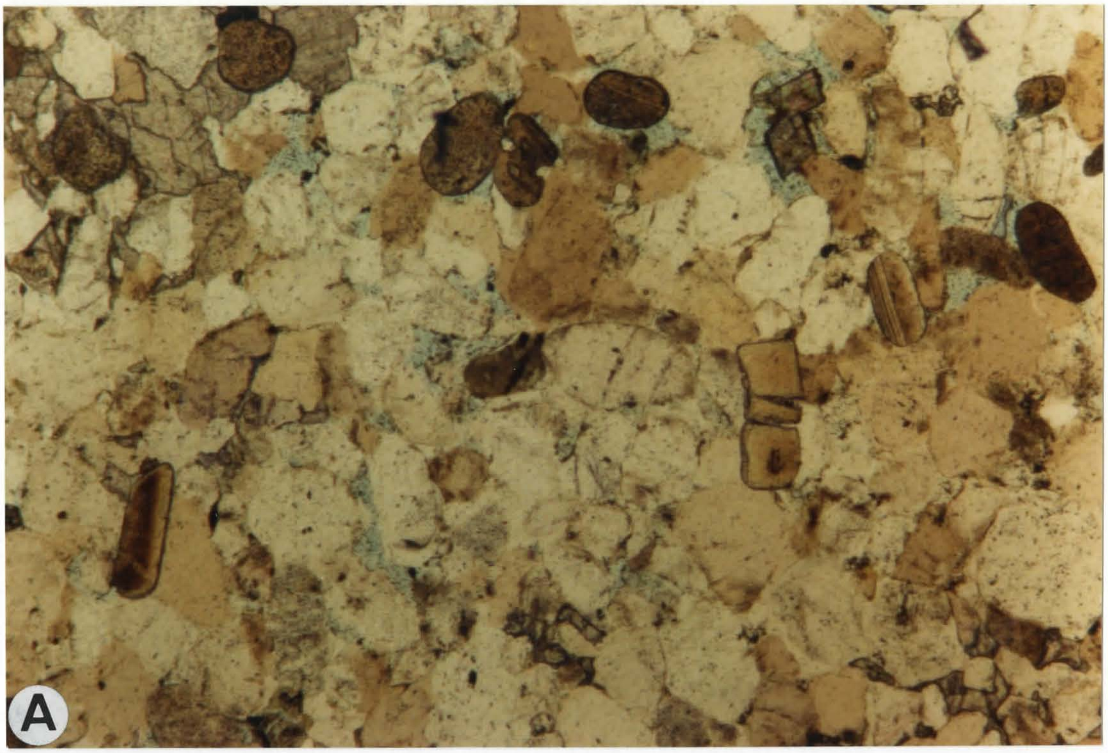
Detrital muscovite was the only mica observed in the samples. It generally occurred as elongate grains squashed between two other framework grains.

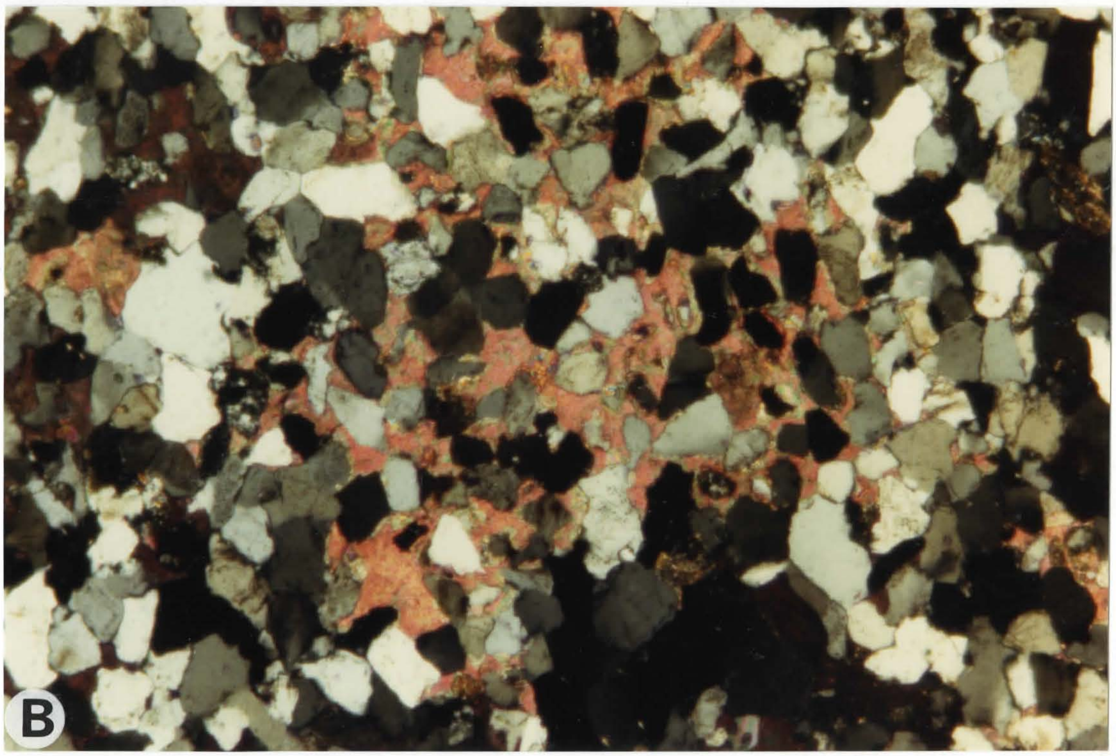
Of the ultrastable heavy minerals, only zircon and tourmaline were observed. They are silt-sized, very well rounded, and occur evenly dispersed in the thin sections, although they may, at times, like the opaques, be concentrated along planes of lamination in the horizontal and current ripple cross-laminated facies. Holstein (1936) noted that zircon seems to be more abundant in the lower part of the Whirlpool.

The metastable heavy minerals are represented in the Whirlpool by phosphatized fossil fragments (Fig. 6-7). They constitute 0% to 2.7% (average is 0.6%) of the total framework, and are largely responsible for the salt-and-pepper appearance of the Whirlpool's sandstone. Fisher

Figure 6-7. Photograph showing numerous phosphatized fossil fragments. They are amber to dark brown in colour (in plane light), and are usually elongate and very well rounded. Most show no internal structure, but some, like those at the top of the photo, show structures resembling fragments of echinoderms. Note that one of these grains (the rectangular-shaped one) has been broken in two places. The blue is porosity. The thin section has been stained for calcite and feldspar. Thin section 106-1, plane light, 40 X.

Figure 6-8. Photograph showing patchy calcite cementation, with the calcite (pinkish orange) displaying a poikilotopic and/or interlocking mosaic texture. Notice that the quartz grains set in this cement lack quartz overgrowths and that their grain boundaries are being corroded by the cement. The darker, (brownish) areas of the cement are phantoms, feldspar grains almost totally replaced by calcite. The thin section has been stained for calcite and feldspar. Thin section LP-1-A(D), cross-polarized light, 40 X.


A


B

(1954) and Caley (1940) attributed this appearance to the presence of magnetite and black chert, respectively. In thin section, the phosphate grains are generally amber or dark brown under plane light, and isotropic under polarized light. They are very well rounded, elongate, or elliptical, in shape, and are usually the same size (average is very fine-grained) as or less than the modal size of the framework. Internally, the phosphate grains are usually structureless, but some do show structures resembling fragments of (in order of abundance) echinoderms, bryozoans, ostracods, ooids, and other, unknown fossils. The high degree of roundness and fragmented nature of these phosphatized fossil fragments suggest a second cycle or multicycle origin for these grains. Post-depositional changes to these phosphate grains include: 1) snapping, or bending; 2) corrosion or partial replacement by quartz, calcite, and dolomite cements; 3) pressure solution; and 4) partial dissolution, forming porosity. The abundance of these phosphate grains is variable and does not show the vertical or regional trends suggested by Holstein (1936), Seyler (1981), and Calow (1983).

CEMENTS

The Whirlpool is a very highly cemented (total cement ranges from 10% to 43% and averages 21% of the rock) sandstone. Quartz is the major cementing agent, but (in order of abundance) calcite, dolomite, feldspar, pyrite, gypsum, anhydrite, hematite, and barite also occur. Calcite and dolomite cementation is generally greater than normal near the base of and in the upper part of the Whirlpool.

Quartz cement, ranging from 4% to 24% of the sandstone, occurs primarily as syntaxial overgrowths on detrital quartz grains. The occasional lack of dust rims and/or inclusions within the quartz grains can make it difficult to distinguish between grains and the cement; as a result, the percentages listed in Table 6-1 may be slightly inaccurate. Both intermediate and advanced stages of authigenic quartz overgrowths are present. The intermediate stage is marked by euhedral crystal faces, and the advanced stage, by irregular, or sutured, boundaries, which form when there is a mutual interference of neighbouring overgrowths. Clay is sometimes present between neighbouring overgrowths, and it may be responsible for impeding, or preventing, further growth of the euhedral quartz overgrowths. Quartz also occasionally occurs as a replacement of calcite.

The amount of calcite in the Whirlpool ranges from 0% to 18%. It's most common occurrence is as a primary pore space filler, filling in pores left behind by incomplete quartz overgrowth cementation. Calcite cementation in the Whirlpool is generally patchy, and where it does occur, framework grains are dispersed and the cement exhibits a poikilotopic and/or interlocking mosaic (single crystal cementation) texture (Fig. 6-8). Calcite also occurs as a replacement of quartz, feldspar, rock fragments, and phosphate grains. Replacement may be partial, as shown by corroded grain boundaries, or complete, as is quite often the case with feldspar replacement. A few small oriented residuals (phantoms), which still take the feldspar stain, are the only evidences of the pre-existing feldspar grains.

Dolomite, occurring as a replacement of calcite and sometimes associated (replacing?) with gypsum and anhydrite, ranges from 0% to 38% (average is generally less than 5%) of the sandstone. The crystals are sometimes euhedral in form, and like the calcite cement, they, too, corrode and embay the framework grains.

Feldspar cement occurs as authigenic overgrowths on detrital feldspar grains. The cement is mainly K-spar, and depending on the amount of pore space, the overgrowths may be subhedral to euhedral (rhombohedral) in form.

Gypsum and anhydite are not volumetrically important cements in the Whirlpool, being present in only 30% of the samples examined. Their occurrence is generally patchy, and is unrestricted to any particular portion (vertical) of the Whirlpool. They commonly exhibit a poikilotopic cementation texture.

Pyrite, too, is unrestricted in its vertical distribution, but is most abundant at the base of the

Whirlpool. It generally occurs in euhedral form, lining burrows, replacing (?) (or in association with) calcite cement, and filling pores and veins.

The presence of hematite, causing red coloration in the Whirlpool, is very obvious at a few localities (e.g. Hilltop Quarry, Salas, 1983; and the Niagara Gorge). The hematite, commonly interspersed with clays, generally occurs as very thin crusts lining the detrital framework grains and/or their syntaxial overgrowths.

CLAY

Clay (mostly illite; Calow, 1983), lining detrital grains and/or their syntaxial overgrowths, is generally present in trace amounts in the Whirlpool. More commonly, clay is found in shale rip-ups and along shale partings in the sandstone; in this way, the clay, whose presence is largely facies controlled (mainly S/F, Srs, and Src), may constitute up to 18% of the rock. Clay also occurs as an alteration of feldspar.

POROSITY

Porosity in the Whirlpool is rather low (ranging from 0% to 10% and averaging less than 3%) due to the high degree of syntaxial overgrowth and pore filling cementation.

Much of the porosity is secondary in origin, but primary pore spaces are present, as well.

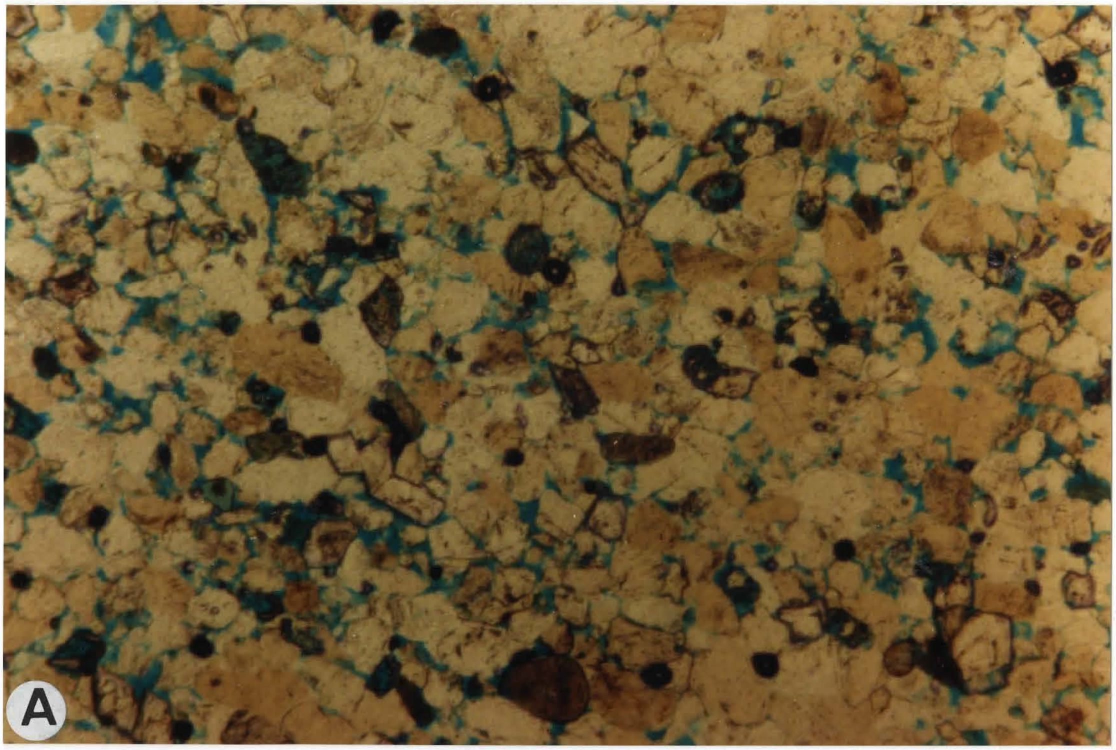
According to Scholle's (1979) classification scheme (which is a modified version of the classifications of Schmidt, McDonald, and Platt, 1977, and Choquette and Pray, 1970), the Whirlpool's secondary porosity is complex, and consists of a combination of three types: 1) dissolution of soluble framework grains; 2) dissolution of authigenic cements; and 3) dissolution of authigenic replacement cements. The three are of equal importance as contributors to the Whirlpool's porosity. Most of the features diagnostic of secondary porosity (Schmidt, McDonald, and Platt, 1977) are present: partial dissolution of framework grains (in this case, feldspars, rock fragments, phosphate grains, and quartz) and cement (calcite, dolomite, quartz and feldspar overgrowths), elongate pores, corroded grain and overgrowth margins, honeycombed grains, oversized pores, and inhomogeneity of packing (Fig. 6-9).

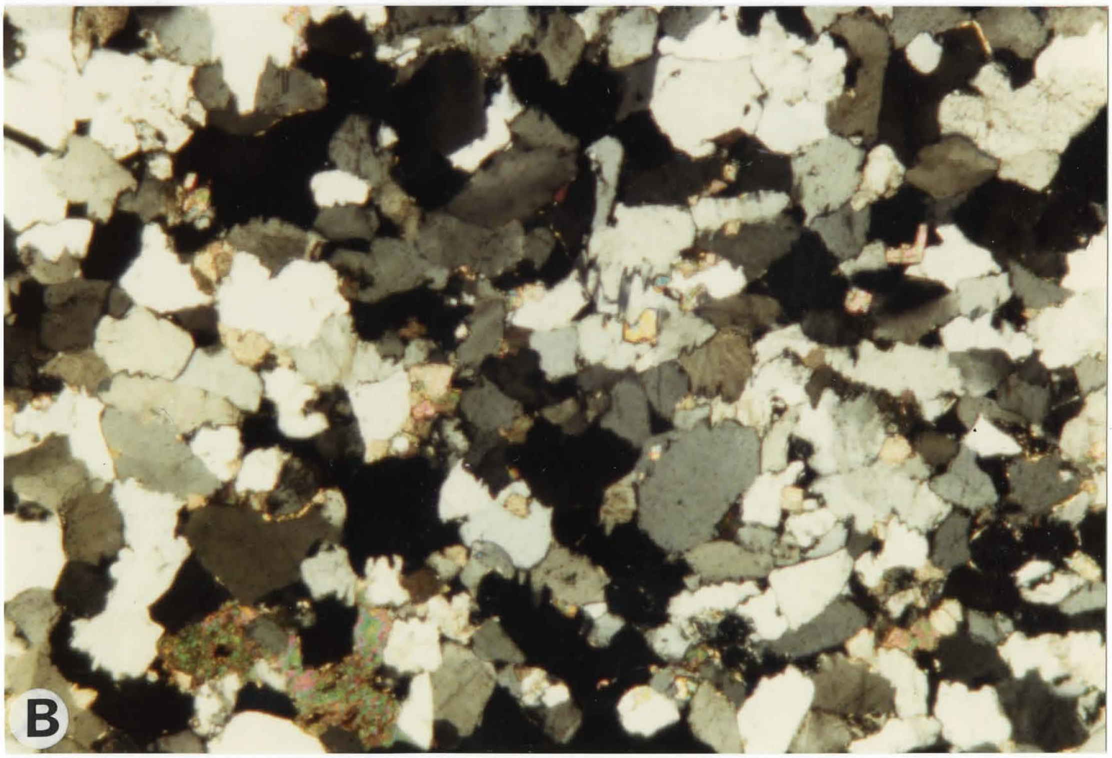
Most primary porosity in the Whirlpool has been obliterated by overgrowth and pore-filling cement, but where primary pores are present, they are bounded by euhedral quartz and feldspar crystal faces, indicating that only early or intermediate stages of overgrowth cementation are present in the pore.

The regional and vertical variability of the Whirlpool's porosity is plotted with the composition in

Figure 6-9. Photograph showing secondary porosity (blue areas) in the Whirlpool. Note the dissolution of feldspars (honeycombed grains) and authigenic cements, the corrosion of quartz grain boundaries and the inhomogeneity of the packing. The thin section has been stained for calcite and feldspar. Thin section CAN-1, plane light, 40 X.

Figure 6-10. Photograph showing suturing of quartz grain contacts. These sutured contacts generally occur in seams, parallel to bedding. Also notice the corrosion of grain boundaries by calcite and dolomite. Feldspar grains (only remnants remain) are being replaced by calcite cement in the lower left part of the photograph. The thin section has been stained for calcite and feldspar. Thin section 676-2, cross-polarized light, 40 X.


A

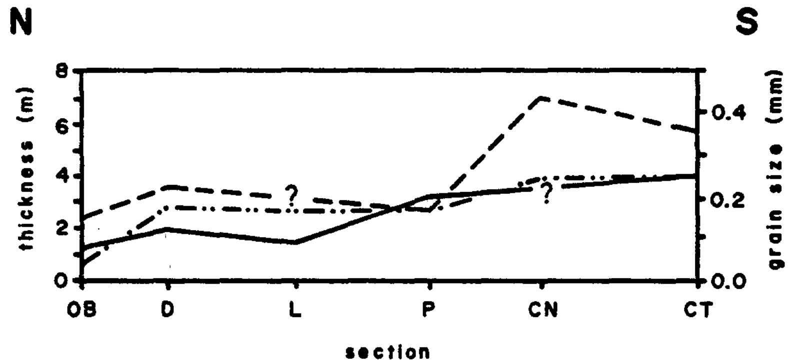

B

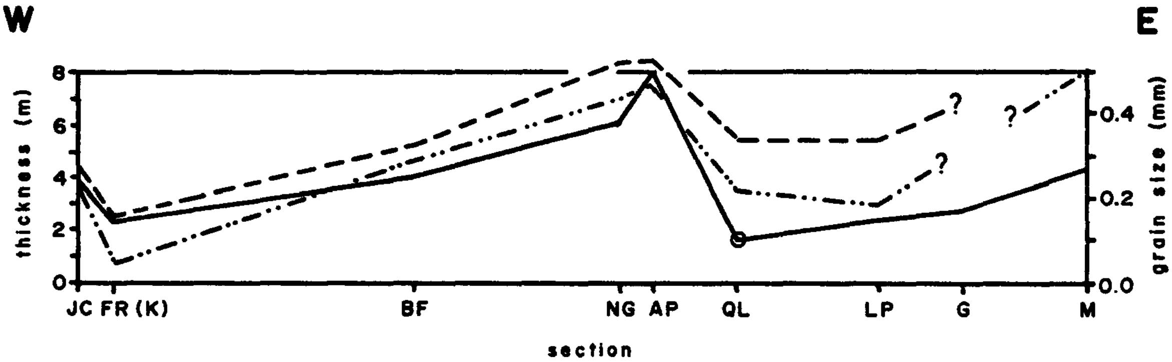
Figures 6-4 to 6-6. The porosity shows no regional or vertical trends, and contrary to what may be expected (Bjorlykke, 1983), the amount of porosity in the Whirlpool does not appear to be directly related to the percentage of feldspar, nor does it appear to be directly affected by the amount of calcite (see Table 6-1); instead, the amount of porosity in the Whirlpool is most likely the result of a complex interaction of several components, namely feldspars, calcite, rock fragments, and shale rip-ups. Feldspar dissolution appears to account for only about 20% of the total porosity.

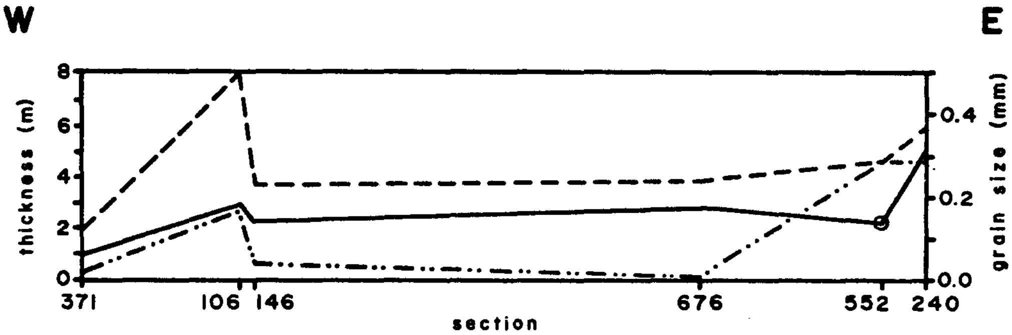
TEXTURE

The Whirlpool's grain size ranges from 0.06 to 0.5 mm, but generally (75% of the samples) averages between 0.0625 and 0.25 mm (very fine to fine sand). The vertical grain size variation can be seen from the section diagrams in Chapter 4. At most localities the Whirlpool shows an overall fining-upward trend, and in areas where the Whirlpool is thickest (e.g. in the Niagara Gorge), it is apparent that there may be two or more fining-upward cycles superimposed on this overall trend. Regionally (Fig. 6-11), the Whirlpool's grain size (within one meter of the base) is quite variable, but it has a tendency to be finer in the more northern and western sections. Figure 6-11 also plots

Figure 6-11. Diagram showing the regional variability of and the relationship between the Whirlpool's grain size and thickness. Note that two thicknesses are shown: the thickness of the lower Whirlpool and the thickness of the entire Whirlpool. The graphs are intended to show the grain size variability of the Whirlpool within one meter of its base. Those samples not from within this interval are indicated with a "?". The horizontal scale shows the relative distance between the sections.







O slightly higher than 1m above Whirlpool base

? grain size near base or thickness unknown

— — — — top of Whirlpool

—·—··—··— top of lower unit

———— grain size

regional thickness variations, in the Whirlpool. There clearly seems to be some direct correlation between the grain size and thickness (either total thickness or thickness of just the lower part) of the Whirlpool, but this is not a 1:1 correlation, and it is not expected to be, considering the variable amount of scouring the Whirlpool has undergone (see Chapters 7 and 8).

The determination of roundness, sphericity, and sorting of the framework grains was somewhat hindered by the high degree of quartz overgrowth cementation. Generally, the grains appear to be rounded (range is subrounded to well rounded), moderately to highly spherical, and well to very well sorted. Only one or two samples show bimodality of grain size. No obvious regional trends in the above three textural parameters appear to be present.

Grain contacts are primarily point to point (some are long), forming an intact framework. Stylolitic seams are present in a few of the thin sections and are characterized mainly by concavo-convex and sutured grain contacts (Fig. 6-10). Calow (1983) noted a decrease in the average number of grain contacts towards the northwest, and attributed this to the shallow depths of burial basin-edge sediments generally experience.

The Whirlpool is texturally a supermature sandstone (Folk, 1974), but it sometimes displays a textural inversion due to the presence of variable amounts of clay.

CATHODOLUMINESCENCE ANALYSIS

Due to time considerations, a cathodoluminescence (CL) analysis of the Whirlpool was not attempted in this study; however, what is described here are the results of an analysis performed by S. Leggitt (pers. comm., 1986) to determine the minus-cement porosity of the Whirlpool Sandstone. The analysis involved the point counting (350 to 1950 points per slide) of a series of colour photographs taken under a Luminescope of five of the thin sections used in this study (C-24, LP-7-A, JC-6-A, JC-8-A, and JC-12-A).

The results of the CL analysis compare well with those of this study. Only minor differences occur, which may be due to operator error, to ineffective staining, and/or to limitations imposed by the use of the petrographic microscope. Although the sandstone classifications remained unaffected, a comparison of the results from the same thin sections showed that in this study the percentage of quartz grains in the rock was, on average, generally overestimated by about 4%, and silica cement, by about 2% while the percentages of feldspar grains and calcite cement in the rock were generally underestimated by about 1% and 4%, respectively.

The following summarizes the findings of the CL analysis on the Whirlpool Sandstone: 1) plutonic and volcanic, low grade metamorphic, and hydrothermal detrital quartz types are present; 2) the plutonic and volcanic and low grade metamorphic types are the most abundant, with the latter generally being twice as abundant as the former; 3) the metamorphic quartz grains also show greater corrosion of the grain boundaries by calcite cement than the igneous quartz grains; 4) the percentage of feldspar in the framework averages about 6% (which is about 1% greater than that which was determined in this study); 5) calcite cement in one sample (C-24) of the upper Whirlpool forms distinct horizontal layers, which may be the result of precipitation from pore waters migrating along bedding plane surfaces or the result of the dissolution of shelly material that was, at one time, concentrated along bedding plane surfaces; 6) minus-cement porosity (the porosity after removing the cement) averages 29% in the Whirlpool; 7) coarser Whirlpool sands tend to have higher minus-cement porosities than finer ones; 8) coarser Whirlpool sands have proportionally more silica cement than finer ones; 9) the abundance of tangential grain contacts suggests early cementation; and 10) from average minus-cement and present porosity values, it is calculated that up to 15% of the Whirlpool's silica cement can be accounted for by grain contact dissolutional processes; the rest probably came from the diffusion of silica from adjacent shales.

DIAGENETIC HISTORY

An in depth discussion of the Whirlpool's diagenesis is beyond the scope of this study. It is a topic that has been covered more thoroughly by Calow (1983), and will be discussed only briefly here.

The first stage in the diagenetic history of the Whirlpool was the reduction of initial porosity due to the mechanical compaction of the grains during burial (depths of burial reached a maximum of 900 to 1400 m; Calow, 1983). Quartz and feldspar, derived from pressure solution, shales, or basin-derived migrating pore fluids, and precipitated as syntaxial overgrowths on quartz and feldspar grains, were the first cements to form. In most cases, cementation reached advanced stages and occluded all primary porosity; however, some areas received only intermediate stages of cementation, and the remaining pore spaces were filled later by calcite and, in some areas, pyrite cement. The source of the calcite is not known; the calcite present in the lower part of the Whirlpool was possibly derived from calcium rich pore fluids migrating up dip from the southeast, and the pyrite, from H_2S rich solutions also originating from the southeast (Calow, 1983). The calcite in the upper unit, however, may be due to the redistribution of carbonate derived from the dissolution of calcareous shells. During and/or following the calcite precipitation, partial or total replacement by calcite of the framework grains and earlier cements occurred. Pyrite replacements of quartz, feldspar, phosphate grains, and calcite may have occurred also at this time. Alteration of the feldspars may have provided the source for some of the clays present.

The final stage of diagenesis involved the formation of secondary porosity. Feldspars, rock fragments, phosphate grains, and quartz and calcite (authigenic and replacive) cements were all affected to varying degrees.

PROVENANCE

A second cycle or multicycle origin for the Whirlpool has been suggested by a number of previous workers (Grabau, 1913; Williams, 1919; Alling, 1936; Holstein, 1936; Seyler, 1981), and is further supported by the findings of this petrographic study. This conclusion is based on the following observations: 1) the Whirlpool is a mineralogically mature sandstone (subarkose to quartzarenite), consisting primarily of quartz and minor amounts (generally less than 10%) of feldspar and rock fragments; 2) all grains are rounded, moderately to highly spherical, and very well sorted, producing a texturally supermature sandstone; 3) the nonopaque ultrastable and metastable groups form the bulk of the heavy minerals present in the Whirlpool, and consist primarily of well rounded zircon, tourmaline, and phosphatized fossil fragment grains; 4) rounded chert grains constitute most of the rock fragment fraction; 5) polycrystalline quartz is not abundant, representing less than 2% of the total detrital quartz present; 6) detrital feldspar constitutes on average less than 8% of the total framework; 7) plagioclase (plagioclase may be highly unstable under stream transport) is primarily untwinned, and constitutes less than 15% of the total feldspar present; and 8) a few rounded quartz overgrowths are present (Pittman, 1970; Pettijohn et al., 1973; Folk, 1974; Blatt et al., 1980).

The source of the Whirlpool's sediments is unknown; however, most workers agree that the sediments were derived from a pre-existing sandstone situated in the Appalachian region (Williams, 1919; Alling, 1936; Holstein, 1936; Fisher, 1954; Calow, 1983). From Calow's (1983) work, it appears that the Whirlpool may have been derived from a recycled orogenic terrain with minor input from low grade metamorphic and hydrothermally veined terrain. Fisher (1954) has suggested that the Oswego Sandstone may possibly be the Whirlpool's source rock, and this is further supported by the Oswego's facies distribution and the location of its erosional edge (Henderson and Timm, 1985; see Chapter 9 for further discussion). The presence of carbonate lithoclasts in the eastern part of the study area (Medina) suggests that more than one source may have supplied the sediments in that area.

CONCLUSIONS

In keeping with the original intention of this petrographic study, the following conclusions can be made: 1) the Whirlpool is a subarkose to quartzarenite; minor compositional variations occur vertically and regionally, but no trends are developed; 2) feldspar (mostly K-feldspar) content, which averages less than 8%, shows minor regional and vertical variability, but no major trends, other than being higher at the most northwestern and western sections, are present; 3) the Whirlpool's porosity (ranges 0% to 10%, averages less than 3%), which is primarily secondary, is variable both regionally and vertically, showing no trends, and is apparently not directly related to the amount of detrital feldspar or calcite cement present; 4) the grain size, which is very fine to fine, shows an overall fining upward at most sections; regionally, the grain size is variable (related in some way to the Whirlpool's thickness), but tends to be finer in the more northwestern and western sections; and 5) no obvious and detectable trends in roundness, sphericity, and sorting are present.

CHAPTER 7

FACIES AND SECTION INTERPRETATIONS

This chapter draws on the data presented in the previous chapters to provide interpretations of the facies, facies assemblages, and environment of deposition of the Whirlpool. Chapter 8 then combines all the ideas presented here and in previous chapters to produce a depositional summary of the Whirlpool Sandstone.

DEPOSITIONAL ENVIRONMENT OF THE WHIRLPOOL

Because the facies and, in some cases, the facies assemblages comprising the Whirlpool could have formed in a number of very different depositional environments, it appears necessary, at the onset of this chapter, to present evidence that would greatly reduce the number of environments needed to be considered. The usual path followed in such environmental analyses involves producing a summary sequence, by Markov chain analysis, that can be compared to proposed models of various environments; however, due to the Whirlpool's thinness and local and regional variability in facies sequences, it is clear that another approach is necessary.

As has already been mentioned, the Whirlpool consists of two very distinctive units, an upper unit and a lower unit. Both of these units possess such different biological and physical characteristics that they surely represent two different depositional environments. The upper unit is clearly marine in origin, as is indicated by the presence of: 1) marine body fossils; 2) trace fossils; 3) marine organic microfossils; and 4) wave-formed structures. The lower unit, on the other hand, possesses a very strong terrestrial signature, as is suggested by: 1) the lack of body fossils and trace fossils (terrestrial organisms had not evolved by the Early Silurian); 2) the absence of wave-formed structures; and 3) the presence of only spore-like microfossils in the microfossil assemblage.

The Whirlpool's fine grain size, good sorting, absence of unstable detrital minerals and widespread red coloration, and presence of frosted grains have led some workers (Wilson, 1903; Williams, 1919; Lockwood, 1942, cited in Bolton, 1957; Fisher, 1954) to propose an aeolian origin for the lower Whirlpool. But the absence of sand flow structures and large scale, moderate- to high-angle cross-strata, and the presence of abundant trough cross-laminations may be sufficient evidence to disprove this theory (Brookfield, 1984; Collinson, 1978), and as was pointed out by Salas (1983), the fine grain size, good sorting, and stable heavy mineral suite can be explained equally well by the deposition of multicyclic sandstones in distal fluvial environments, and the frosted grains, by diagenetic effects. A shallow lacustrine depositional environment may similarly be ruled out, for its characteristic deposits--coarsening-upward sequences containing turbidites, varves, wave-formed structures, and chemical precipitates (Blatt et al., 1980)--are not present in the lower Whirlpool. So, by elimination, the fluvial environment remains to be considered, and comparing the Whirlpool's deposits with those of both modern and probable ancient fluvial deposits (e.g. Walker and Cant, 1984; Reading, 1978; Cant, 1982), and considering the textural characteristics (Salas, 1983), it appears that the lower Whirlpool is most likely fluvial in origin.

Anastomosing and straight river systems may be dismissed as possible mechanisms for the Whirlpool's deposition, based on the Whirlpool's sheet-like geometry and the lack of thick accumulations of vertical accretion deposits, which generally typify the deposits of such environments. Of the two remaining river system types, braided and meandering, the sandy braided river produces deposits that resembles better the features present in the Whirlpool. This conclusion is supported by the following observations made of the lower Whirlpool's deposits: 1) the Whirlpool is a sheet sandstone displaying regional variability in thickness and facies; 2) vertical accretion deposits are rare to absent; 3) lateral accretion deposits are not recognized (although Salas, 1983, reports the possible presence of one at the Milton quarry); 4) channelisation occurs in some areas and is characterized by vertical aggradation rather than lateral accretion; 5) paleocurrents are unidirectional, displaying good consistency, except those from planar tabular cross-laminations, which show high divergences from the grand vector mean; 6) vertical facies transitions are frequent, sharp, and characterized by erosive contacts; 7) sections show local lateral variability in the facies sequences; and 8) scour surfaces are present and form the base of stacked fining-upward sequences, indicating the lateral shifting and vertical aggradation of channels. A sandy braided river origin is also supported by the fact that in the Early Silurian, land vegetation, if at all present, was probably not abundant enough to support the existence of meandering river systems (Schumm, 1968).

With regards to the upper Whirlpool's depositional environment, the presence of wave-formed structures, shallow water features (e.g. wrinkle marks, and desiccation and synaeresis cracks), and shallow water fossils and trace fossils rules out the basin plain and continental slope environments. The grain size, too, in the upper Whirlpool's sandstone beds is somewhat coarser (3.5 - 3 phi, or very fine sand) than is generally found (silt) in these two environments. Similarly, the laterally continuous sandstone interbeds, the presence of traces comprising the *Skolithos* ichnofacies (generally indicative of high energy environments), the presence of "nonrestrictive" fossils, and the absence of any evidence suggesting the presence of a barrier (in the Whirlpool, Power Glen, Cabot Head, or Manitoulin) all rule out a lagoonal, or back barrier, depositional environment. An estuarine environment, too, is not likely, for its characteristic deposits and faunal assemblages--tidal sedimentary structures, channelised sands displaying large scale cross-bedding, marked lateral and vertical facies changes, and brackish faunal assemblages (Clifton, 1982)--are not present in the upper Whirlpool. Instead, the features and facies of the upper Whirlpool can be best accounted for by the processes operating in a nearshore shallow marine environment. Further details concerning this nearshore environment are discussed in the section concerning the interpretation of facies S/F, Shcs, and Sb (this chapter).

FACIES INTERPRETATIONS

Having now established the two depositional environments of the Whirlpool, the many possible interpretations for the various facies have been considerably reduced. This section proposes environmental and hydrodynamic interpretations for the facies of the lower (facies St, Src, Sh, Sp, Sl, Sm, Sc) and upper (facies S/F, Sb, Sw, Shcs, Sl) units in accordance with the proposed depositional environments.

Facies St

The migration of linguoid and lunate dunes under flow conditions in the upper part of the lower flow regime is responsible for the trough cross-laminations of facies St. In sandy braided fluvial systems showing some degree of topographic differentiation (e.g. the South Saskatchewan River), the greatest abundance of dunes occurs in the deepest portions of active channels (Miall, 1985a,b,c; Cant, 1982; Walker and Cant, 1984; Cant and Walker, 1978). They are generated here during flood stage, and continue to migrate throughout the waning stage, forming thick sequences of trough cross-laminations. Coleman (1969) reports thicknesses of up to 16 m being formed during single flood events of the Brahmaputra. The thickness of the trough cross-sets depends on the amount of bedload material available, the rate of migration, and the size of the dunes; the latter, in turn, appears to be directly related to the water depth (Cant and Walker, 1978; Reading, 1978).

Dunes also have been observed to be present in topographically higher, shallower channels, formed by falling stage bar dissection or avulsion during high stages and on submerged portions of bar and sand flat margins and tops, where they migrate during waning flood stages (Miall, 1977; Walker and Cant, 1984; Cant and Walker, 1978; Smith, 1970).

Because the greatest abundance of dunes occurs on channel bottoms during flood stage, and because during bankfull stage many small channels combine to form larger ones, the azimuths of trough cross-laminations are generally very good, consistent downstream indicators (Coleman, 1969). Of course, variability is introduced by the dunes present in the shallower channels and on bar tops, which are somewhat influenced by waning and low stage conditions.

Evidence of frequent stage fluctuations and catastrophic creation of new channels in the Whirlpool exposures of facies St is indicated by the presence of broad, shallow scour surfaces (Niagara Gorge). The large, rounded shale clasts that form a lag along these surfaces, and the smaller (1 cm) shale clasts lying within the trough cross-laminations, are indicative of the previous, but short, existence of vertical accretion deposits. Gibling and Rust (1984) describe similar features in the Morien Group, and suggest that bank collapse during falling water levels is responsible for these features. Mud supplied to channel floors in this way are further rounded, rolled, and/or transported, depending on their size, and become incorporated into the sediment record as lags on channel bases or as intraclasts within cross-beds. Because of the rapidly shifting nature of braid channels, abundant mud intraclasts should be expected in braided river deposits (Gibling and Rust, 1984).

The small to large (3 m to more than 40 m) channels, or scours, that cut through some of the exposures of facies St and, to a lesser extent, facies Sr are products of processes that occur during stage fluctuations. The larger channels (e.g. at Lockport) have composite fills (facies Sw, Sr, St) and show vertical aggradation rather than lateral accretion. These channels were probably formed by avulsion during high water stages, and later infilled during waning stages, or by progressive abandonment, caused by other avulsions farther upstream (Miall, 1977, 1985a,b,c). The smaller channels with composite fills probably represent bar dissection during waning flood stages (Cant and Walker, 1978; Miall, 1977; Blodgett and Stanley, 1980). Very small channels, or troughs (about 3 m wide), with symmetrical, homogeneous fills may be scour pool sediments formed in the lee of very large dunes. Orientation of these large and small channels and of the cross-bedding within them can deviate greatly from the downstream direction of the river, and cannot always be considered as representing the true paleocurrent direction of the system (Coleman, 1969; Cant and Walker, 1978).

In conclusion, thick (greater than about 1 m) accumulations of facies St in the Whirlpool probably represent in-channel deposits, while thinner accumulations most likely represent bar top, bar dissection or shallow channel deposits.

Facies Sr

Subfacies Src. The small scale cross-laminations of subfacies Src are due to the migration of sinuous- to linguoid-crested current ripples. Because they are lower flow regime bedforms, current ripples are generated during falling and low water stages mainly in the shallow areas of active braid channels (Miall, 1985a,b,c; Cant, 1982; Walker and Cant, 1984), although, in the Brahmaputra, ripples have been reported to occur at water depths of 33 m (Coleman, 1969). Such shallow areas include the tops of linguoid bars and sand flats (ripples and dunes are responsible for the transport of sediment to bar crests), the upper reaches of point bars, within dissection channels, and the stoss sides of dunes (which may be in dissection channels or on bars: Miall, 1977; Walker and Cant, 1984; Coleman, 1969; Smith, 1970). The cross-laminations produced by ripple migration have an erosional relationship with the underlying strata and their dip direction may be similar to or oriented 90 degrees away from that of the underlying cross-strata (Collinson, 1970). As noted in the Tana River by Collinson (1970), current ripples also occur in the lee of linguoid bars, where they form counter-current ripples, and also along the margins of these bars, where they laterally accrete during intermediate stages. The flow direction of the water producing the ripples in the latter case is generally parallel to the bar slipface. On distal braidplains subject to highly flashy discharge, ripples may form during the waning of flash, or sheet, floods, the deposits of which include mainly facies Sh and Sl (Miall, 1985a,b,c).

Capped-off current ripples, such as those observed at Duntroon, are formed at low stage by the planing action of waves acting on linguoid bars. They may also form subaerially under the abrasive action of saltating wind-blown sand (Collinson, 1970).

Climbing ripples, indicative of high rates of sedimentation (Harms et al., 1982), are typically found in levee deposits, but such deposits may not always be preserved in braided river sequences. In the Brahmaputra, where sediment supply is high, climbing ripples occur on the tops of larger bedforms (e.g. bars, megaripples), and the resulting cosets of cross-laminations may reach as much as 1 m during falling stage (Coleman, 1969).

Literature on the presence and formation of ripple fans in braided fluvial environments is meager. Similar features occur in the lee of dunes in the Barmouth Estuary, Wales (Allen, 1985; p. 65). The ripple fans present in the

Whirlpool are probably the result of runoff of water down dune slipfaces during falling and low water stages. If, at low stage, the dune becomes exposed and the scour pool collects water, these ripples may be further enhanced or modified by wind-derived water disturbances.

Subfacies Srs. Symmetrical ripples are the product of wave action; however, their occurrence is not necessarily restricted to marine or lacustrine environments. Those that do occur in marine settings form in a variety of environments ranging from shoreface to distal offshore. The interpretation of the symmetrical ripples present in the upper Whirlpool are discussed more fully with the facies S/F interpretation.

Symmetrical ripples have been observed in the Tana River by Collinson (1970). They are formed during falling stage by waves reworking current ripples on linguoid bars. Wave-formed symmetrical ripples may also form independently of earlier current ripples in areas between beach ridges, which develop on linguoid bar margins.

In conclusion, the various features of facies Sr in the Whirlpool were probably produced by ripples on bar tops and margins, in shallow channels, on braidplains, and in the lee of dunes and bars.

Facies Sh

The horizontal (plane) laminations of facies Sh are interpreted to be the product of plane beds formed under upper flow regime conditions (indicated by the presence of parting lineation and heavy mineral shadows) (Harms et al., 1982; Cheel, 1984).

In sandy braided rivers, plane beds formed during flood stage generally occur on the floors of active channels (Miall, 1977, Coleman, 1969). During falling and low water stages they may still be found on channel bottoms (Blodgett and Stanley, 1980), but most often occur on the tops of active transverse and linguoid bars and sand flats (in water depths less than 25 mm) (Smith, 1970; Cant and Walker, 1978). Low amplitude sandwaves, formed on bar tops under water depths of 5 to 15 mm and flow velocities of 14 to 34 cm/sec, may also produce horizontal laminations (Smith, 1971).

In the Brahmaputra, Coleman (1969) has noted the presence of horizontal laminations in crevasse splay deposits (composed of facies Sm, Sh, Sc, and Sr), but the preservation potential of such sequences may be very low in ancient braided river sequences.

Distal braidplain environments that show little topographic differentiation and experience highly flashy discharges are sites where thick accumulations (1 to 4 m) of horizontal laminations and minor ripple cross-laminations, planar tabular cross-laminations, low-angle cross-laminations, and convolute laminations may be deposited by a single sheet flow as occurred in Bijou Creek, Colorado (McKee et al., 1967). During waning stages, when flow is confined to main channels, horizontal laminations may occur on the floor of these channels.

In summary, facies Sh in the Whirlpool is probably the result of upper flow regime plane beds formed in channels during flood stages, on bars and sand flats during low stages, and on distal braidplains during sheet floods.

Facies Sp

The planar tabular cross-laminations of facies Sp result from the migration of transverse, linguoid, and diagonal bars and sandwaves in sandy braided rivers. The bars develop during flood stages and continue to migrate during waning stages due to the migration of dunes, ripples, and plane beds on their stoss side (Smith, 1970; Miall, 1977). The sandwaves, on the other hand, being lower flow regime bedforms, develop generally during falling stages.

Bars form in areas where there is flow expansion. During falling stage, when these bars become emergent, some may act as a nucleus for further deposition as other bars coalesce with them, producing sand flats (Cant and Walker, 1978) During subsequent floods, transverse and diagonal bars, sandwaves, and dunes are driven up onto the sand flats, giving rise to, in vertical section, large planar tabular cross-sets (the original 'nucleus' bar) overlain by smaller planar tabular cross-sets and minor trough cross-laminations and ripple cross-laminations. Such processes, as described above, have been observed in the South Saskatchewan River (Cant and Walker, 1978; Walker and Cant, 1984).

Apart from occurring on sand flat tops, sandwaves may also occur on point bars and in shallow, dissection channels (Miall, 1977; Cant 1982; Walker and Cant, 1984).

Bars and sandwaves undergo erosional and depositional modifications during low stages. Features commonly associated with planar tabular cross-strata and indicative of low water modifications include reactivation surfaces, capped off current ripples, symmetrical ripples, and accretions of current ripples (paleoflow parallel to strike of slipface) (Collinson, 1970).

Planar tabular cross-laminations may also occur in distal braidplain environments, where they form a small part of sheet flow deposits (see under facies Sr and Sh).

Because of the variable orientation of bars in braided rivers and the irregular shape of their crests, planar tabular cross-laminations produced from bars and superimposed sandwaves can be expected to show high paleocurrent divergencies from the main channel trend (Smith, 1972; Walker and Cant, 1984).

In summary, facies Sp in the Whirlpool is probably the result of bar or sandwave migration in main channels or dissection channels.

Facies Sl

The processes by which low-angle cross-stratification form in sandy braided rivers is not well understood (Miall, 1977). Some of the processes suggested for their formation include bar migration, shallow water flowing at low velocities, crevasse splays, and filling of scours (Reineck and Singh, 1980; Miall, 1985b). Thick sequences (up to 2.5 m; Miall, 1985b) of horizontal laminations and low-angle cross-laminations are common in the ancient record, and have been interpreted as the product of flash floods in ephemeral and distal braidplain deposits based on modern ephemeral stream studies by McKee et al. (1967) and Picard and High (1973).

Antidunes, which form in the upper part of the upper flow regime, produce low-angle cross-strata that dip both upstream and downstream at angles less than 10 degrees (Middleton, 1965; Harms and Fahnestock, 1965). Such cross-laminations, however, are very faint and are unlikely to be well defined or recognizable in the ancient record.

Cant and Walker (1976) and Bluck (1980) interpreted the low-angle cross-strata in the Battery Point and Old Red Sandstone, respectively, as floodplain, or vertical accretion, deposits.

Due to the lack of vertical accretion in the lower

Whirlpool, the possibility of facies Sl being the result of crevasse splays seems rather low. Likewise, the planar nature and high definition of the laminations rules out scour filling and an antidune origin, respectively. The facies associated with facies Sl (see Balls Falls, Jolley Cut, and Kenilworth section diagrams) are probably the best clues to its origin. Facies Sl, at Balls Falls and The Jolley Cut, is most likely a bar top facies formed during waning or low stages, while at Kenilworth it may be due to bar migration.

The occurrences of facies Sl in the upper part of the Whirlpool are associated with facies S/F and are probably the result of storm deposition within an otherwise low energy, nearshore environment.

Facies Sm

Truly massive, or structureless, sandstones are uncommon in fluvial deposits. Studies of modern braided rivers have shown massive sandstone to be present in crevasse splay deposits and in longitudinal bars (Coleman, 1969; Smith, 1970).

Most interpretations of massive sandstone in ancient braided fluvial deposits have been based primarily on its facies relationships. Massive sandstones forming the base of channels in the Kinderscout Grit have been interpreted by McCabe (1977) as having formed in the lee of large bedforms by the rapid movement of the reattachment point. Conaghan and Jones (1975) suggest falling-stage aggradation in scours is the origin of massive sandstones in the Hawkesbury Sandstone. However, Jones and Rust (1983) attribute its occurrence to the liquefaction of laminated sand followed by downslope movement. Large bedforms and channel banks, which provide the slope for such movement, accumulate large volumes of underconsolidated sand during major floods. Liquefaction can be triggered easily (by seismic shock, loading, changes in water level, impact waves) and can cause mass flow down foreset or bank slopes, resulting in massive sediments, if movement is great enough, and convolute laminations (Jones and Rust, 1983).

Massive sediments may also result from the rapid deposition of sediment from suspension during deceleration of a heavily sediment-laden current (Collinson and Thompson, 1982; Blatt et al., 1980).

Considering the facies associated with facies Sm in the Whirlpool, it appears that facies Sm was probably formed by two different processes. Those occurrences that are associated with facies Sc (see core diagrams) may indicate a process of formation involving liquefaction of laminated sediment and subsequent movement down a gentle slope (of a bar?) during rapidly changing water levels. The other occurrences of facies Sm (see northern sections) are associated with facies Sr, Sh, and Sw, and are more difficult to interpret. They may represent rapid deposition under a decelerating sheet flood that covered various areas of the floodplain or rapid deposition under waning flow in shallow channels of a more proximal environment (e.g. Cataract).

Facies Sc

Convolute lamination is caused by the plastic deformation of partially liquefied sediments soon after deposition (Collinson and Thompson, 1982). Liquefaction of braided river sediments may be brought on by rapid fluctuations in water levels, loading of sediment (either by bank collapse or rapid deposition), or shocks from seismic or water waves (Coleman, 1969; Bluck, 1980; Jones and Rust, 1983). Additional forces acting to deform the sediments include drag, from sediment-laden currents, and gravity, which causes the downslope movements (Doeglas, 1962; Blatt et al., 1980).

In modern braided rivers, convolute lamination or evidence of its presence (quicksand and sand volcanoes) has been reported to occur on bar margins, in natural levee and floodplain deposits, and in sheltered parts of the main channels (Coleman, 1969; Williams and Rust, 1969; Rust, 1972; Reineck and Singh, 1980). Ball-and-pillow structures, or flow rolls, may occur in channel bar deposits as well (Coleman, 1969). Jones and Rust (1983) attribute the deformed cross-strata in the Hawkesbury Sandstone to liquefaction and mass movement of bar and bedform foresets (see facies Sm).

Facies Sc of the Whirlpool includes convolute-laminated, ball-and-pillow, and possible minor slump structures, and each requires a somewhat different interpretation. Due to their appearance, the disturbed laminations present in the cores are interpreted as minor slump structures. Their association with facies Sm possibly suggests formation by mass movement down a foreset slope, although the presence of bars or bedforms is not indicated in two of the cores. At Balls Falls, the facies associations and the downcurrent dip of the convolute lamination's axial plane suggest deformation due to the current's shear stress acting on a bar top or on the bed of a dissection channel. The ball-and-pillow structures at the Artpark are more difficult to explain. The whole section represents in-channel deposition, but apparently there was a sudden decrease in the energy (avulsion?) producing the thin shale layer just below the ball and pillows. Reintroduction of sand and their subsequent disturbance may have produced the ball-and-pillow structures.

Facies Sw

Wavy laminations, such as those comprising facies Sw, represent regular changes in the transport or deposition of sediment, and are normally considered to be indicative of tidal environments (Reineck and Singh, 1980). Their presence in the sandy-braided part of the Whirlpool is therefore rather difficult to explain. Similar features were observed by Coleman and Gagliano (1965) in the levee deposits of the Mississippi River deltaic plain, but it is unlikely, considering the associated facies, that the Whirlpool's facies Sw is a levee or floodplain deposit. Facies Sw probably represents deposition of fine sand or coarse silt and mud in relatively shallow, topographically high channels that are only active during flood stages (corresponding to levels 2 and 3 of Williams and Rust, 1969). During low stage fines settle out in the pools of standing water, forming a continuous or discontinuous drape over the underlying bed. Wind-blown sand or a minor pulse in current activity may be the origin of the interlayers of sand. The characteristic waviness of these structures is probably a consequence of minor irregularities on the underlying surface.

As will be discussed in the next section, the upper Whirlpool is interpreted as having been formed in a nearshore, quiet water environment, where frequent storm activity resulted in the emplacement of layers of sand. In keeping with this interpretation, most of the occurrences of facies Sw appear to have formed in the more distal areas of this environment, with the sandstone:shale ratio possibly indicating the relative distances from shore (low values indicate greater distances). The wavy, thin, sandy interlayers may be the result of fine sand settling out of suspension onto an irregular muddy surface during and slightly after storms. Between these storm episodes, however, burrowing organisms disturbed the sediments to varying degrees. As an alternative explanation, facies Sw may in fact represent deposition closer to shore, with the sandy layers representing wind-induced wave disturbances.

Facies S/F, Shcs, and Sb

Facies S/F, Shcs, and Sb are interpreted as having formed in the same depositional environment, and therefore will be discussed together in this section.

As mentioned previously, the marine, or more specifically, the shallow marine, origin of these three facies is indicated by the presence of marine microfossils and macrofossils, and by the occurrence of Cruziana and Skolithos ichnofacies. Synaeresis cracks and wave-formed structures, such as HCS and symmetrical ripples, although not independently diagnostic of this environment, further support this shallow marine interpretation.

The interbedding of sandstone and shale in facies S/F is indicative of an environment experiencing periodic fluctuations in hydrodynamic conditions. The environment appears to have been a quiet one, favouring the deposition and preservation of mud and supporting a diversity of deposit-feeding organisms. The serenity of this environment, however, was frequently interrupted by storms of varying intensities, which deposited sand in layers covering considerable distances within the depositional area. Each sandstone bed in facies S/F records a single event, and displays many of the features characteristic of storm beds: 1) the presence of HCS; 2) sharp, erosive bases, with sand layers amalgamated onto or separated by shale from adjacent sandstone layers; 3) laterally continuous beds; 4) allochthonous fossils; 5) tops of sandstone beds bioturbated by traces constituting the Skolithos ichnofacies, indicating a brief occupation by opportunistic fauna; and 6) sequences of sedimentary structures indicative of waning flow, such as parallel or low-angle cross-lamination overlain by current and wave ripple cross-laminations (Blatt et al., 1980; Johnson, 1978; Goldring and Bridges, 1973; Frey and Pemberton, 1985).

Interbedded sandstones and bioturbated shales displaying many of the features listed above are widely accepted as indicative of deposition in the lower shoreface or offshore, between fairweather wave base and storm wave base, where the absence of fairweather wave processes, which are normally restricted to the shoreface, allow for the deposition and bioturbation of mud and for the preservation of storm-derived sandstone beds. Similar deposits have been observed off the coast of Georgia (Howard et al., 1972; cited in Hallam, 1981).

The formation of HCS is still a matter of controversy (Harms et al., 1982; Dott and Bourgeois, 1982; Walker et al., 1983; Walker, 1984; Brenchley, 1985); nevertheless, because of the associated sedimentary and biogenic structures and the stratigraphic positioning of HCS between offshore muds and sands and shoreface-to-fluvial sands (Bourgeois, 1980), most workers agree that storm waves acting below fairweather wave base are responsible for the formation of HCS. The depth of fairweather wave base varies, but generally lies between 5 and 15 m (Walker, 1984).

Considering the features present in facies S/F, Shcs, and Sb, it would at first appear that the upper Whirlpool represents deposition between fairweather wave base and storm wave base, but it seems unlikely that this same environment could have produced the wrinkle marks (observed at Lockport), desiccation cracks, and the abundant synaeresis cracks. Wrinkle marks require very shallow water conditions for formation (Reineck and Singh, 1980), and are also good indicators of emergence (Allen, 1985), as are desiccation cracks. Restricted, shallow waters subject to periodic fluctuations in salinity are optimal sites for the formation of synaeresis cracks (Leeder, 1982; Reineck and Singh, 1980).

The features and deposits of the upper Whirlpool can be explained by considering Irwin's (1965) model for sedimentation in epeiric seas. Although this model applies to carbonate sedimentation, there is no reason why a parallel one should not exist for terrigenous detrital environments. The model requires a broad, shallow sea with a very low gradient shelf (generally less than 20 cm per km), and these conditions probably did exist during the deposition of the upper Whirlpool: a broad, flat, low gradient plain was provided by the earlier deposition of the lower Whirlpool, and the transgressing seas were epeiric, with depths not likely exceeding 200 m (Johnson, 1978).

According to the model, in such a shallow sea "normal" waves dissipate their energy long before reaching the shore. The area receiving and dampening this wave energy, zone B, is a narrow, intermediate- to high-energy belt, where the constant action of waves and tides prevent the deposition of mud. Deposits formed in zone B will probably be clean, well sorted, and cross-bedded sands. Seaward of zone B is a wide belt, zone A, which lies below fairweather wave base. This zone, like its pericontinental equivalent, is a low-energy environment periodically affected by storm processes. Deposits of this zone will probably be similar to those formed below wave base on pericontinental shelves; that is, they will include interbedded sandstone and bioturbated muds, HCS, and bioturbated muddy sands, and the ichnofauna will consist of alternations of the *Cruziana* and *Skolithos* ichnofacies.

Shoreward of zone B lies a wide, very shallow belt, zone C. This, too, because of the dissipation of tidal and wave energy in zone B, is a low-energy environment, and because of limited tidal exchange with the open ocean, it is generally characterized by limited water circulation and extreme fluctuations in temperature and salinity. Local winds may cause some wave disturbances. Mud is deposited here, but like zone A, storm processes introduce sand into the area, producing deposits of interbedded sandstone and bioturbated shale. The deposits of zone C may, in fact, be difficult to distinguish from those of zone A, but the presence of emergent or very shallow water features should aid in the distinction. Although this is a very shallow water environment, HCS and other storm beds, which rarely survive fairweather processes on "normal" shorefaces, will be preserved in this quiet environment (Irwin, 1965; Heckel, 1972; Hallam, 1981).

Although Irwin's (1965) theoretical model has never really been well established, it has been discussed here to illustrate the type of environment the upper Whirlpool may have been deposited in. Without implying that all three zones existed during the time of the upper Whirlpool's deposition, it is proposed here that the facies of the upper unit of the Whirlpool probably formed in an environment similar to zone C. Such an environment can account for the presence of the shallow water structures, and can equally well account for the ichnocoenoses, the interbedding of storm deposits and bioturbated shales, and the lack of beach- and tidally-related sedimentary structures. Seasonal aridity or periods of restricted marine conditions is indicated by the presence of synaeresis and desiccation cracks and celestite vugs. This area will be referred to, henceforth, as "nearshore", as the term "shoreface" seems inappropriate to use in this setting.

The presence of facies Sb at the top of some of the Whirlpool sections and its presence in some of the sections displaying minor amounts of fluvial Whirlpool suggest that this facies probably formed in two areas of this nearshore environment. Where this facies is found capping Whirlpool deposits, it likely represents deposition in distal nearshore areas, where the depth and the distance from shore combined to produce a very quiet water environment that experienced less storm disturbance than the more proximal areas, thereby allowing sufficient time for the abundant fauna to thoroughly bioturbate storm and quiet water sediments. Small thicknesses of fluvial Whirlpool are interpreted here as being indicative of intense storm scouring activity. Where facies Sb overlies these thin units, it is likely that it formed in sheltered topographic depressions produced by the storm scouring.

HCS could have formed anywhere in this nearshore environment. The hummocky to bioturbated amalgamated HCS may reflect proximity to the source of sand, frequency of storms, absence of mud deposition, or intense storm activity. The bioturbated amalgamated HCS represents a more distal (or sheltered?) environment, where the infrequent interruption by storms enabled near thorough bioturbation of earlier storm deposits.

The absence of the cross-bedded sandstones (that would have been formed seaward of the Whirlpool's depositional area by the diminishing wave activity) in the upper Whirlpool, Manitoulin, Cabot Head, and Power Glen is interesting; however, if this high-energy area had been narrow and if it had been subjected to intense wave activity during storms, it is quite possible that the sand normally restricted to this zone had become redistributed as storm beds both in the offshore and onshore direction, thereby preventing any record of this zone from being preserved in the stratigraphic record, especially if storm frequency had been high.

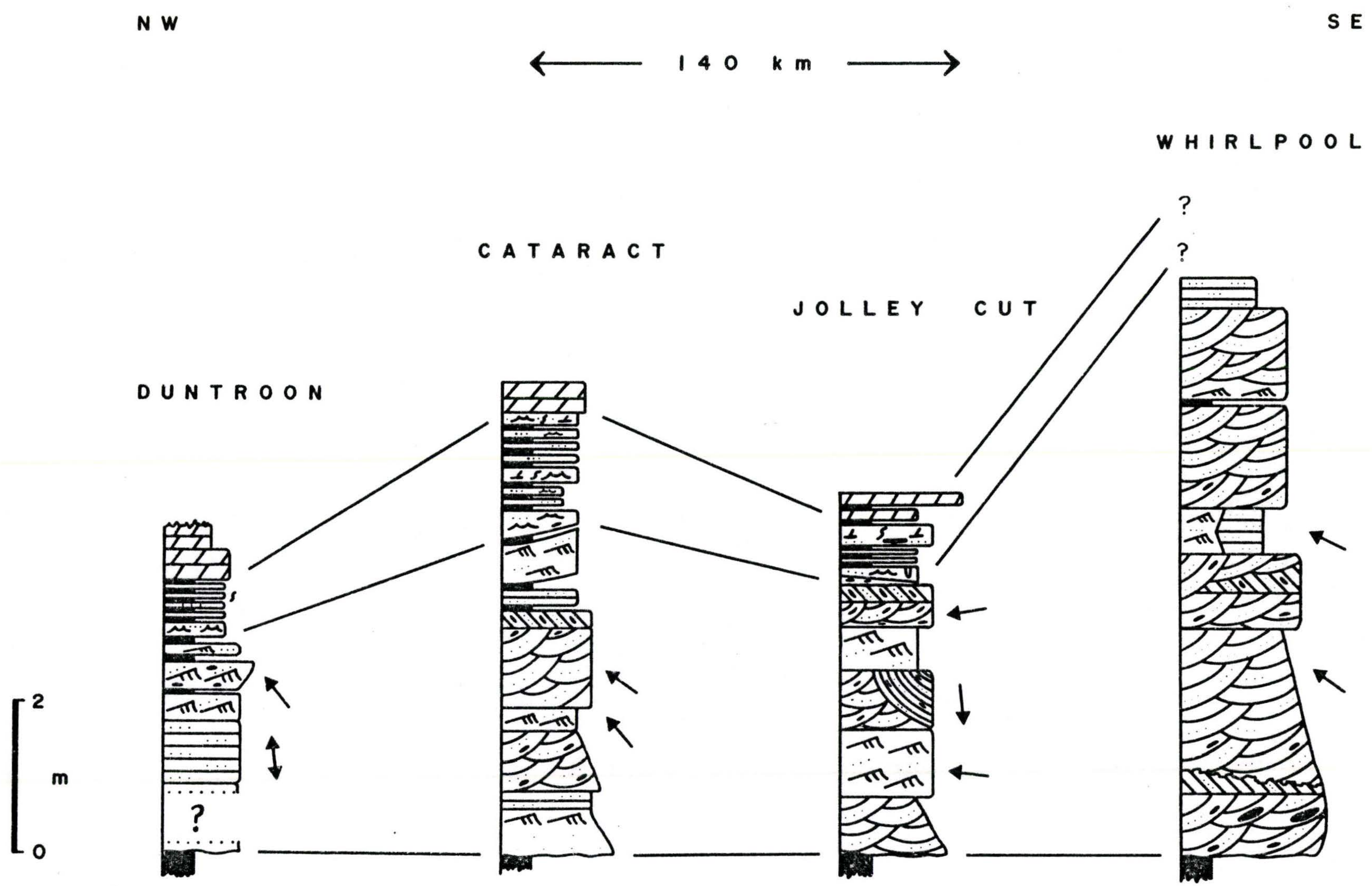
SECTION INTERPRETATIONS

This section proposes possible environmental interpretations for some of the better exposed sections of the Whirlpool. Interpretations of sections not discussed here are indicated on the section diagrams accompanying each section description, provided that the outcrops are well enough exposed to allow for such interpretations.

Regional analysis of the Whirlpool's facies shows that there are three main facies associations in the lower Whirlpool. In the southeast, between Lockport and Balls Falls, the lower unit is primarily trough cross-bedded (facies St) and contains minor elements of the other lower unit facies. Further to the northwest, between Hamilton and Orangeville, the percentage of the Whirlpool occupied by facies St is reduced, and the lower Whirlpool is characterized, instead, by a mixture of approximately equal amounts of facies St, Src, and Sh, and by minor amounts of the other lower unit facies. And finally, northwest of Cannings Falls, facies St disappears altogether, and the lower Whirlpool becomes predominantly horizontal and ripple cross-laminated (Fig. 7-1).

The three facies associations most likely are indicative of different geographic areas and fluvial styles within the Whirlpool braided river system. Sections dominated by facies St represent the most channelised portions of the braided river (more proximal), where the depth and channelisation of flow were appropriate for the formation and migration of three dimensional dunes. The river in this area was probably characterized by a relatively low braiding parameter (Rust, 1978b). Frequent

Figure 7-1. Diagram showing the regional change in facies associations. Although the trend is best represented by The Whirlpool, The Jolley Cut, and Duntroon sections, the Cataract section shows the minor deviations that can occur in this trend. The Whirlpool section, with a predominance of facies St, represents sections located in the southeast portion of the study area, between Lockport and Balls Falls. The Jolley Cut section, showing a mixture of facies St and Src, represents sections more centrally located, between Hamilton and Orangeville. The Duntroon section, with a predominance of facies Sh and Src, represents the northern sections, northwest of Cannings Falls.


NW
SE
140 km
WHIRLPOOL
CATARACT
JOLLEY CUT
DUNTROON
2
m
0

stage fluctuations and/or channel shifting resulted in the removal of any lower flow regime bedform deposits that may have been superimposed and also in the stacking of fining-upward in-channel deposits. The mixed facies association, on the other hand, represents less channelised areas of the river (more distal areas, where the braiding parameter is higher), possibly due to a reduction in slope, where the gradual and/or avulsive abandonment of intermediate-sized channels, the presence of transverse and longitudinal bars (Salas, 1983), and the finer grain size account for the mixture of in-channel, channel fill, bar, and bar top deposits. The third facies association, that dominated by facies Sh and Src, is interpreted as representing deposition in the most distal areas of the river system, where, due to further decreases in the depositional slope, channel confinement of flow was restricted to only low stages. During floods, flow in the river was largely unconfined, and resulted in the deposition of sheet flood deposits on the river's braidplain. As an alternative explanation, however, this facies association may indeed represent in-channel deposits, but with plane beds replacing dunes due to the fine grain size in these distal parts.

The downstream changes in the Whirlpool River's fluvial style and deposits show similarities to Miall's (1985a,b) architectural models 10, 11, and 12. Model 10, which is characterized by well differentiated channel, bar, and bar top facies (due to greater channel depth or stage fluctuations) and by fining-upward cycles, resembles the Whirlpool deposits in the southeast part of the study area. Model 11 represents deposition in distal braidplain environments and is characterized by thinner fining-upward cycles, reflecting the shallower nature of the channels, and by poorly defined channels. It resembles the Whirlpool's mixed facies association, which was deposited in the central portion of the study area. Model 12, also representative of distal braidplain environments, shows a predominance of flash flood-derived facies Sh. The deposits of the Whirlpool in the most northern portion of the study area are similar to those of this model.

Regionally, the upper unit remains fairly constant in appearance (consisting of facies S/F), except at Kenilworth Ave. and in the subsurface areas, where there appears to have been more pronounced scouring of the lower Whirlpool by the transgression. Here, the upper unit is dominated by facies Sb, Sw, and HCS rather than facies S/F.

Lockport Road Cut

The presence of channel-like features and the abundance of facies St at this locality suggest that the lower unit consists entirely of braided fluvial in-channel deposits. Deposition occurred within north-northwest flowing channels and was characterized by vertical aggradation, reflecting the channels tendency to shift and avulse, superimposing younger channel sediments onto older ones. Lockport shows the stacking of three channel deposits. The first, best seen on the SE - NW wall (Fig. 4-42), consists of in-channel dune deposits. It extends from the Whirlpool's base to the base of the first channel-like feature, and possibly forms the lower part of unit #1 on the SW - NE wall. The second channel deposit, also consisting of in-channel dune deposits, forms most of unit #1 and scours into the lower channel deposit, as can be seen on the SE - NW wall. The SW - NE wall shows unit #1 being cut by a westward-flowing channel, whose deposits are represented by unit #2 and #3. Unit #2 probably did not formed at the time the channel was cut, but instead was formed during a low stage or a short term abandonment, as is indicated by the presence of shale and the lower flow regime sedimentary structures. Renewed channel activity produced unit #3.

The beginning of the transgression is placed at the bottom of unit #4 (facies Srs). Orientation of the symmetrical ripples is 161 - 341 degrees, indicating that the transgression probably came from the southwest (251 degrees). Both units #4 and #5 represent deposition within the low energy nearshore zone of a broad, shallow epeiric sea, where the ongoing quiet water sedimentation was frequently interrupted by storms of varying intensities. An exceptionally large storm was responsible for the thick sandstone bed containing HCS. The sediments were occasionally subjected to very shallow and subaerial conditions, as is indicated by the presence of wrinkle marks and desiccation cracks (at the railroad cut).

The Lockport Railway Cut

Like the road cut, the railway cut also contains channel-like features and an abundance of facies St, suggesting that the lower Whirlpool here also represents the in-channel deposits of northwestward flowing streams. The importance of this exposure, the longest and best preserved of all the outcrops examined in this study, cannot be overemphasized, for it is here that there is evidence that the Whirlpool River must have continued to flow for some time after the onset of the transgression. The east wall shows this very clearly. Here, both fluvial and marine units of the Whirlpool are cut by a very large channel-like feature (300 m + wide) which is characterized by abundant trough cross-bedding and western paleocurrents (277 degrees). There is no indication (e.g. shale layers, wave ripples, or fossils) that this channel may be marine in origin.

The Niagara Gorge Sections

The lower part of the Whirlpool in the Niagara Gorge is interpreted as being the result of the superposition of in-channel deposits. That this area was possibly the most channelised part of the Whirlpool River, most likely representing the main tract, is indicated by the predominance of in-channel dune deposits, the coarse grain size, the fairly consistent northwest paleocurrent, and the small proportion of shallow channel or bar deposits.

Stage fluctuations must have been frequent and rapid, as is indicated by the presence of abundant and large mud intraclasts, derived from bank erosion, and by the presence of well-defined scour surfaces, which may represent in-channel scouring or the shifting and/or catastrophic formation of new channels by avulsion processes.

The relatively low abundance of falling stage deposits, such as planar tabular and ripple cross-laminations, and shallow dissection channels probably reflects their inability to survive the erosional processes accompanying stage fluctuations and channel shifting.

Evidence of bar or sandwave development is greater here than anywhere else in the study area. Paleocurrents indicate that these bars were possibly of both the transverse and diagonal types. Although Devil's Hole shows one feature interpreted here as superimposed bars, sand flats, like those in the South Saskatchewan River, probably never formed in the Whirlpool River.

The upper unit of the Whirlpool is interpreted as having been formed in the low energy nearshore zone of a broad, shallow, epeiric sea. The upper portion, that which grades into the Power Glen, may represent a more distal nearshore environment.

Kenilworth Avenue

Kenilworth Avenue, being an anomalous section, is rather difficult to interpret. Unit #1 shows no evidence of being marine in origin and is interpreted as having been formed by bar migration in a braided river. The scours and the fan-like feature are possibly the result of low stage bar modifications.

The rest of the Whirlpool, units #2 to #5, are marine in origin, as is evidenced by the presence of corals and wave-formed structures. The thinness of the total Whirlpool and the lower unit suggests that the fluvial Whirlpool had undergone considerable reworking and/or scouring, prior to the deposition of the upper unit. The entire upper unit is believed to have formed in the low energy nearshore zone of a very shallow epeiric sea. Not characterized by deposits of facies S/F, this area was probably the site of either intense storm erosion or little mud deposition, resulting in the amalgamation of HCS. Deposition of the upper unit most likely took place in a topographic depression formed by the pronounced erosion of the lower Whirlpool.

Unit #2, displaying flaser bedding, possibly represents rare tidal activity occurring in this low energy environment. The orientation of symmetrical ripples (123 to 303 degrees) suggests that the transgression probably came from from the southwest (213 degrees). Unit #3, a cross between facies St and Sp, is the only example anywhere of large scale cross-lamination in the upper Whirlpool. With paleocurrents indicating a northwest flow (334 degrees), that is, obliquely away from the shoreline, it may possibly represent dune migration within a rip channel. Unit #4, the only evidence of appreciable mud accumulation, is scoured into by unit #5, which exhibits facies Shcs.Ah-b. At least seven episodes of storm activity can be distinguished. The erosion of the interstorm mud, if any was present, was effected by storm waves and currents, the erosional potentials of which were increased by the shape of the topographic depression. An increase upward in the thickness of the bioturbated portion of the sedimentation units possibly indicates increasing distality or decreasing storm frequency.

The incorporation of well preserved corals within the storm beds suggests that this area may have been the site of coral habitation or that the corals were brought in from somewhere else during storms.

The Jolley Cut

The lower unit of the Whirlpool at the Jolley Cut, showing approximately equal proportions of facies St and Sr, probably represents deposition within less channelised portions of the Whirlpool River (compared to the Niagara region); that is, in an area characterized by relatively shallow channels and a high braiding parameter. Southwestward-trending paleocurrents (242 degrees) suggest that this may have been a distributary of the main river tract.

Both facies St and Src are interpreted as in-channel deposits. Facies St represents dune migration on the channel floor during flood stages, while facies Src is the result of ripple migration and accumulation during waning stages. The frequent shifting of channels is indicated by the erosional contacts and the superposition of facies St on facies Src. The large troughs showing possible southward paleocurrents are difficult to explain. They may be the product of exceptionally large dunes formed on the bottom of a channel forced to take a more southward route due to channel aggradation.

The small proportion of bar deposits in the stratigraphic record may merely reflect the low preservation potential of such deposits in such an unstable environment. The sequence at section D is interpreted, from bottom to top, as bar, bar top, and shallow dissection channel deposits.

The transgression, which is marked by the first appearance of symmetrical ripples, HCS, or shale, appears to have come from the southwest, as is indicated by the orientation (177 to 357 degrees) of the symmetrical ripples. Despite the proximity of this section to the Kenilworth section, pronounced scouring of the lower Whirlpool did not occur here. Deposition, like at Kenilworth, occurred within a low energy nearshore zone of a very broad, shallow epeiric sea. Frequent storms resulted in the deposition of HCS, symmetrical climbing ripples, and low-angle cross-laminations. Increasing distality is indicated by the upward increase in bioturbation and the presence of bioturbated amalgamated HCS (at section E).

Cataract

The lower unit of the Whirlpool is believed to have formed in a similar environment as the Jolley Cut section. The approximately equal proportions of facies Src and St, the erosional contacts, and the paucity of facies Sp suggest that deposition occurred in a part of the river that was highly braided, with relatively shallow channels, and subject to frequent flooding, during which bank erosion and channel shifting processes were widespread. Yet the thickness of the section, the coarse grain size, and the abundance of facies St suggest that this area was somewhat more channelised than some areas to the south, near Georgetown, where facies St is not so abundant. The shifting of channels resulted in destroying bar deposits and in placing younger in-channel deposits (facies St, Sh, and Src) in erosional contact with older ones. Direction of flow of this part of the river was to the northwest (314 degrees).

The shale layers present near the top of the lower unit probably formed in very shallow, topographically high channels that were left with standing pools of water during low stages. Channel reactivation during floods resulted in the deposition of facies Src on top of the shale layers. The symmetrical ripples present at the 3 m level are possibly low stage bar modification features.

The transgression, which probably came from the west (265 degrees), is marked by symmetrical ripples and by a hummocky scour surface, which may be similar to that present in the Hilltop and Brockton quarries (measured by Salas, 1983) in the Georgetown area. This surface possibly represents the scouring activity of large storm waves on the top of the fluvial Whirlpool. The rest of the upper Whirlpool, showing an increase in bioturbation and carbonate content upward, is interpreted as the fairweather and storm deposits of a low energy nearshore zone of a very shallow and broad epeiric sea.

Cores

The cores were included in this study because it was hoped that they would provide information on whether the pinchout of the lower unit is erosional or depositional.

There is no evidence of a gradual change in the fluvial style of the lower Whirlpool in the Lake Erie region; in fact, the westward change from fluvial to marine is very abrupt and suggests scouring and total reworking of the lower Whirlpool. The pinchout, which occurs between cores 106 and 108, is therefore most likely erosional in nature.

Unlike the outcrop sections, most of the cores appear to be predominantly marine in origin, and there is considerable variability in the nature of the upper unit. Evidence of frequent storms in an otherwise quiet water environment is present in a few of the cores (by facies S/F or facies ?Shcs.A), but most cores show evidence of only occasional disturbance by storms, as is suggested by the abundance of facies Sb. The environment suggested by this facies was either close to shore, but in a sheltered area, such as a topographic depression, or further offshore, where the infrequent disturbance by storms enabled thorough bioturbation of the sediment.

The thinness or absence of the lower unit in most cores can be interpreted in two ways: either the lower Whirlpool was very thin to begin with in the Lake Erie region, and was partially or totally removed by moderate scouring during the transgression, or the Whirlpool was average in thickness, and was subjected to considerable scouring activities during the transgression.

The lower unit of the Whirlpool is rather difficult to interpret in the cores. The absence of facies St suggests that the area was away from the more channelised portion of the Whirlpool River, possibly representing deposition within very shallow channels or on the river's braidplain. The convolute lamination in core 240 is interpreted as slump structures caused by the liquefaction of bar foreset slopes.

SUMMARY

The following is a summary of the interpretations proposed in this chapter for the facies and depositional environment of the Whirlpool Sandstone. See text for a more detailed discussion.

Depositional Environment

lower Whirlpool -- a **sandy braided river** is indicated by the Whirlpool's geometry, paleocurrents, facies associations and erosional features.

upper Whirlpool -- a **low energy nearshore marine** environment is indicated by the presence of fossils, wave-formed structures, shallow marine trace fossils, facies S/F, and shallow water indicators.

Facies Interpretations

Facies St represents the migration of dunes in the deepest part of active fluvial channels during flood to waning stages and in shallow channels and on bar tops and margins during waning stages. Large channels and scour surfaces indicate stage fluctuations and/or avulsion. Shale intraclasts are indicative of vertical accretion deposits, lateral erosion, and bank collapse.

Facies Src represents the migration of current ripples during waning to low stages in shallow reaches of active braid channels (e.g. in shallow channels, on tops and margins of bars and dunes, and on braidplains). Ripple fans were formed in the lee of dunes during falling and low water stages. Capped-off ripples indicate subaerial exposure or planing by waves during low stages.

Facies Srs was probably formed in a nearshore setting by waning storm waves acting on the tops of storm-derived sandstone beds.

Facies Sh is the product of upper flow regime plane beds that probably formed on the floors of active fluvial channels and on distal braidplains during flood stage and in channels and on tops of active bars during waning stages.

Facies Sp represents the migration of bars and sandwaves in shallow or main channels and on other bars during flood and waning stages. The presence of ripple cross-laminations are indicative of low stage modifications to bar or sandwave tops and margins.

Facies Sl in the lower Whirlpool represents either bar migration or a bar top facies formed during waning and low stages. In the upper Whirlpool, it represents storm deposition in a low energy nearshore environment.

Facies Sm represents the rapid deposition of sediment from a decelerating, sediment-laden current on a braidplain or shallow channel. Where associated with facies Sc, facies Sm represents the liquefaction and subsequent downslope movement of bar foresets or channel margins during changing water levels.

Facies Sc, where associated with facies Sm, probably represents minor slump structures (see above); otherwise, deformation was likely due to the current's shear stress acting on a bar top or channel bed.

Facies Sw in the lower Whirlpool probably formed in shallow, topographically high channels where low stage mud deposition alternated with sand derived from the wind or minor current activity. The wavy laminations may reflect sediment surface irregularities. In the upper Whirlpool, facies Sw, if bioturbated, probably represents distal nearshore deposition of mud and storm-derived sand on an irregular surface. If nonbioturbated, deposition probably occurred in proximal regions with the sand being aeolian in origin.

Facies S/F, Shcs, Sb all represent deposition in a very shallow, low energy nearshore environment, where wave energy was dissipated far from the shoreline. Facies S/F, which displays HCS, traces constituting the Skolithos and Cruziana ichnofacies, and fragmented fossils, represents alternating quiet water and storm deposition. Hummocky to bioturbated HCS may reflect shoreline proximity, storm frequency or intensity, or lack of mud deposition. Bioturbated amalgamated HCS may represent a more distal environment where the infrequent occurrence of storms enabled thorough sediment bioturbation. The bioturbation intensity of facies Sb is directly related to distance from the shoreline; however, topographic depressions close to shore may have also produced facies Sb with strong bioturbation.

Regional Changes in Fluvial Style

The northwest-flowing (301 degrees) Whirlpool River experienced downstream changes in its fluvial style, as is indicated by the presence of three facies associations:

1) **Predominantly Facies St.** Confined to the

southeastern portion of the study area, this association indicates that the Whirlpool River, here, was moderately braided, with a few well-defined, deep channels that experienced frequent stage fluctuations and channel shifting.

2) **Mixture of Facies St, Src, and Sh.** Located in the study area's central portion, this association indicates that, here, the river was more highly braided with shallower, constantly shifting channels in which dunes, ripples, plane beds, and minor bars were the predominant features.

3) **Predominantly Facies Sh and Src.** Situated in the northern part of the study area, this association indicates that, here, the river was most highly braided with very shallow, constantly shifting channels. Flood waters, unable to be confined by these channels, spilled over onto the braidplain as sheet flows, depositing abundant rippled and horizontally-laminated sediments.

CHAPTER 8

ENVIRONMENTAL RECONSTRUCTIONS

The following environmental reconstructions are based on the facies, petrographic, paleontological, and ichnological data presented in the previous chapters of this thesis.

THE WHIRLPOOL RIVER

General Characteristics

During the Early Silurian, Southern Ontario and western New York State were situated approximately 20 to 25 degrees south of the equator (Ziegler et al., 1977; Scotese et al., 1979), where temperature conditions were, no doubt, warm to hot. The predominance of flood and waning stage-related sedimentary structures (e.g. trough cross-bedding, scour surfaces, and horizontal laminations) in the lower Whirlpool suggest that this area experienced large amounts of rainfall; however, the presence of low water features, such as desiccation cracks (Salas, 1983), and capped-off ripples, indicate that some seasonal aridity also did occur.

The deposition of the Queenston Shale (Upper Ordovician) in a lower to mid deltaic environment and its probable subsequent uplift and erosion produced a broad, flat, very gently sloping (0.001) plain onto which the Whirlpool was later deposited (Middleton and Rutka, 1986; Smosna and Patchen, 1978; Brogly, 1984). The cause of this uplift, which is believed to be related to the earlier crustal loading in the Appalachian region, is discussed more thoroughly in Chapter 9.

Sometime during the Early Llandovery, the braided Whirlpool River began its course over the mudcracked Queenston Shale. The northwest-trending paleocurrents, the overall fining to the northwest, and the petrographic evidence of the multicyclic- or second cycle-nature of the Whirlpool Sandstone all indicate that the river's sediment was derived from the erosion of a sandstone body (the Oswego Sandstone?) situated somewhere within the Appalachian region. An additional source, a pre-existing oolitic limestone, which lay somewhere to the east of Medina, New York, and which supplied minor amounts of sediment to that immediate area is indicated by the presence of micritized ooids in the Whirlpool at the Medina section.

Details concerning the dimensions of the Whirlpool River are difficult to determine because much erosion has taken place since the Whirlpool's deposition (by the transgression which deposited the upper part of the Whirlpool Sandstone, and by more recent events which led to the formation of the Niagara Escarpment). However, considering that the river's direction of flow was to the northwest (301 degrees), that the river probably did not flow much beyond the arch that most workers believe existed near the present day Findlay-Algonquin arch (Sanford, 1972; Bolton, 1957), and that there is evidence of the river having been present in central Ohio and Pennsylvania (Knight, 1969; Cate, 1961), it appears that the Whirlpool River was at least 450 km long and that it migrated over an area at least 450 km wide.

Because of the instability of the Whirlpool's paleochannels, resulting in much erosion and superposition of channel deposits, and because of the limited geographic extent and length of Whirlpool outcrops, gaining accurate or meaningful information about the Whirlpool paleochannels is very difficult. Nevertheless, from the consistent northwestward-trending paleocurrents, the paucity of shale and lateral accretion surfaces, the erosional facies relationships, the vertical aggradation within channels, the lack of vegetation during the Early Silurian, the thinness of the fining-upward cycles (no thicker than 4 m), and the predominance of flood stage-derived facies, it appears that the Whirlpool's braided river channels were probably bed-load-dominated and were characterized by slightly sinuous channel patterns, a moderate to high braiding parameter, high width-depth ratios, lateral erosion, and by frequent stage fluctuations brought on by flashy discharges

(Galloway, 1985; Bridge, 1985; Rust, 1978b). Fining-upward sequences in the Niagara Gorge range in thickness from 1 m to 4 m, which means that the channels responsible for these deposits ranged from at least 1 m to 4 m in depth, respectively (Miall, 1985a,b). If the width/depth ratio is taken to be 40:1 (Schumm, 1972), the width of these channels can be calculated, resulting in widths ranging from at least 40 m to 160 m wide.

The paucity of vertical accretion deposits in the Whirlpool is not atypical of braided fluvial deposits. Most fines were probably flushed through the river system as wash-load, and those that were deposited in overbank areas were quickly eroded by the shifting channels. It is also possible that the source rock may have had a deficiency of fines.

The lack of any evidence of scouring into the Queenston and the presence of facies Sm and poorly-defined facies St at the base of the Whirlpool suggest that most of the streams' energy was used primarily for the transportation of its heavy load rather than for erosion of channels into the underlying bedrock. However, considerable intraformational erosion did occur during the frequent floods the river experienced, as is indicated by the presence of scour surfaces, erosional facies relationships, and lack of vertical accretion deposits. Lack of advanced and abundant plant life at this time meant that there was probably an immediate response to storms and that the streams' banks, being very unstable, were unable to confine the flood waters, resulting in much channel erosion, shifting, and avulsion (Schumm, 1968).

The downstream decrease in slope and stream competency affected the fluvial style of the Whirlpool River in such a way that three areas, each distinctive on the basis of the degree of braiding, average channel depth, topographic differentiation, sediment grain size, and type of bedforms present, can be recognized. In the southeast, or proximal, portion of the study area the thick fining-upward cycles (up to 4 m and averaging greater than 2 m in thickness), the preservation of some channel margins, the predominance of facies St, and the coarseness of the grains (up to 0.5 mm) in the Whirlpool seem to suggest that in this area the Whirlpool River was probably moderately braided (braiding parameter of about 2 or 3; Rust, 1978b), with a few well-defined, relatively deep channels, in which three-dimensional dunes were the predominant bedform. In the central part of the study area, where the Whirlpool is characterized by a finer grain size, thinner fining-upward cycles (averaging less than 2 m), and a mixture of facies St, Src, Sh and minor Sp, the river was most likely more highly braided, with shallower and less well-defined channels, in which dunes, current ripples, and, to some extent, plane beds, sandwaves, and transverse bars were the predominant bedforms or features. As well, stream competency was somewhat less here than in the southeast area. In the northern, or distal, area the absence of facies St and of evidence of channelisation, as well as the fine grain size, and the abundance of facies Sh and Src seem to suggest that the river in this area was possibly even more highly braided than in the central region. Stream competency may have been reduced, and the channels were probably so shallow that flood waters, unable to be confined, spilled over onto the braidplain as sheet flows. Plane beds and ripples were probably the dominant bedforms.

The downstream changes in fluvial style reflected in the Whirlpool outcrops show similarities to Miall's (1985a,b,c,) architectural models 10, 11, and 12. Although there is no attempt here to rigidly assign one of these models to a specific area of the Whirlpool River, it is interesting to note that the changes in fluvial style occurring from model 10 to model 12 can also be recognized in the Whirlpool's deposits, from proximal to distal regions, respectively (see previous chapter for more discussion).

Flood Stage

The response to flooding was somewhat different in each of the three areas. During floods, the waters in the southeast and central regions of the river rose above the braid bars, probably temporarily forming one or a few larger channels. The channels in the southeast area, being deeper, probably were better able to confine the rising waters; nevertheless, as suggested by the presence of scour surfaces, large shale intraclasts, erosional facies relationships, stacked fining-upward sequences, well-preserved channel fills, and by the paucity of vertical accretion deposits, much channel erosion, shifting, and possibly avulsion occurred in this region, as well. The rising flood waters were effective in eroding previously deposited in-channel deposits (producing scour surfaces), bars (hence the paucity of facies Sp in these deposits), channel banks, causing channel shifting, and all overbank fine-grained material, which later became incorporated as shale clasts within the bedforms and on the scour surfaces. Flood waters in vertically aggraded channels (e.g. Lockport road cut) were probably forced to take other, steeper routes, resulting in the formation of new channels, possibly having scour surfaces at their bases. Dunes and plane beds were the dominant bedforms in the river's channels at this time. Overbank deposition most surely occurred, but the type of bedforms produced in these areas is not known due to the lack of preservation of these deposits in the Whirlpool.

In the northern part of the study area, the shallowness of the channels probably forced flood waters to spill out onto the braidplain as sheet flows. Any fine-grained overbank material present was eroded and became incorporated as shale clasts into the plane bed and current ripple bedforms that characterized these flows. In-channel bedforms, probably because of the fine grain size, consisted mostly of plane beds rather than dunes, with minor amounts of current ripples; occasionally the rare dune was able to form, as well.

Waning Stage

During waning stages in the southeast and central regions of the river, plane beds and dunes probably continued to form or migrate in the deeper parts of the channels, while current ripples, sandwaves, dunes, and plane beds formed and their deposits aggraded in the shallower parts of the river, namely on bar tops and on the channel margins. With a further drop in water levels, the braid bars became emergent and shallow dissection channels were formed on the bars (e.g. Cataract, Cannings Falls, Jolley Cut, The Whirlpool). Other modifications to the bars included lateral accretion of current ripples on the bar margins and in the lee of the bars (e.g. Devil's Hole), formation of symmetrical ripples by waves on the bar margins (e.g. Artpark), and slumping of bar foresets due to liquefaction or erosion (e.g. cores ?146, 552, and 240).

The presence of trough and ripple cross-laminations and minor plane beds within sequences interpreted as shallow channels suggests that during waning stages, vertical accretion of dune, ripple, and minor plane bed deposits was the main process in dissection channels and other shallow channels. With further stage falls dunes became emergent and ripple fans were formed in their lee (e.g. Whirlpool State Park, Rice and McHarg Quarry; Salas, 1983).

During waning stages in the northern region, plane beds were probably confined to in-channel areas while current ripples formed in both in-channel and braidplain areas. The presence of capped-off current ripples at the Duntroon Quarry suggests that with further falling stage levels, ripples became emergent and, in some areas, were planed off by waves or the wind (evidence of waves in the lower Whirlpool is rare; Artpark and Cataract contain the only known examples).

Low Stage

The occurrence of facies Src capping shallow channel sequences suggests that during low water stages in the southeast and central areas of the river (e.g. Cataract, The Jolley Cut, Balls Falls, The Whirlpool, Artpark, Quarry Lake), current ripples were possibly the predominant bedform in the shallow areas of the river, that is in shallow channels, on channel margins, and on tops of bars and dunes. Topographically higher areas (such as braidplains, bar tops, and very shallow channels) and temporarily abandoned channels were probably left with standing pools of water, where the deposition of mud and wind-blow sand possibly took place. Evidence of this can be seen at Quarry Lake, Lockport, and cores 240 and ?552, where the presence of wavy laminations suggests a specific process of formation, whereby quiet water sedimentation alternates with minor current or wind-blown sand sedimentation.

In the northern part of the Whirlpool River, low stage waters likely were confined within the shallow channels, with current ripples possibly being the major bedform.

The length of time represented by the lower Whirlpool is difficult to determine. It is possible, considering the thinness of the formation, that the river operated over a fairly short period of time, possibly less than a million years.

The Whirlpool Sandstone is unusual for a sandy braided river, for it shows a paucity of bar deposits. Had the river been a weakly braided system, it would account for the lack of bar deposits; however, it is more likely that the bar deposits actually had been present, but were eroded by the frequent shifting of channels. The river, with its apparent paucity of bar deposits and abundance of dune, ripple, and plane bed deposits, appears to lack a modern analog. It does not fit any of Miall's (1978) well-known models nor does it fit other well-known rivers, such as the Tana or the Brahmaputra. A possible explanation for this may be that the lack of abundant and advanced types of vegetation in the Early Silurian allowed for more lateral erosion than is possible in modern rivers.

THE TRANSGRESSION

General Characteristics

The shallow epicontinental sea that had covered much of the Continental Interior since the Middle Ordovician had begun its transgression of the eastern landmass sometime during the deposition of the fluvial Whirlpool. Because it is generally agreed that symmetrical ripples form parallel to the shoreline (Potter and Pettijohn, 1963), the regionally and vertically consistent northwest-southeast orientation of the upper unit's symmetrical ripples (Fig. 4-44) suggest that the transgression must have come from the southwest (255 degrees) and that the shoreline, throughout the transgression, maintained its 165 - 345 degree orientation (Chapter 9 discusses the possibility that the transgression may have also come from the southeast). But there remains one thing to be explained: how is it that the northwestward-dipping alluvial plain formed by the northwestward-flowing (301 degrees) Whirlpool River could be transgressed obliquely without showing any evidence (from symmetrical ripple orientation) of a curved shoreline in the northwest, where the land was at a lower elevation than in the southeast? One possible explanation for this is that there may have been an uplift in the northwest part of the study area that had elevated the land to roughly the same height as the southeastern area, thereby causing the alluvial plain to dip roughly in the direction from which the transgression came. In this way the shoreline would have been able to maintain a constant trend throughout the transgression. But the absence of emergent features in the northwest questions the validity of this theory. It is more likely that the equivalent effect of an uplift in the northwest took place: a subsidence in the southeast. The cause and nature of this subsidence, or southward tilting, are discussed more fully in Chapter 9.

Although the features of the upper Whirlpool--interbedded sandstone and bioturbated shale, laterally continuous, sharp-based sandstone beds with bioturbated tops (Skolithos ichnofacies), and the presence of allochthonous fossils, HCS, and waning flow structures--would generally be indicative of deposition within an environment between fairweather and storm wave bases, where quiet water sedimentation is occasionally interrupted by storms, the presence of shallow water features in the upper Whirlpool, such as desiccation and synaeresis cracks and wrinkle marks, call for a much shallower depositional environment. For shale to be deposited and for both shale and storm layers to escape fairweather wave reworking in such a shallow environment, the transgression must have occurred along a very broad, low-gradient shelf, where the dissipation of wave and tidal activity occurred some distance from the shoreline. Deposition of the Whirlpool, therefore, likely occurred in a broad area near the shoreline, where the quiet waters were favourable for the deposition and accumulation of mud. However, the presence of sandstone beds displaying the various features mentioned above indicate that storms of varying intensities must have occurred occasionally to interrupt this normally quiet-water environment; judging by the amount of shale preserved in the upper Whirlpool, it appears that they may have occurred with a frequency of much less than once every 1000 years.

It is not known what was being deposited to the west and northwest, beyond the limits of the Whirlpool's deposition. Perhaps the Manitoulin was forming at this time in the Michigan Basin. It is also possible that it was not, and that a thin shale layer, which later became eroded by the transgression, was the Whirlpool's equivalent.

Fairweather Conditions

During fairweather conditions tides and waves that were generated some distance offshore dissipated their energy long before reaching the shoreline, resulting in the formation of a low-energy zone that extended a considerable distance from shore (up to ?100 km). Mud deposition was predominant here, but the presence of facies Sw in the upper Whirlpool sediments (see Osler Bluff, Mitchell's Mills, and cores) suggests that locally-generated winds may have caused some water disturbances, producing surface irregularities, and also may have introduced aeolian sand into the sediments, thereby accounting for the presence of terrestrial spores in the marine Whirlpool. The absence of normal wave and tidal activity in this area also meant that beach deposits, the seaward-dipping low-angle cross-laminations common to pericontinental coastlines, and tidally-related sedimentary structures were never really developed here (Irwin, 1965).

The source of the upper Whirlpool's mud is not clear. It may have been mud that had been carried in suspension through the Whirlpool River and which became reworked and redistributed during the transgression, mud derived from the Whirlpool River, which appears to have existed during the transgression (evidence at the Lockport railroad cut), or mud derived from another source and carried into the depositional area by alongshore currents.

The quiet water conditions of this environment supported a diversity and an abundance of organisms, whose crawling and feeding traces constitute the _Cruziana_ ichnofacies. The upward increase in bioturbation intensity, trace fossil diversity, and shale thickness that is observed at many of the Whirlpool sections is a natural consequence of the transgression, with distal, slightly deeper deposits being superposed onto more proximal, shallower sediments. The observed increase in shale thickness upwards in some of the sections suggests that the frequency of storm interruption and/or the erosive power was probably greater closer to shore than in the more distal, slightly deeper regions of the shelf. The bioturbation intensity trend, too, may be indicative of storm frequency and/or erosiveness. The more distal areas would experience less storm interruption and storm erosion than the more proximal areas, thereby allowing for more complete bioturbation and preservation of the muddy interlayers. The bioturbation intensity, as well as the diversity, trend may also be reflecting temperature and salinity changes in the offshore direction. Close to shore, where the water was quite shallow, fluctuation in salinity and temperature conditions may have existed, resulting in an environment hospitable to only a few euryhaline deposit-feeding organisms (e.g. bivalves, gastropods, ostracods, lingulids), while further offshore, the deeper waters were more effective in regulating temperatures and salinities, thereby resulting in supporting both an abundance and diversity of deposit-feeding organisms.

This nearshore environment appears to have been subjected to occasional spells of aridity, where evaporation exceeded compensating freshwater runoff or open ocean water. The resulting low water levels, the changes in salinity, and the temporary subaerial exposure of areas close to shore produced wrinkle marks, desiccation cracks, and abundant synaeresis cracks on the muddy or sandy sediment surfaces.

The paucity of evaporite deposits in the upper Whirlpool is significant in that it probably suggests that the environment normally experienced humid climatic conditions; as a result, the waters were subjected to variable salinity conditions, ranging from brackish and normal marine to slightly hypersaline during the dry periods (hence the synaeresis cracks). The continuous influx of terrigenous mud and storm-derived sand was probably another major factor in preventing the growth of evaporite and carbonate deposits in the environment (Blatt et al., 1980). Nevertheless, it appears that "restricted" marine conditions may have occurred occasionally, as is indicated by the presence of celestite-filled vugs near the top of the Whirlpool. (It is possible, however, that the celestite vugs may be diagenetic in origin.)

Storm Conditions

As previously mentioned, it appears that large storms (large tropical cyclones: Duke, 1982) may have occurred quite frequently, possibly on the order of every few hundred years. During these storms, storm-surges may have developed, raising water levels possibly by as much as a few meters. The sharp, erosive sandstone bases and the amalgamated HCS beds are evidence that the intense wave activity accompanying these storms often reworked or eroded the uppermost few centimeters of sediment in the nearshore area. The thinness of the fluvial Whirlpool at Kenilworth Ave. and in some of the cores indicates that the shoreline, during unusually large storms, must have suffered pronounced scouring into the fluvial deposits, producing minor, but noticeable, depressions in the shelf floor topography. The presence of laterally continuous sandstone beds exhibiting waning flow structures and fossil fragments indicate that the sediments and organisms eroded during the storms were redistributed over the entire nearshore area, possibly by strong storm-surge ebb currents. (The presence of trough cross-strata in the upper Whirlpool at Kenilworth is difficult to explain, but their 334 degree paleocurrent suggests that they may be the result of seaward-migrating dunes in obliquely-oriented-to-shore rip channels. Such channels may have been responsible for some of the scours in the fluvial Whirlpool.) As the sand settled out of suspension, intense oscillatory wave activity and/or strong unidirectional currents worked the sediment into plane beds, and as the currents waned, current rippling possibly developed. With further decreases in the ebb-current strength, oscillatory wave motions reworked the top of the sandstone layers into symmetrical ripples.

Where and when HCS formed is difficult to determine. It is likely the result of exceptionally large storms, and could have formed anywhere within the environment. Amalgamation likely occurred close to shore, in the topographic depressions, where the proximity to the source of sand, the pronounced erosion during storms, and the possible channeling of the sediment-laden currents made conditions ideal for the formation of amalgamated HCS.

The presence of Skolithos ichnofacies burrows on the tops of the sandstone beds indicates that during the final stages of the storms and for a short time afterwards, conditions were suitable to support an abundance and diversity of suspension-feeding organisms. Eventually, however, conditions returned back to normal, with mud deposition resuming, preserving the underlying sediments, and the deposit-feeders regaining occupation of their territory.

The frequent occurrence of facies Sb in the western cores (e.g. cores 371, 146, 678), in sections containing little fluvial Whirlpool (e.g. core 512, Kenilworth Ave.), and at the top of Whirlpool deposits suggest that the more distal portions of the depositional area and some of the topographic depressions may have escaped storm disruption quite frequently because of the sheltering effect. In these areas burrowing organisms were given plenty of time to churn both the mud and sand (from earlier storms) layers, with the result that a thoroughly bioturbated, homogeneous mix of mud and sand (facies Sb) was produced.

The above account of the upper Whirlpool's deposition is based on some of the ideas put forth by Irwin (1965) for sedimentation in epeiric seas. Because vast epeiric seas like those present in the geological past simply do no exist in the present day, it is not possible to present a modern example with which to compare the depositional environment outlined here for the upper Whirlpool.

The rapid transition of the upper Whirlpool into the overlying formations suggests that the transgression over the fluvial Whirlpool occurred quite rapidly. That it was possibly coupled with a fair amount of subsidence is suggested by the preservation of the sand and mud interlayers (upper unit), which otherwise would have been eroded during subsequent storms.

The amount of fluvial Whirlpool eroded, reworked, and redistributed in the transgressing sea is difficult to determine. Examination of the sections, especially the cores, indicates that in some places as much as 4 m may have been eroded; however, the average was likely around 1 or 2 m.

CHAPTER 9

TECTONIC CONTROL OF THE WHIRLPOOL'S DEPOSITION

INTRODUCTION

Up to this point the thesis has focused primarily on the interpretation of the depositional environment of the Whirlpool and the processes operating within this environment. There has been little discussion of the large-scale controls on the Whirlpool's deposition and how the Whirlpool fits into the overall picture of Appalachian Basin history. This chapter briefly reviews a model of lithospheric flexure that accounts for the structural and stratigraphic evolution of such foreland basins as the Appalachian Basin (Beaumont, 1978, 1981; Quinlan and Beaumont, 1984), and it attempts to show how the Whirlpool and the overlying formations can be explained by this model. In so doing, it is hoped that the following aspects of the Whirlpool's deposition can be explained: 1) the planar-erosional nature of the Whirlpool/Queenston contact; 2) the fluvial character of the lower Whirlpool; 3) the source of the Whirlpool River's sediment; 4) the southwest tilting of the Whirlpool alluvial plain prior to the transgression; 5) the nature of the transgression; and 6) why, if the transgression came from the west-southwest, the Whirlpool is overlain by a deeper-water facies in the south and southeast than in the north and northwest (see Chapter 2, Fig. 2-4).

FLEXURAL MODEL

The model, which was developed by Beaumont (1978) and later applied successfully to the Alberta and Appalachian Basins by Beaumont (1981) and Quinlan and Beaumont (1984), respectively, involves a temperature-dependant viscoelastic lithosphere, which under an applied load responds in such a way that a downwarped flexural moat and an upwarped peripheral bulge are formed around the load (Fig. 9-1a). The width of the flexural moat is mainly a function of the lithospheric thickness, with the distance increasing as the third power of the lithospheric thickness (Quinlan and Beaumont, 1984). The peripheral bulge is a very broad, low amplitude feature, with a width approximately equal to the width of the flexural moat, or foreland basin, and a height (distance above the depositional baseline) ranging from 1% to 3% of the depth of the foreland basin (Beaumont, pers. comm., 1986).

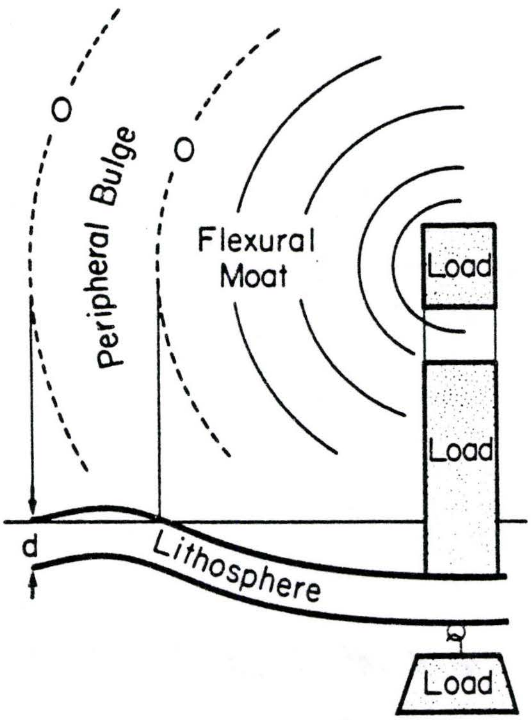
As the load remains in place and if no additional loads are applied, the lithosphere under the load relaxes the stress, thereby producing a deeper central depression. As the flexural moat increases in depth, the peripheral

Figure 9-1. Deformation of a viscoelastic lithosphere under an applied load. From Quinlan and Beaumont (1984).

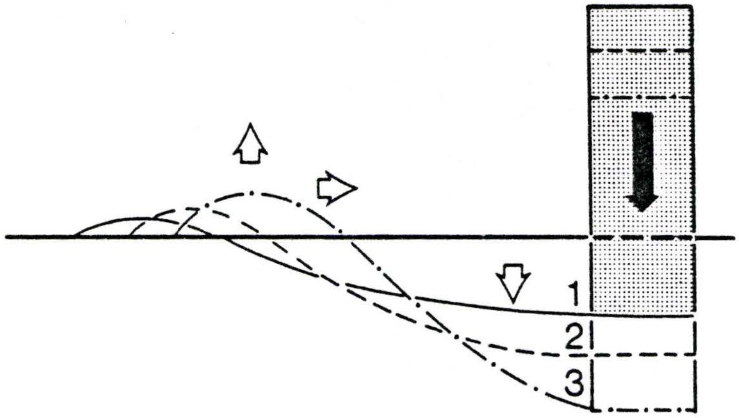
a) Diagram showing the formation of a peripheral bulge and flexural moat in response to loading on a viscoelastic lithosphere.

b) Diagram showing how the peripheral bulge uplifts and migrates toward the load during the relaxation phase.

a.


Peripheral Bulge
Flexural Moat
Load
Load
Lithosphere
d
Load

b.


1
2
3

bulge rises and migrates toward the load (Fig. 9-1b). Eventually, if the lithosphere can totally relax, a state of local Airy isostatic equilibrium will be reached.

If, however, additional loads are continuously applied, as is the case with advancing thrust sheets, the lithosphere never really reaches a relaxation phase. Instead, the foreland basin and peripheral bulge maintain a constant profile and are pushed ahead of the advancing thrust sheets at a rate equal to that of the advance of the overthrusts (Quinlan and Beaumont, 1984).

Although the peripheral bulge is a very subtle feature in either case, it is prominent enough to be responsible for some of the unconformities present in the stratigraphic record of arches.

Figure 9-2 illustrates the flexural interaction between a foreland basin and an intracratonic basin. Although the diagram is intended to show how the lithosphere responds to the interaction of two basins situated at various, fixed distances apart, it also serves to show the various interactive stages as a foreland basin formed by advancing thrust sheets migrates radially toward a slowly subsiding intracratonic basin. When the basins are far enough apart there is no flexural interaction between them, and they are considered to be in a decoupled position. As the foreland basin and its peripheral bulge migrate further towards the intracratonic basin, the two peripheral bulges

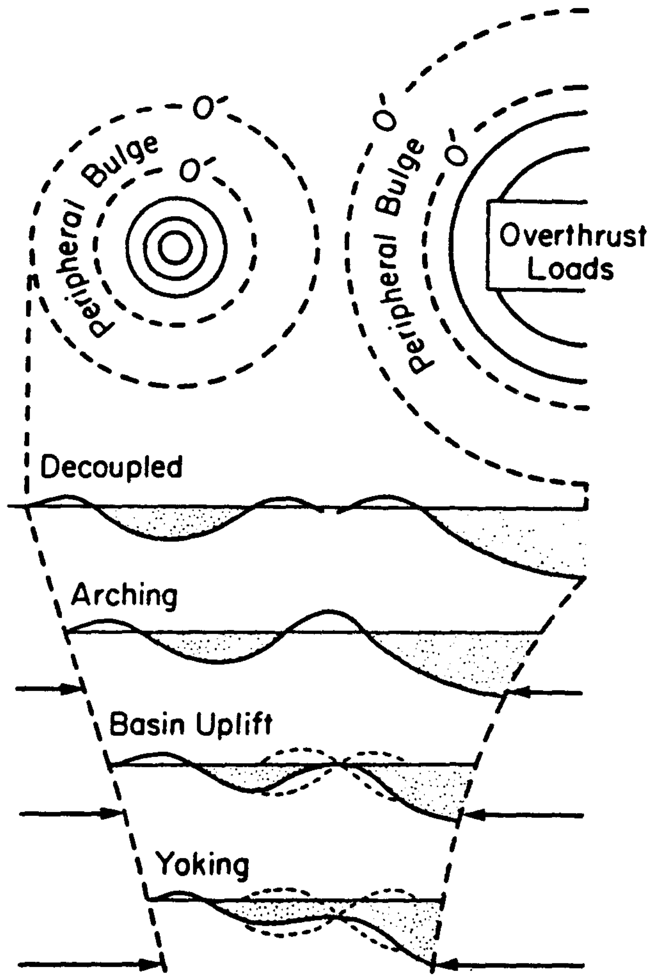


Figure 9-2. Flexural interaction between a foreland basin and an intracratonic basin. See text for discussion. From Quinlan and Beaumont (1984).

interact constructively, forming an arch which has its greatest amplitude along the line joining the two basin centers. As the basins continue to move closer together, the peripheral bulges interact destructively to produce a basin uplift. Although an arch is still present it is a very low amplitude feature, probably not having an elevation much above the depositional baseline. Finally, as the basins become very closely spaced, yoking occurs, with the result that the two basins lose their separate identities.

THE WHIRLPOOL: A CONSEQUENCE OF LITHOSPHERIC FLEXURE

Quinlan and Beaumont (1984) have shown that the Appalachian Basin stratigraphy may have been controlled primarily by the lithosphere's response to overthrust loading. If this was the case, it should be possible, by examining the stratigraphic record, to reconstruct the series of events that led to the deposition of the lower and upper part of the Whirlpool and the overlying formations. The following account of the Whirlpool's deposition is based on Beaumont's (1978, 1981) and Quinlan and Beaumont's (1984) model of lithospheric flexure, and although there are minor details that remain to be worked out, the model appears to be sufficient in explaining the presence and features of the Whirlpool, Manitoulin, Cabot Head, and Power Glen.

During the Late Ordovician (Cincinnatian), overthrust loading in the region of Pennsylvania resulted in the yoking of the Michigan and Appalachian Basins and the deposition of the Taconian clastic sequence, culminating in the formation of the Queenston delta (Quinlan and Beaumont, 1984). Exactly what happened after the Queenston deposition and prior to the Silurian is difficult to determine, but if there is to be any consistency with what is being proposed here for the Whirlpool, it appears that the two basins were probably soon decoupled by lithospheric relaxation during a brief, tectonically quiescent period. During the decoupling, the Appalachian Basin's peripheral bulge probably uplifted and migrated towards the southeast, eroding material from the previously deposited Queenston Shale in the Southern Ontario and western New York area. Although this is a feasible mechanism for producing the unconformity between the Queenston and the Whirlpool, there is the obvious question concerning the whereabouts of the sediment that was eroded on either side of the migrating peripheral bulge. If it is present at the top of the Queenston, it would certainly lend credence to the occurrence of this relaxation episode. The relaxation phase probably continued until the peripheral bulge was somewhere within eastern Pennsylvania and New York State (this is approximately the eastern limit of the Whirlpool Sandstone), at which time the relaxation phase was terminated by the arrival of another set of overthrusts from the east. The renewal of the overthrusting just prior to the Silurian probably sent the peripheral bulge migrating towards the north-northwest once more.

Exactly how or when the Whirlpool fits into the picture remains somewhat obscure. Although the peripheral bulge was broad and of low amplitude, it could have been a prominent enough feature to supply sediments to the Whirlpool River. This hypothesis that the Whirlpool River received its sediments from a sandstone unit that was uplifted by the migrating bulge is strengthened by the Whirlpool's second- or multi-cyclic nature, which precludes the idea of the new thrust sheets or the Queenston's source being the Whirlpool's source. The source must have been a pre-existing sandstone that was situated somewhere in eastern Pennsylvania and lower New York State and that became uplifted by the bulge just prior to and for some time after the renewal of overthrusting and the northwestward migration of the peripheral bulge.

The unknown sandstone could have been a formation that is no longer preserved in the stratigraphic record, having been totally eroded by the migration of the peripheral bulge, but there in now evidence that the Oswego Sandstone (an eastern equivalent of the Queenston Formation) may be the Whirlpool's source. Fisher (1954) originally suggested the idea, and this is further supported by the regional facies distribution of the Oswego, as shown in a paper by Henderson and Timm (1985). They show that the Oswego's depositional strike is roughly northeast-southwest through the eastern half of Pennsylvania and New York State, and that northwestward from its source area in New Jersey and southeastern Pennsylvania, depositional environments must have once been alluvial-fluvial, coastal-deltaic, tidal flat, offshore, shallow marine, and fully marine. East of an imaginary north-south line passing through Llion, New York, the Oswego has been totally eroded away, and what makes this most interesting is that the erosion has taken place predominantly in the nearshore shallow marine facies of the Oswego. The Oswego Sandstone, more specifically the shallow marine facies, is therefore a good candidate for the Whirlpool's source rock, for the Whirlpool's maturity and phosphatized fossil fragments can be accounted for if its sands came from a unit that had once been in a shallow marine environment, where fauna were probably abundant and much abrasion and winnowing probably took place.

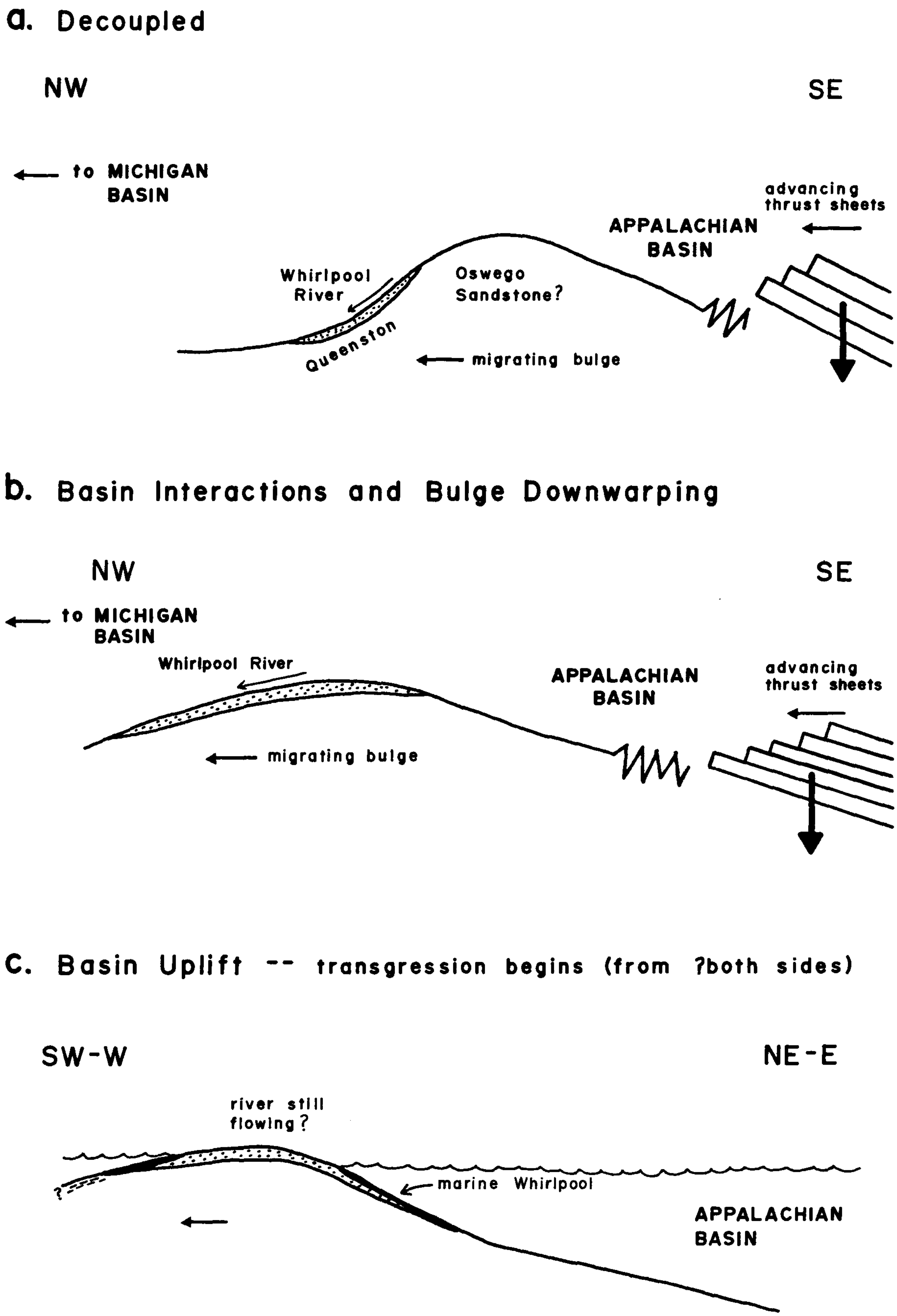
As the peripheral bulge migrated west-northwestward, minor uplifting of the Queenston Shale on the northwestern margin of the bulge may have resulted in further, although minor, erosion of the Queenston. The uplifted unknown sandstone was eroded and its sediments supplied the bedload material for the braided Whirlpool River which flowed to the northwest over the Queenston Shale on the northwestern side of the migrating bulge (Fig. 9-3a).

Figure 9-3. Sketches showing the deposition of the Whirlpool Sandstone as a consequence of the lithosphere's flexural response to overthrust loading. See text for discussion.

a) During the decoupled stage the Whirlpool River flowed over the Queenston Shale on the northwest side of the northwest-migrating peripheral bulge. Its sediments are indicated by the dotted area.

b) As the thrust sheets advanced and as the bulge continued migrating to the northwest, interactions with the Michigan Basin caused downwarping of the bulge; as a result, the Whirlpool's depositional slope was reduced.

c) Further basin interactions and the emplacement of overthrusts in the south (which tilted the Whirlpool's alluvial plain to the south-southeast and resulted in a new paleoslope to the southwest) resulted in a marine transgression (from ?both sides of the bulge) over the Whirlpool's fluvial deposits.


a. Decoupled
NW
SE
to MICHIGAN BASIN
advancing thrust sheets
APPALACHIAN BASIN
Whirlpool River
Oswego Sandstone?
Queenston
migrating bulge
b. Basin Interactions and Bulge Downwarping
NW
SE
to MICHIGAN BASIN
Whirlpool River
APPALACHIAN BASIN
advancing thrust sheets
migrating bulge
c. Basin Uplift -- transgression begins (from ?both sides)
SW-W
NE-E
river still flowing?
marine Whirlpool
APPALACHIAN BASIN

As the bulge continued its west-northwestward migration out of the source area, initial interactions with the Michigan Basin probably occurred, and this may have caused the peripheral bulge to lose some of its topographic differentiation. As well, the Whirlpool River, at this time, was probably now flowing near the top of the bulge, where depositional slopes were less, resulting in a decrease in stream competency. Both of these situations, the decrease in bulge topography and the reduction in slope, may be responsible for the overall fining-upward trend observed in the Whirlpool Sandstone. Inevitably as the bulge passed by, previously deposited Whirlpool River sediments may have become uplifted and probably experienced some minor erosion, supplying its own sediments to the Whirlpool River (Fig. 9-3b).

With further bulge migration, complex lithospheric interactions of the Michigan, Appalachian, and possibly the Illinois Basins, coupled with the emplacement of a new set of thrust sheets to the south-southeast (source of the Tuscarora and Grimsby Sandstones), caused the Whirlpool's alluvial plain to be tilted towards the south-southeast. This tilting, combined with the Whirlpool's original northwest paleoslope, resulted in a new paleoslope direction, to the southwest (Middleton, pers. comm., 1986).

As the basins continued to migrate towards each other--the Michigan Basin likely underwent a slow but steady subsidence (Quinlan and Beaumont, 1984)--the lithosphere responded by further downwarping the bulge, or arch, producing a basin uplift situation. It was this process of downwarping that actually initiated the transgression over the fluvial Whirlpool deposits, although it is probable that a eustatic sea level rise, caused by the deglaciations in northern Africa at this time (McKerrow, 1979), may have contributed to it, as well. The interesting thing about this transgression is that not only did the transgression come from the southwest (255 degrees), but also, due to the complicated, three-dimensional, lithospheric interactions of the Michigan, Illinois, and Appalachian Basins, which may have opened up a gap somewhere further south, thereby allowing water to enter into the Appalachian Basin, it is possible that a transgression may have come from the south or southeast, as well (Fig. 9-3c).

On the west-southwest side of the rapidly subsiding bulge the epeiric sea waters transgressed a very low-gradient slope, eroding the upper few meters of the fluvial Whirlpool deposits and redepositing them in the very shallow, low-energy nearshore zone. On the southeast side of the bulge the slope was slightly steeper but still low enough that the upper Whirlpool formed in a similar environment as on the west-southwest side. The deeper water on the south-southeast side, however, accounts for the upper Whirlpool's lower sandstone:shale ratio and its transition into what are probably deep water facies, the Cabot Head Shale and Power Glen Shale, in sections east of Stoney Creek, Ontario, and in the Lake Erie region.

As the peripheral bulges of the two basins continued to migrate towards each other, further downwarping of the intervening arch, possibly combined with a minor eustatic rise in sea level, resulted in the yoking of the Michigan and Appalachian Basins and in the joining of the two bodies of water formerly separated by the bulge, or arch (Fig. 9-4a). Prior to and during this time, carbonate sedimentation (Manitoulin Dolomite), normally restricted to the center of the Michigan Basin, had probably already begun to extend its depositional boundaries towards the east, due to the eastward transgression of the epeiric sea. Similarly, in the 'Appalachian Basin' the Cabot Head and Power Glen, which were forming on the southeast and south margins of the arch, and which probably received their supply of sediment from the Appalachian Highlands, began to extend westward and northwestward their depositional boundaries, due to the apparent rise in sea level and, possibly, to an increase in sediment supply from the south-southeast.

Further bulge downwarping, or the apparent rise in sea level, resulted in superposing the Manitoulin and Cabot Head or Power Glen deposits on those of the Whirlpool's (Fig. 9-4a). An imaginary line passing through present day

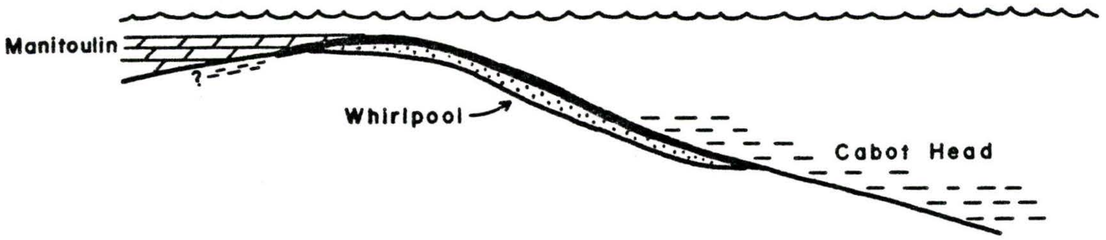
Figure 9-4. Sketches showing the deposition of the Medina formations. See text for discussion.

a) Further basin interactions resulted in the yoking of the Michigan and Appalachian Basins. The depositional boundaries of carbonate (Manitoulin) and shale (Cabot Head) sedimentation were extended eastward and northwestward, respectively, over the Whirlpool's sediments.

b) A regression displaced the Cabot Head's depositional area further northwestward while the sands and shales of the Grimsby and Thorold were deposited closer to the shoreline. The resulting stratigraphic interval bounded by the Whirlpool and Thorold constitutes the Medina Group.

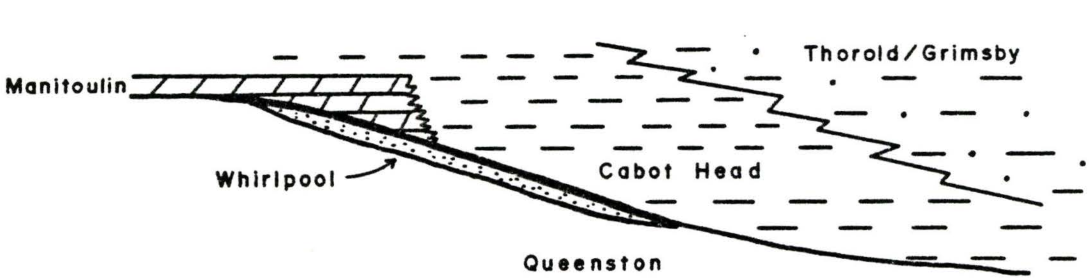
a. Yoking -- advanced stages of the transgression

SW-W NE-E



b. Medinan Stratigraphy

SW-W NE-E



formed at this time as the bulge uplifted and eroded a previously deposited sandstone unit and supplied the sediments to the Whirlpool River which was flowing northwestward in front of the migrating bulge. As the bulge migrated further northwestward, initial interactions with the Michigan Basin caused the bulge to lose some of its topographic differentiation. Further basin interactions, coupled with the emplacement of thrust sheets to the south-southeast caused further downwarping of the bulge and also caused a south-southeast tilting of the Whirlpool's alluvial plain. The net result of this tilting was an alluvial plain that now sloped to the southwest instead of to the northwest. Further basin interactions may have opened a gap south of the Michigan Basin, allowing water to seep into the Appalachian Basin (south-southeast side of arch), caused additional bulge downwarping, and initiated the transgression, from both sides of the bulge, over the Whirlpool's fluvial deposits. Some of the Whirlpool's fluvial sediments were eroded and were redeposited in a very shallow, low-energy nearshore zone on the southwest side of the arch and in a somewhat deeper, although still low-energy, nearshore zone on the south-southeast side. Further arch downwarping, possibly coupled with a small eustatic rise in sea level, superposed the Manitoulin Dolomite and deeper water Cabot Head and Power Glen Shales on the Whirlpool sediments.

It must be remembered, however that the above account of the controls on the Whirlpool's deposition is highly conjectural. While it can account well for many aspects of the Whirlpool's deposition, it cannot account for others. The six aspects of the Whirlpool's deposition mentioned at the beginning of this chapter appear to be sufficiently explained by the lithospheric flexure model: 1) The planar, sharp contact separating the Whirlpool and Queenston is erosional in nature and may be due to the migration of the peripheral bulge during the decoupling stage in the late Ordovician and/or after the emplacement of new thrust sheets in the east. 2) The fining-upward trend and perhaps even the downstream change in fluvial style may be the result of a combination of bulge downwarping, due to initial interactions with the Michigan Basin, and the position of the river on the migrating bulge. 3) The source of the Whirlpool River's sediment was a pre-existing sandstone that was probably situated somewhere in eastern Pennsylvania and New York State and that became uplifted by the peripheral bulge formed by the west-northwestward advancing thrust sheets in the Appalachian region. The facies distribution and the location of the erosional edge of the Oswego Sandstone makes it a good candidate for the Whirlpool's source rock. 4) The south-southeast tilting of the Whirlpool's northwest-dipping alluvial plain (resulting in a new paleoslope to the southwest) prior to the transgression was probably due mostly to the emplacement of new thrust sheets to the south in the Appalachians, although the complex lithospheric interactions of the Michigan, Appalachian, and possibly the Illinois Basins may have contributed to the effect, as well. 5) The transgression, too, was probably a consequence of basin interactions and of overthrust loading in the south. The transgression probably began during the more advance stages of basin lithospheric interactions, when the bulge became downwarped, producing a basin uplift situation, and the waters of the Michigan Basin to the west-southwest began to transgress over the fluvial Whirlpool deposits. 6) Although from the northwest-southeast orientation of the Whirlpool's symmetrical ripples it is clear that the marine transgression over the fluvial Whirlpool must have come from the southwest, a transgression coming from the south or southeast is also needed to explain why the Whirlpool is overlain by a deeper-water facies (Power Glen and Cabot Head) in the south and southeast than in the north and northwest (Manitoulin).

Some questions regarding the application of the lithospheric flexure model to the Whirlpool's deposition remain to be explained: 1) why are the symmetrical ripples oriented northwest-southeast in sections east of Stoney Creek, if the transgression is believed to have come from the south or southeast? 2) can the peripheral bulge migrate from a decoupled stage to an arched stage in one million years, which is believed to be the time needed for the lower Whirlpool's deposition? and 3) where are the Queenston sediments that were eroded during the relaxation phase prior to the renewal of overthrusting or during the northwestward migration of the bulge, ahead of the Whirlpool River?

CHAPTER 10

CONCLUSIONS

The following conclusions can be made regarding the depositional environment, petrography, and cause of deposition of the Whirlpool Sandstone:

GEOMETRY, FACIES, AND DEPOSITIONAL ENVIRONMENT

1. The Whirlpool Sandstone (Lower Llandovery) is a sheet-like sandstone, less than 9 m thick, forming the base of the Medina Group in Southern Ontario and western New York. Its lower contact with the Queenston Shale is sharp, relatively flat, and unconformable while its upper contact with the Manitoulin in the northwest part and the Cabot Head and Power Glen in the south and southeast part of the study area is gradational.
2. Two units, a lower and an upper, distinctive on the basis of their facies, paleocurrent patterns, and the absence or presence of body and trace fossils and microfossils, are recognized in the Whirlpool.
3. The lower unit, constituting approximately two-thirds of the Whirlpool's total thickness, lacks body

and trace fossils, marine microfossils (but does have spore-like microfossils), and wave-formed structures, and is most likely terrestrial in origin. The sheet-like geometry, facies and facies associations, stacked fining-upward sequences, consistent northwest paleocurrents, scour surfaces, erosional nature of facies contacts, vertically aggraded channels, and lack of lateral and vertical accretion deposits all support a braided fluvial interpretation for the lower Whirlpool.

4. The facies of the lower unit, in order of decreasing relative abundance, include: trough cross-laminated (St), ripple cross-laminated (Sr), horizontally-laminated (Sh), planar tabular cross-laminated (Sp), low-angle cross-laminated (Sl), massive (Sm), convolute laminated (Sc), and wavy-laminated (Sw) sandstones.

5. Paleocurrents obtained from trough cross-laminations, small scale rib-and-furrow structures, parting lineations, current crescents, planar tabular cross-laminations and fold axes of convolute laminations indicate that the Whirlpool River flowed to the northwest (301 degrees). In the absence of advanced and abundant terrestrial plant life, the river's channels shifted constantly and caused the river to migrate over a vast area roughly 450 km

square. The presence of three facies associations are indicative of downstream changes in the fluvial style. In the southeast, where sections are dominated by facies St, the river was moderately braided, well channelised, carried a coarser bedload, and was subject to frequent stage fluctuations. Farther to the northwest, where sections show a mixture of facies St, Sr, and Sh, the river was characterized by a higher braiding parameter, shallower, less well-defined channels, finer bedload, and frequent channel shiftings. More distally, where sections are dominated by facies Src and Sh, the river was even more highly braided, and channels were so shallow that sheet floods on the braidplain were very common.

The river was frequently flooded. In-channel bedforms consisted of dunes and plane beds, with vertically aggraded ripples forming, as well, in the more shallow channels. Bar top bedforms included plane beds, ripples, sandwaves, and dunes. Braidplain deposits consisted of ripples and plane beds.

6. The thinness of the lower Whirlpool and absence of major internal stratigraphic breaks suggest that the river possibly operated over a period of about 1 million years.

7. The <u>upper unit</u> is clearly marine in origin, as is indicated by the facies and the presence of body and

trace fossils, marine microfossils, and wave-formed structures. Facies in the upper unit, in order of decreasing relative abundance, include: interbedded sandstone and shale (S/F), bioturbated sandstone (Sb), wavy-laminated sandstone (Sw), hummocky cross-stratified sandstone (Shcs), and low-angle cross-laminated sandstone (Sl). These facies and the presence of HCS, wave ripples, desiccation and synaeresis cracks, wrinkle marks, Cruziana and Skolithos ichnofacies, abundant and diverse spore-like microfossils, and the lack of typical shoreface and beach deposits, suggest that the upper Whirlpool formed in a low-energy nearshore zone of a shallow, low-gradient epeiric sea, where wave energy was normally dissipated some distance from shore.

8. The deposits of this low-energy nearshore zone consisted of an alternation of sand and shale layers. The shale interlayers drape over the sandstone layers and are thoroughly bioturbated with traces comprising the Cruziana ichnofacies, suggesting that the environment normally experienced very quiet water sedimentation and hosted a variety of deposit-feeding organisms. The sandstone interlayers display sharp, erosive bases, allochthonous fossils, laterally continuous beds, HCS, waning flow structures, symmetrical ripples, and traces comprising the

Skolithos ichnofacies, indicating that this nearshore environment was frequently interrupted by large storms which eroded and redistributed the fluvial sediments.

The lack of evaporite deposits in the inner zone possibly suggests that the climate was normally humid; however, the presence of desiccation and synaeresis cracks, euryhaline fossils, and celestite vugs indicates that some seasonal aridity or restricted conditions probably existed.

9. Northwest- to southeast-striking symmetrical ripples indicate that the transgression came from the southwest.

10. Fluvial scouring into the Whirlpool's marine unit at Lockport suggests that the Whirlpool River may have still been operating at the time of the transgression.

11. The scouring processes of the transgression effected an erosional pinchout of the lower Whirlpool deposits in the west.

PETROGRAPHY

1. The Whirlpool Sandstone is a subarkose to quartzarenite. The grains are moderately spherical, rounded, and well-sorted, and are silica- and carbonate-cemented.

2. Feldspar content averages less than 8% of the framework and is variable both regionally and vertically, showing no major trends other than being higher in the most northwestern and western sections.

3. No major compositional differences exist between the upper and lower unit Whirlpool sands, further supporting the view that the upper Whirlpool is reworked lower Whirlpool.

4. The Whirlpool's porosity, which is secondary and comprises less than 3% of the rock, shows no regional or vertical trends. The porosity does not seem to be directly related to the amount of detrital feldspar (feldspar dissolution accounts for 20% of the total porosity) and calcite cement.

5. The average grain size of the Whirlpool is fine to very fine sand. Vertically, the Whirlpool shows an overall fining-upward trend, which is most likely the result of reduced stream competency, caused by the gradual reduction of the depositional slope through the course of the river's history. Superimposed on this overall trend are smaller fining-upward cycles, interpreted as representing stacked channel-fill sediments. Regionally, the grain size is quite variable, although there appears to be an overall fining to the northwest and west. This trend and the variability reflect the downstream changes in the

Whirlpool's fluvial style. The coarsest grains occur in the more channelised areas (regionally) of the formation, where the greatest thicknesses of the lower unit (or total thickness) also occur.

6. The sandstone's mineralogical and textural maturity, the rounding of some quartz overgrowths, the low feldspar content, and the predominance (within the appropriate framework component) of ultrastable heavy minerals, untwinned feldspar, and rounded chert grains indicates that the Whirlpool is of a second cycle or multicycle origin.

7. The Whirlpool's sediments are derived from a pre-existing sandstone somewhere to the southeast of the study area. The Oswego Sandstone (an eastern equivalent of the Queenston Formation) has been suggested as a possible source (Fisher, 1954).

TECTONIC CONTROLS

1. The presence and features of the Whirlpool may be a consequence of the lithosphere's flexural response to overthrust loading in the Appalachian region during the Taconic Orogeny.

2. The unconformity lying between the Queenston and Whirlpool may be erosional in nature, formed either during a relaxation phase prior to the renewal of

overthrusting or during the overthrusting, which caused the northwest migration of the peripheral bulge and the Whirlpool's deposition.

3. The Whirlpool River's sediments were derived from a pre-existing sandstone unit that was probably situated somewhere in eastern Pennsylvania and New York State and that became uplifted by the peripheral bulge. The facies distribution and location of the erosional edge of the Oswego Sandstone make it a good candidate for the Whirlpool's source rock.

4. Deposition of the lower Whirlpool occurred on the northwest side of the migrating bulge while the Michigan and Appalachian basins were in a decoupled state (the bulge supplied the sediments to the northwest-flowing braided river).

5. The Whirlpool's decrease in grain size upward and its downstream changes in fluvial style may be the result of the migration of the peripheral bulge and of basin interactions, which in either case would have caused the Whirlpool to flow near the top of a lower amplitude bulge.

6. The complex lithospheric interactions and the emplacement of new thrust sheets to the south caused the Whirlpool's alluvial plain to be tilted to the south-southeast. This tilting, combined with the initial northwest paleoslope, resulted in a new paleoslope to

the southwest.

7. Further basin interactions may have opened a gap to the south, allowing water to seep into the Appalachian Basin from the Michigan Basin, caused further downwarping, and initiated the transgression over the fluvial deposits from the southwest, south and southeast sides of the arch.

8. Yoking of the two basins superposed the Manitoulin Dolomite and Power Glen and Cabot Head Shales over the Whirlpool. An imaginary line (separating the Manitoulin from the Cabot Head) passing from Stoney Creek, Ontario, through to northern Lake Erie possibly represents the least downwarped area of the arch.

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APPENDIX 1

FIELD GUIDE TO THE WHIRLPOOL SANDSTONE EXPOSURES MEASURED FOR THIS THESIS

APPENDIX 1

FIELD GUIDE TO THE WHIRLPOOL SANDSTONE EXPOSURES MEASURED FOR THIS THESIS

INTRODUCTION

This appendix provides the exact locations of and detailed directions to all of the sections and cores measured for this study. The approximate locations of all the sections within the study area are shown on the small-scale general location map (Fig. 1-1) in Chapter 1. Much larger scale maps, showing the exact location of each section, are provided in this appendix. Due to the limited areal extent of these maps, however, it would be wise to obtain a road map or topographic map sheet before setting out to see the sections. The directions to the outcrops are given first, and are listed in geographical order, from northwest to southeast. The exact locations of the cores follow, and are listed roughly in geographical order, from west to east. The section descriptions (Chapter 4) also contain some information concerning the nature and location of the exposures.

All outcrops are easily accessible by car, and a short walk, generally for not more than 10 to 15 minutes, is necessary at most. The sections were measured during the summer and fall of 1984, and it is possible that accessibility conditions may have changed since then.

Other Whirlpool outcrops, not examined in this study due to their poor exposure, may be located on the maps of the Paleozoic Geology of Southern Ontario (Ontario Division of Mines, 1976).

The following abbreviations are used: Hwy, for highway; RR, for regional road; and CH, for county highway.

DIRECTIONS TO WHIRLPOOL EXPOSURES

Mitchell's Mills (Figure A1-1a; M.M.): The Whirlpool and Manitoulin form a 10 m high waterfall in Kolapore Creek, just 2.5 km southeast of Duncan and 6.75 km southwest of Ravenna. The Whirlpool, which outcrops at the base of the waterfall, is rather poorly exposed here. It is probably best to examine this section during dry periods, when water levels are considerably reduced. The exposure is on private property and is located in lot 7, conc. XI, of the Collingwood Township. Grid reference is NV439177 on the Collingwood map sheet. From Toronto, take Hwy 401 or the QEW west to Hwy 10, and follow north to the junction with Hwy 89. Turn left and after 4 km, turn right (north) onto Hwy 24. Follow for 30 km and turn left (west) onto Hwy 4. After 10 km, turn right (north) onto RR 2 and follow for

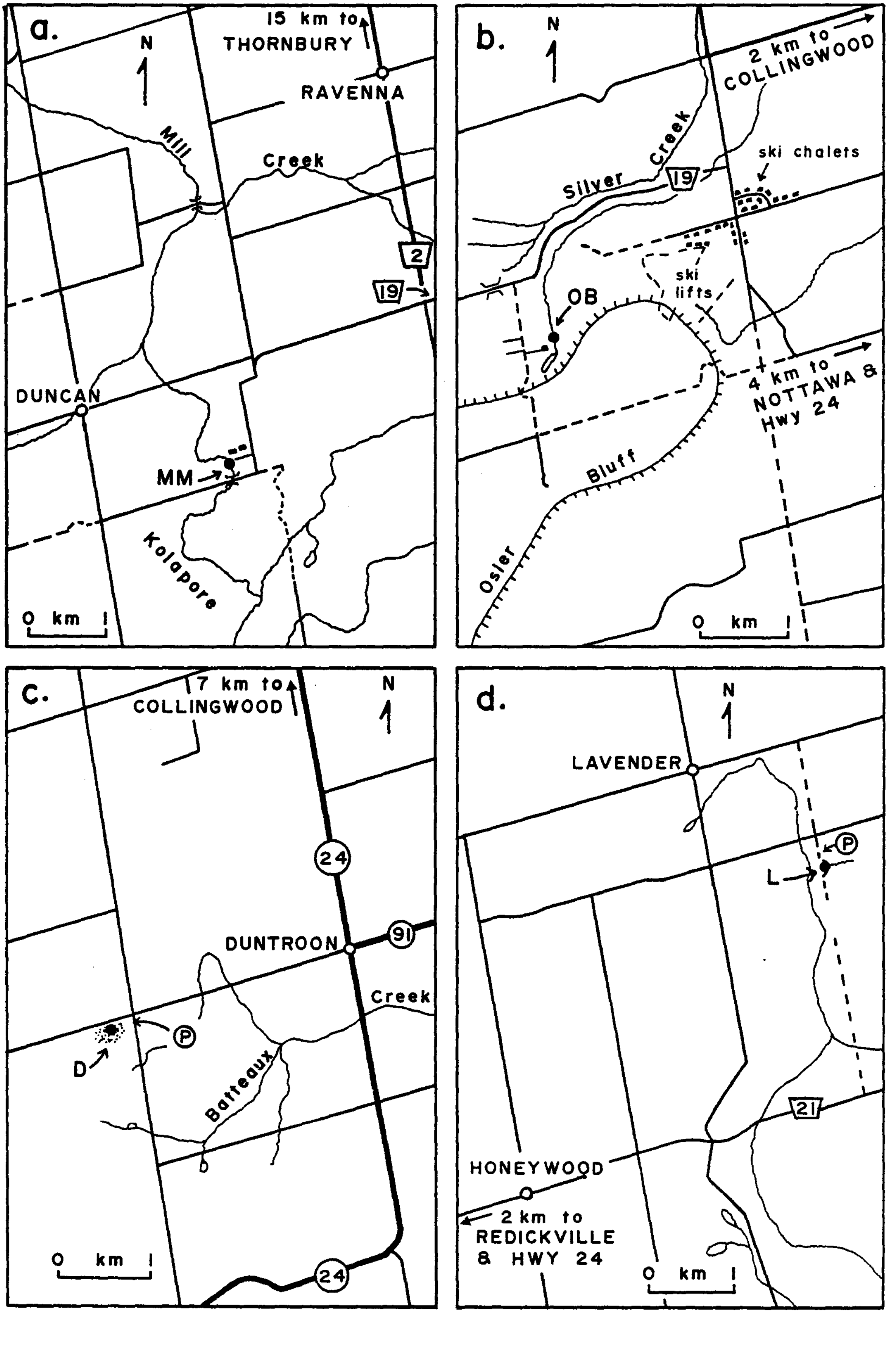
Figure A1-1. Outcrop location maps for the Mitchell's Mills, Osler Bluff, Duntroon, and Lavender sections. The circled 'P' indicates the best place to park.

a) The Mitchell's Mills section (MM).

b) The Osler Bluff section (OB).

c) The Duntroon section (D).

d) The Lavender section (L).


a.
N
15 km to
THORNBURY
RAVENNA
Mill
Creek
2
19
DUNCAN
MM
Kolapore
0 km
b.
N
2 km to
COLLINGWOOD
Silver
Creek
19
ski chalets
ski
lifts
OB
4 km to
NOTTAWA &
Hwy 24
Bluff
Osler
0 km
c.
7 km to
COLLINGWOOD
N
24
DUNTROON
91
Creek
P
D
Batteaux
0 km
24
d.
N
LAVENDER
P
L
21
HONEYWOOD
2 km to
REDICKVILLE
& HWY 24
0 km

14 km to the junction with RR 19 (see middle of far right side of Fig. A1-1a). Turn left and use Figure A1-1a as a guide to the Mitchell's Mills section. The section can be examined at the bottom of a steep path, located about 100 m past the end of the owner's driveway.

Osler Bluff (Figure A1-1b; O.B.): The Whirlpool and Manitoulin form a small, 4 m high waterfall in Black Ash Creek, 7.3 km southwest of Collingwood and 12 km northeast of the Mitchell's Mills section. The section is on private property and is very easily accessible. It is quite a poor exposure and is probably best examined during dry periods, when water levels are low. The section is located in lot 8, conc. II, Collingwood Twp. Grid reference is NV553222 on the Collingwood map sheet. From Mitchell's Mills, return to RR 19 and follow eastward for about 8 km. After passing over a bridge or before the road veers to the left, turn right onto a gravel road and see Figure A1-1b for more directions.
From Toronto, take Hwy 401 or the QEW to Hwy 10 and follow north to Hwy 24. Continue north on Hwy 24 and 1.8 km past Nottawa, turn left and follow 5.5 km to Osler Bluff (just northeast of ski lifts). See Figure A1-1b for further directions to the section. The outcrop is 300 m from the gravel road and is best reached by driving up the owners driveway and parking by the house. On foot, follow the driveway down the hill and where the road bends sharply,

take the path on the left that leads to the falls, just 50 m north of the house.

Duntroon Quarry (Figure A1-1c; D): The Whirlpool is well exposed and easily accessible in this quarry, which is situated 8 km southeast of the Osler Bluff section, and 2.6 km west of Duntroon. The quarry is located in lot 24, conc. XI, Nottawasaga Twp., and the grid reference is NV615152 on the Collingwood map sheet. Follow same directions to Osler Bluff but when on Hwy 24, turn left (west) at Duntroon (junction of Hwy 24 and 91), which is 7 km south of Nottawa. See Figure A1-1c for further instructions to the quarry. The Whirlpool is situated in the northeast corner (upper lift) of the quarry.

Lavender (Figure A1-1d; L): The Whirlpool and Queenston crop out at a small, 3 m high falls, 7.5 km south of Creemore and 1.8 km southeast of Lavender. Note that this section is not at Lavender Falls, which is 3.5 km west of the village of Lavender. The exposure is somewhat poor and is best examined during dry periods, when the amount of water flowing over the falls is considerably reduced. The section is located in lot 30, conc. II, Mulmur Twp. Grid reference is NV683008 on the Collingwood map sheet. As for the northern sections, from the QEW, take Hwy 10 to Hwy 24 and follow northward to Redickville, at the junction of

Hwy 24 and RR 21. Turn right (east) onto RR 21, and 2.5 km, or second road intersection, after passing through Honeywood, turn left. Take first right, and then another right onto the undeveloped road that leads to the section (see Fig. A1-1d). Drive about 150 m and park. The exposure is under a small bridge, about 50 m further down the road.

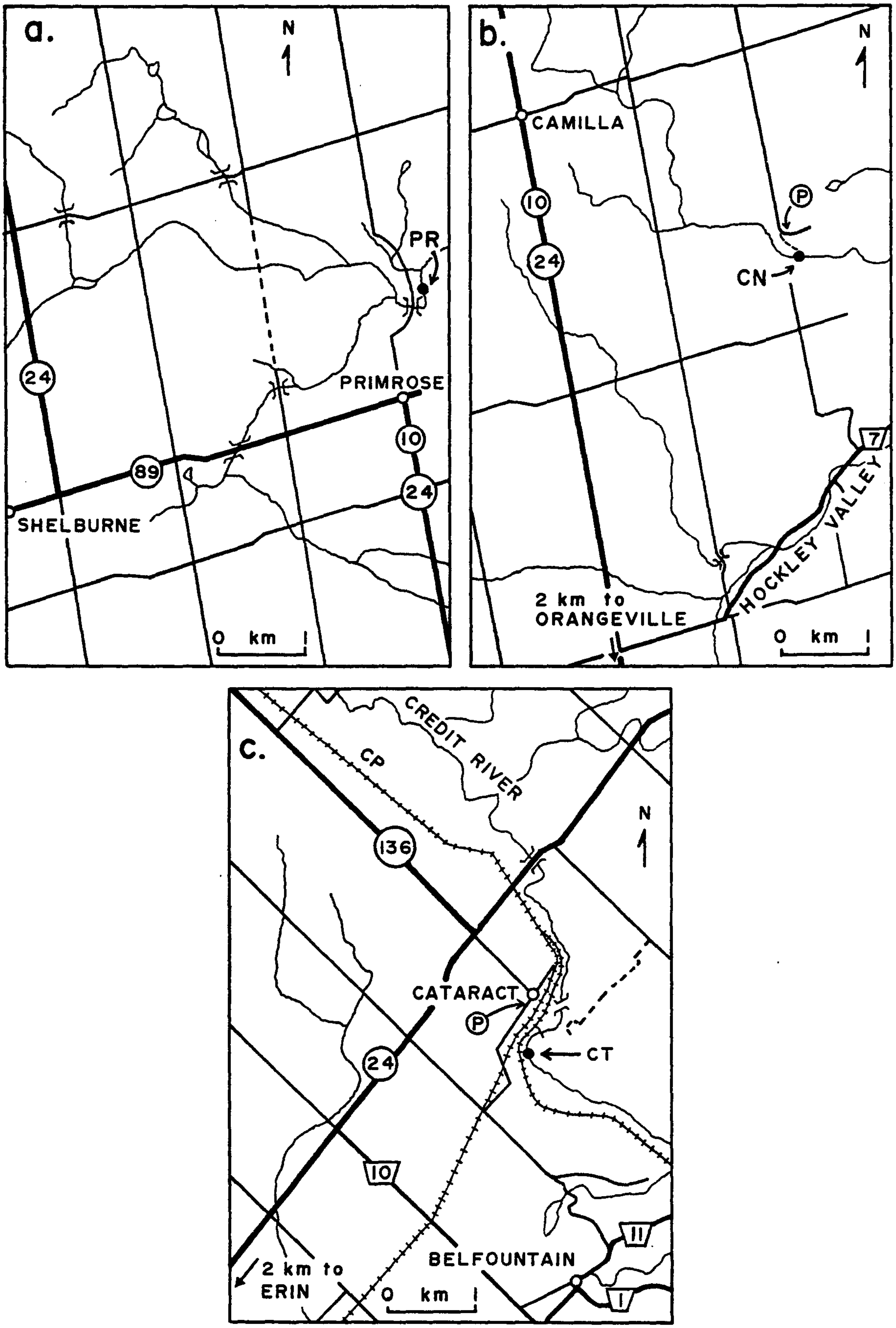
Primrose (Figure A1-2a; PR): The Whirlpool and Manitoulin crop out on the east and west sides of the Boyne River, 1 km north of Primrose and 4.2 km east of Shelburne. Being a stream section, the Whirlpool is rather poorly exposed and is best examined during low water levels. The section is located in lot 2, conc. I, Mulmur Twp. Grid reference is NU691833. From the QEW, take Hwy 10 north to Primrose (junction with Hwy 89). Continue north on this road (no longer Hwy 10), and about 1.3 km north of Primrose, after going over the bridge, park in the space provided on the right side of the road. East of the road, find the path leading down to river. The Whirlpool is best exposed on the east side of the river about 100 m downstream from the parking area. The Queenston/Whirlpool contact is exposed about another 50 m further downstream. During low water levels it should be possible to cross the river without getting wet.

Figure A1-2. Outcrop location maps for the Primrose, Cannings Falls, and Cataract sections. The circled 'P' indicates the best place to park.

a) The Primrose section (PR).

b) The Cannings Falls section (CN).

c) The Cataract section (CT).


a.
N
PR
PRIMROSE
24
89
10
24
SHELBURNE
0 km 1
b.
N
CAMILLA
10
24
P
CN
7
HOCKLEY VALLEY
2 km to
ORANGEVILLE
0 km 1
c.
CP
CREDIT RIVER
N
136
CATARACT
P
CT
24
10
11
1
2 km to
ERIN
BELFOUNTAIN
0 km 1

Cannings Falls (Figure A1-2b; CN): The Whirlpool, Queenston, and Manitoulin crop out in a deep valley cut by the northern tributary of the Nottawasaga River, about 7 km north of Orangeville and 3.3. km southeast of Camilla. Two falls are present. The upper is smaller and exposes the upper Whirlpool, while the lower exposes the lower Whirlpool and about 9 m of the Queenston. The section can be examined only during low water levels. The Manitoulin is very well exposed further (400 m) upstream at Scott's Falls. The section is located in lot 12, conc. II, Mono Twp. Grid reference is NU738706 on the Orangeville map sheet. From the QEW, take Hwy 10 north, and about 8.2 km north of Orangeville (at Camilla) turn right onto the township road (see Fig. A1-2b). After 2.8 km, turn right and park where shown on Figure A1-2b. Search for the path at the bend in the road (see dashed line on Fig.A1-2b), and follow down and to the left for about 250 m to the lower (larger) falls. The path is quite steep in some places.

Cataract (Figure A1-2c; CT): The Whirlpool, Queenston, and Manitoulin are exposed along the walls of a gorge cut by the Credit River, 6.2 km northeast of Erin and 0.5 km south of Cataract. The Whirlpool is excellently exposed on both sides of the gorge, but is accessible only on the west wall. Grid reference is NU785522 on the Orangeville map sheet. From Hamilton take the QEW to Hwy 25 and follow north to the junction with Hwy 24. Turn right (east) onto Hwy 24 and follow to the junction with Hwy 136 (about 7 km past Erin). Turn right and see Figure A1-2c for where to park. Parking is not allowed on the main road, but local residents may permit the use of their driveways. Walk along the path (abandoned road) leading into the park area and after crossing the bridge over the second set of railway tracks, turn down the path on the right and follow the railway tracks south. About 60 to 70 m past the falls, there is a steep path on the left leading down into the gorge. About halfway down, turn left and follow path back towards the falls and the Whirlpool outcrop.

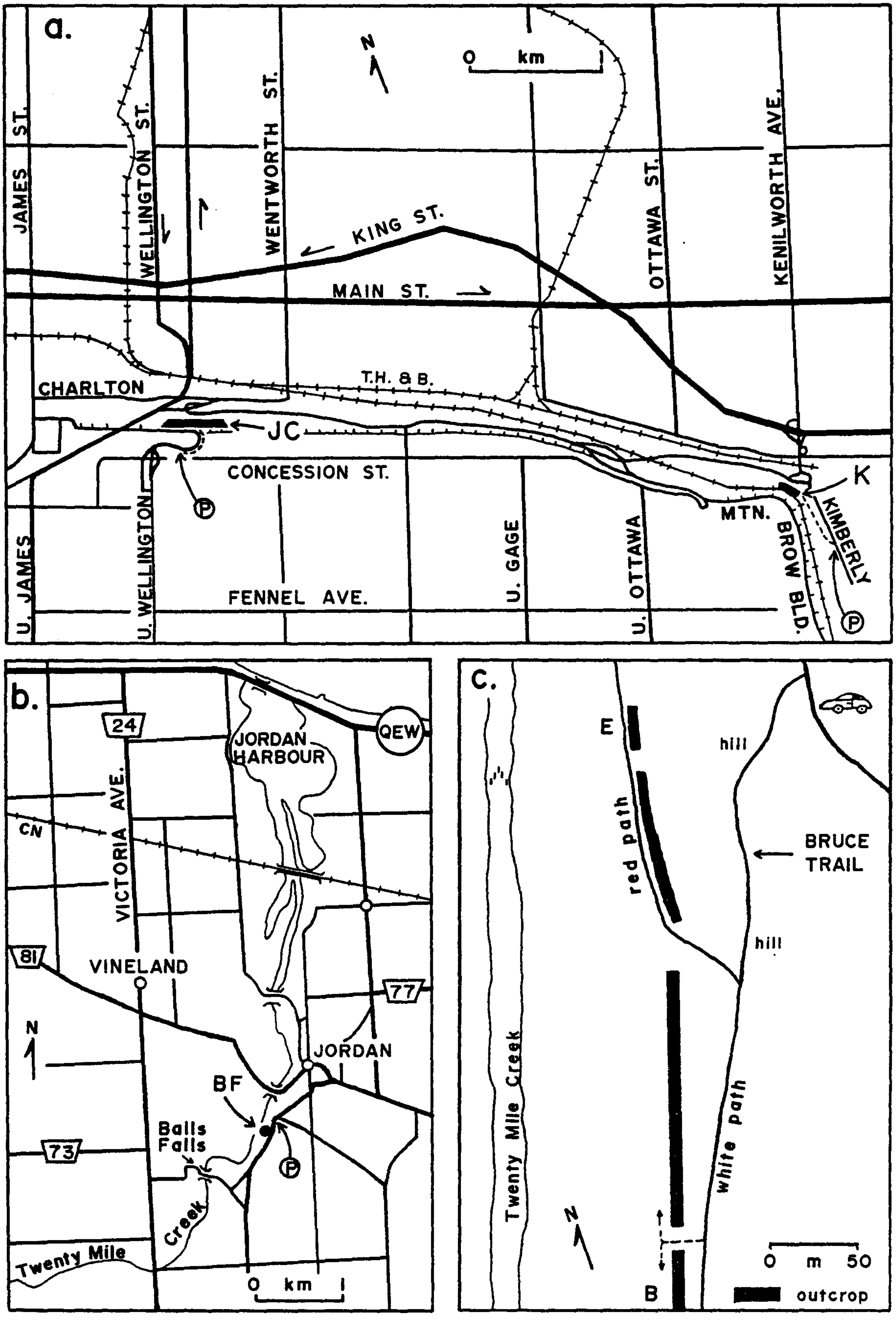
<u>The Jolley Cut (Figure A1-3a; J.C.)</u>: The Whirlpool and the other Medina formations are excellently exposed along the Niagara Escarpment throughout much of Hamilton. The Jolley Cut is located at the foot of Upper Wellington Street (see middle left of Fig. A1-3a). Grid reference is NT926885 on the Hamilton-Grimsby map sheet. Park at the lookout point, as shown. The section is about 200 to 300 m from the parking area and can be reached by following the path (dashed line) on the right (east) down to the sidewalk below. Climb over the rail and follow path (over the Cabot Head) about half way down the escarpment. (The path is quite steep and can be dangerous when wet). The Whirlpool crops out on both sides of the path, forming a 350 m + long,

Figure A1-3. Outcrop location maps for The Jolley Cut, Kenilworth Avenue, and Balls Falls sections. The circled 'P' indicates the best place to park.

a) The Jolley Cut and Kenilworth Avenue sections (JC,K).

b) The Balls Falls section (BF).

c) The locations of sections B and E at Balls Falls.


a.
N
0 km
JAMES ST.
WELLINGTON ST.
WENTWORTH ST.
OTTAWA ST.
KENILWORTH AVE.
KING ST.
MAIN ST.
T.H. & B.
CHARLTON
JC
CONCESSION ST.
P
K
MTN.
BROW BLD.
KIMBERLY
U. JAMES
U. WELLINGTON
FENNEL AVE.
U. GAGE
U. OTTAWA
b.
24
QEW
JORDAN HARBOUR
VICTORIA AVE.
CN
81
VINELAND
77
N
JORDAN
BF
Balls Falls
73
P
Creek
Twenty Mile
0 km 1
c.
E
hill
red path
BRUCE TRAIL
hill
Twenty Mile Creek
white path
N
B
0 m 50
outcrop

continuous exposure.

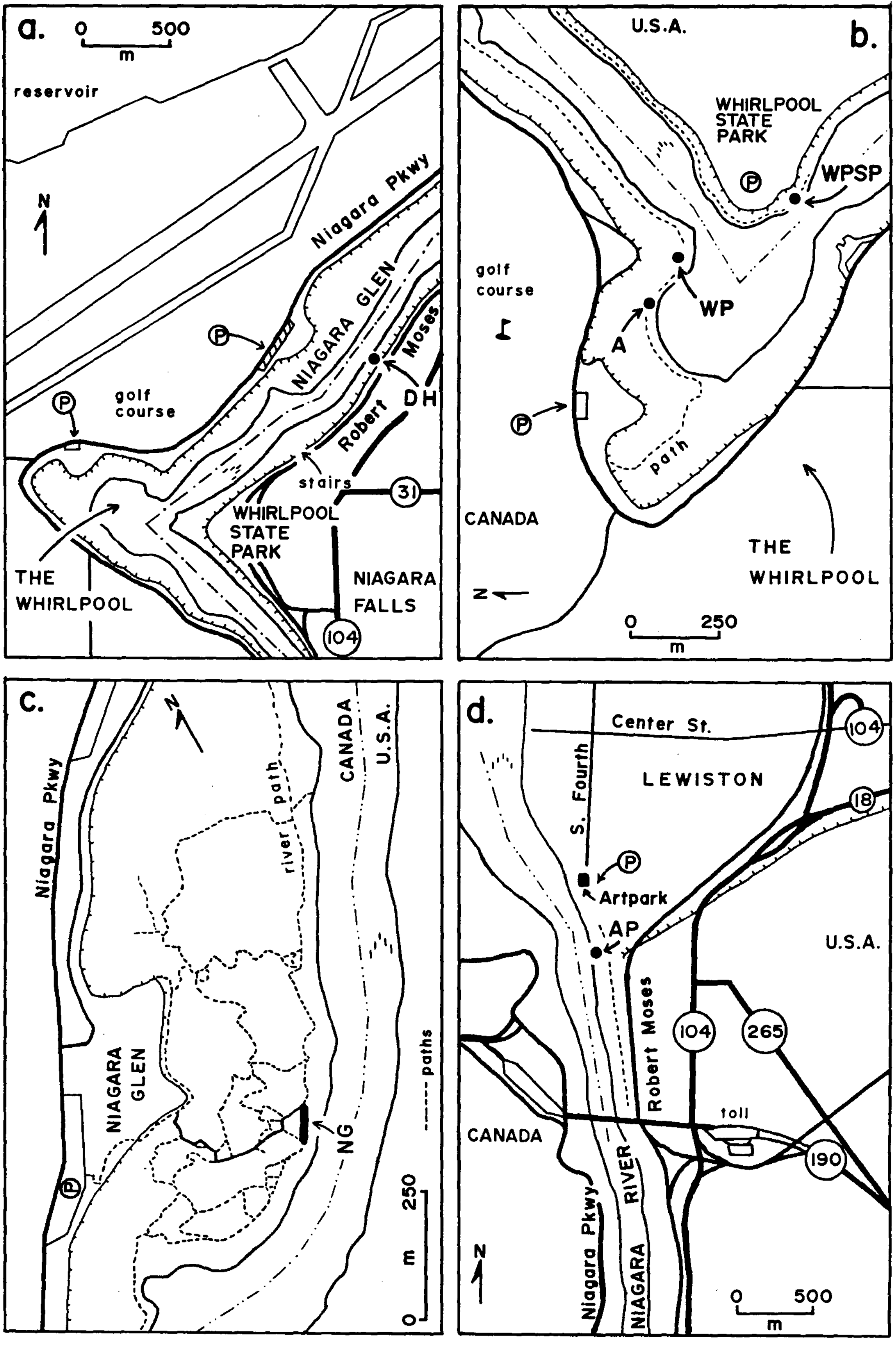
Kenilworth Avenue (Figure A1-3a; K): About 4 km east of the Jolley Cut, the Whirlpool crops out half way up the Niagara Escarpment at the foot of Kenilworth Avenue (lower right of Fig. A1-3a). The Whirlpool (2.5 m thick) is excellently exposed, but during the summer season, garden shears may be necessary to clear the tall grass and shrubs covering the outcrop. Grid reference is NT962868 on the Hamilton-Grimsby map sheet. Park on east side of Kimberley Drive, as shown. Cross the street and climb the Queenston Shale upward and to the right (see dashed line) to the Bruce Trail. Follow the trail around to the north face of the escarpment and walk up about 10 m to a leveled area (Queenston/Whirlpool contact). The exposure is about 20 m further to the west on this level. Note that the Whirlpool is exposed below the railroad tracks.

Balls Falls (Figure A1-3b,c; B.F.): The Whirlpool is exposed discontinuously for about 400 m along the sides of a ravine cut by Twenty Mile Creek. It is a good exposure, but somewhat weathered. The section is located in lot 20, conc. V, Louth Twp. Grid reference is PT321772 on the Niagara Map Sheet. From Toronto or Hamilton, take the QEW towards Niagara. Just before St. Catharines, and 6.5 km past the Beamsville turn off, turn right onto Victoria

Figure A1-4. Outcrop location maps for The Whirlpool, Niagara Glen, Whirlpool State Park, Devil's Hole, and Artpark sections. The circled 'P' in each diagram indicates the best place to park.

a) The Niagara Gorge showing the general locations of all the sections except the Artpark section.

b) Diagram of The Whirlpool Basin showing the locations of The Whirlpool (WP,A) and Whirlpool State Park (WPSP)



a.
0 500
m
reservoir
N
Niagara Pkwy
NIAGARA GLEN
P
golf course
Robert Moses
DH
stairs
31
WHIRLPOOL STATE PARK
THE WHIRLPOOL
NIAGARA FALLS
104
U.S.A.
b.
WHIRLPOOL STATE PARK
P
WPSP
golf course
WP
A
path
CANADA
THE WHIRLPOOL
N
0 250
m
c.
N
Niagara Pkwy
river path
CANADA
U.S.A.
NIAGARA GLEN
NG
paths
0 250
m
P
d.
Center St.
104
S. Fourth
LEWISTON
18
P
Artpark
AP
U.S.A.
Robert Moses
104
265
CANADA
toll
190
Niagara Pkwy
NIAGARA RIVER
N
0 500
m

the Niagara-Lewiston exit immediately to the right and follow the Robert Moses Pkwy north, for Artpark, or south, for the other sections (see Fig.A1-4d).

Niagara Glen (Figures A1-4a,c; N.G.): Numerous, well-trodden paths (Fig. A1-4c) lead down to the water's edge, where the Whirlpool is very well exposed continuously for about 750 m. However, only one exposure (80 m long) is easily accessible and this is indicated on Figure A1-4c as 'N.G.'. The grid reference is PT58057660 on the Niagara and Queenston map sheets. The solid line in the Glen area (Fig. A1-4c) indicates the best route to this section. Walking time from the parking area is about 15 to 20 minutes. The Whirlpool section can be reached by following the River Path 1 km to the south.

The Whirlpool (Figures A1-4a,b; WP): The Whirlpool Sandstone is excellently exposed here at its type section. Exposures consist of extensive vertical sections and bedding planes, and can be reached by following the step-path (dashed line, Fig. A1-4b) down into the Whirlpool Basin. From April to November water levels are high (see Chapter 4), making accessibility to the Whirlpool's base impossible along much of the exposure; however, the entire Whirlpool at Section A (Figure 4-22, Chapter 4) is accessible all year round. Grid reference of section A is PT56957607 on the

Niagara and Niagara Falls map sheet. The bedding plane exposure, 'WP', (Fig.4-23) is 150 m east of section A, with a grid reference of PT571760. Another bedding plane (not examined in this study) lies across the basin on the Canadian side; grid reference is PT572755. The path down into the Whirlpool is steep in some places. From the parking area to section A requires a walk of about 20 to 30 minutes in duration.

Whirlpool State Park (Figures A1-4a,b; WP.S.P.): The Whirlpool State Park section consists of an excellent, very extensive, 140 m x 40 m bedding plane exposure. Some vertical exposures are present, but seasonally fluctuating water levels limit their accessibility. The grid reference of the large bedding plane, 'WPSP', is PT57357565 on the Niagara Falls and Niagara map sheets. Park at Whirlpool State Park and follow path northward for about 300 m to the Oniagara Staircase (Fig A1-4a). Descend, and at the bottom of the gorge, turn left and follow path (abandoned railway line) to the large bedding plane. From the parking area to the section, a walk of 45 to 60 minutes is involved. Rock falls, some quite large, disrupt the path in several places, making the going quite rough and potentially dangerous.

Devil's Hole (Figure A1-4a; D.H.): The Whirlpool is excellently and continuously exposed north of the Oniagara

Staircase. One of the best and most easily accessible exposures is located almost directly across from the Niagara Glen section, about 700 m north of the staircase. Grid reference is approximately PT583768. The section can also be reached by descending the Devil's Hole Staircase (grid reference PT588773) and following the path southward for about 700 to 800 m. The section is about 40 m long and is the last good exposure of the Whirlpool above the path; south of here the Whirlpool begins to crop out below the path.

Artpark, Lewiston (Figure A1-4d; AP): Access to the extensive Whirlpool exposure at Artpark is limited to only a few areas; one of the best exposures is indicated on Figure A1-4d ('AP'). Grid reference is PT58938035 on the Queenston and Niagara map sheets. See Figure A1-4d for directions to Artpark from the Robert Moses Parkway. Park in parking lot C on the left (east) side of the theater and walk south towards the abandoned railway line path (which rests on the top of the fluvial Whirlpool). Where the Niagara Gorge intersects the Niagara Escarpment, turn right onto the path that leads halfway down the Queenston Shale. The Whirlpool section is on the left, near the top of the path.

Quarry Lake (Figure A1-5a): The Whirlpool is exposed along the walls of Quarry Lake, situated (in a Boy Scout Camp) in

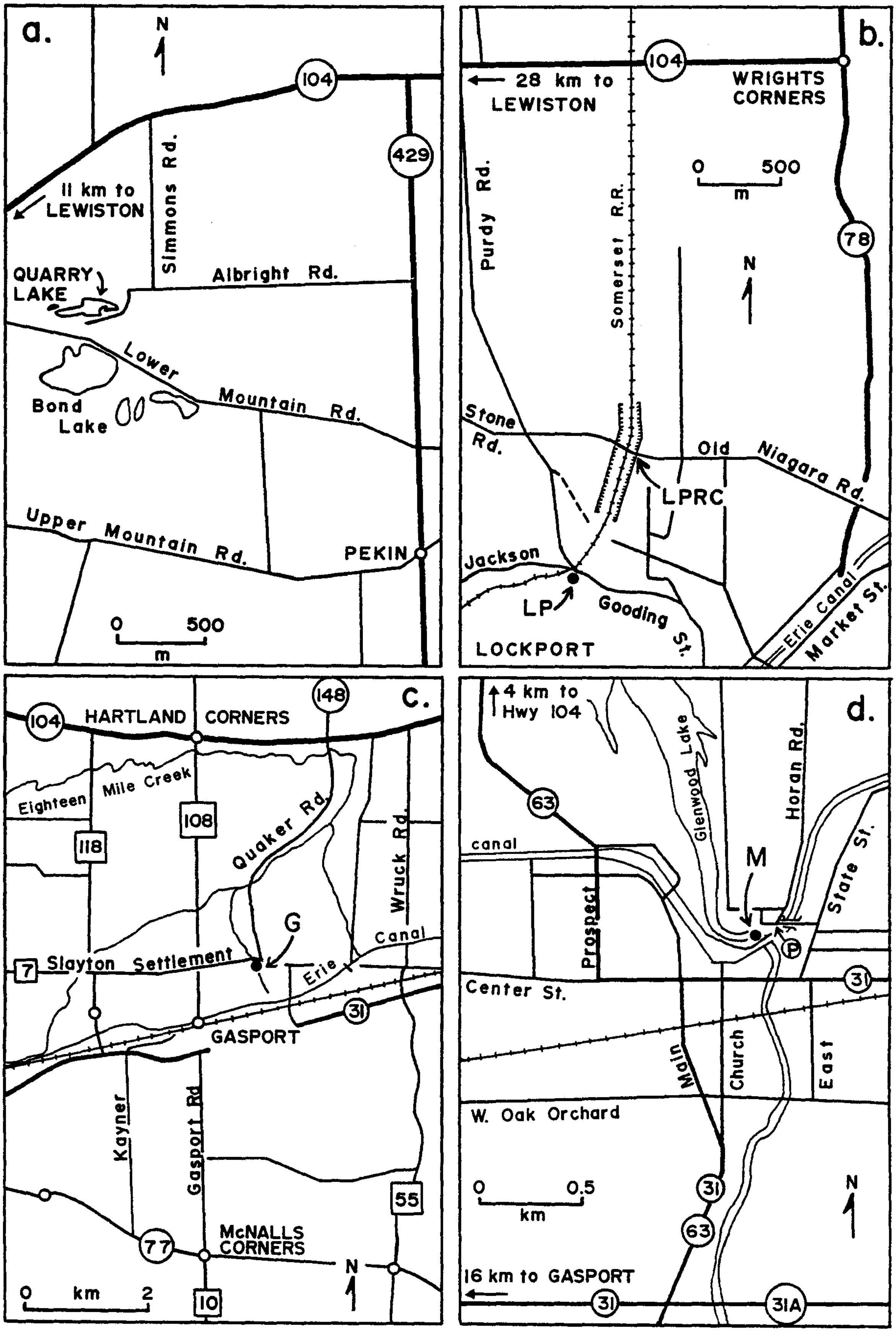
Figure A1-5. Outcrop location maps for the Quarry Lake, Lockport, Gasport, and Medina sections. The circled 'P' indicates the best place to park.

a) The Quarry Lake section.

b) The Lockport road cut (LP) and railway cut (LPRC) sections.

c) The Gasport section (G).

d) The Medina section (M).


a.
N
104
429
11 km to LEWISTON
Simmons Rd.
QUARRY LAKE
Albright Rd.
Lower Mountain Rd.
Bond Lake
Upper Mountain Rd.
PEKIN
0 500 m
b.
104
28 km to LEWISTON
WRIGHTS CORNERS
0 500 m
78
Purdy Rd.
Somerset R.R.
N
Stone Rd.
Old Niagara Rd.
LPRC
Jackson
LP
Gooding St.
LOCKPORT
Erie Canal
Market St.
c.
148
104
HARTLAND CORNERS
Eighteen Mile Creek
108
118
Quaker Rd.
Wruck Rd.
G
7
Slayton Settlement
Erie Canal
31
GASPORT
Kayner
Gasport Rd.
55
77
McNALLS CORNERS
N
0 km 2
10
d.
4 km to Hwy 104
Glenwood Lake
Horan Rd.
63
canal
M
Prospect
State St.
P
Center St.
31
Main
Church
East
W. Oak Orchard
0 0.5 km
31
63
N
16 km to GASPORT
31
31A

Bond Lake Park, 3 km northwest of Pekin, N.Y. Figure 4-31 in Chapter 4 shows the locations of the four sections measured in this abandoned, water-filled quarry. The grid reference for the quarry is PT693834 on the Ransomville, N.Y., map sheet. From Lewiston, take Hwy 104 east for 11 km (1.9 km past Dickersonville) and turn right onto Simmons Rd. At the road's end, turn right and follow road into the park area (see Figs. A1-5a and 4-31). If the park entrance gates are closed, park and walk along the road towards the quarry.

Lockport (Figure A1-5b; LP, LP.R.C.): Excellent exposures of the Whirlpool occur at a road cut (junction of Jackson and Gooding Roads) and a railway cut (junction of the Somerset Railroad and Old Niagara Road) in the north end of the city of Lockport, N.Y. The grid reference for the road cut ('LP') is PT86658360, and the railway cut ('LP.R.C.'), PT86958450. From Lewiston, travel east on Hwy 104. The second road past Warrens Corners, 28 km from Lewiston, turn right onto Purdy Road and refer to Fig A1-5b for further directions to the two exposures.

Gasport (Figure A1-5c; G): The Whirlpool is poorly exposed in the lower half of a small waterfall (eastern branch of Eighteen Mile Creek) at the junction of Quaker and Slayton Settlement (CH 7) Roads, 1.5 km northeast of Gasport, N.Y. Grid reference for the section is PT977865 on the Toronto, Canada, U.S.G.S. map sheet. Only parts of the exposure are accessible. Figure 4-37 (Chapter 4) is based on exposures on the far left and right sides of the two falls that are present. A path on the right, along side a drain, leads to the right side of the falls. From Lewiston, travel east on Hwy 104 past Lockport, through Wrights Corners, and at Hartland Corners (junction with CH 108), 40 km from Lewiston, turn right (south) onto Hartland Road and refer to Figure A1-5c for further directions. The section may also be approached from Niagara Falls or Lockport along Hwy 31. At the junction with Gasport Road (CH 10), turn left and refer to Figure A1-5c for further directions.

Medina (Figure A1-5d; M): The Whirlpool forms an 8 m high waterfall in Oak Orchard Creek in the City of Medina, New York. The exposure is not very easily accessible and is best seen during low water levels. Grid reference is QT125890 on the Toronto, Canada, U.S.G.S. map sheet. From Lewiston travel east on Hwy 104 and at Ridgeway, about 55 km from Lewiston, turn right onto Hwy 63 and follow into the city. See Figure A1-5d for further directions. Just after the bridge on Horan St., park on the left in the area provided and, on foot, follow the sidewalk southwestward along the canal for about 150 m. Locate the tree with the steps, descend into the small gorge and follow the path towards the falls. The top part of the exposure is accessible only during low water levels. The lower part can be reached by descending the south side of the gorge.

Core Locations:

The core numbers used in this study are actually the Ontario Petroleum Institute's core storage numbers. The actual well names and the essential information needed for their location are given below. The Lake Erie region is divided into a number of blocks (1 to 480), each of which, in turn, are divided into 25 tracts (A to U). All wells can be located on the Oil and Gas Pools map compiled by Booth-Horst and others (1982) of the Ontario Ministry of Natural Resources.

Core 371:

WELL NAME:	Anschutz	BLOCK/TRACT:	92-N
COUNTY:		LATITUDE:	42-32-16 N
LOT, CONC.,TWP:	Lake Erie	LONGITUDE:	80-18-46 W

Core 108:

WELL NAME:	Long Point, Port Dover No.3	BLOCK/TRACT:	14-S
		LATITUDE:	42-46-06 N
COUNTY:	Norfolk	LONGITUDE:	80-11-02 W
LOT, CONC.,TWP:	Lake Erie		

Core 106:

WELL NAME:	Anschutz-B Lake Erie 89-D	BLOCK/TRACT:	89-D
		LATITUDE:	42-34-06 N
COUNTY:	Norfolk	LONGITUDE:	80-03-43 W
LOT, CONC.,TWP:	Lake Erie		

Core 146:

WELL NAME:	CPOG Haldimand 1	BLOCK/TRACT:	131-G
	Lake Erie 131-G	LATITUDE:	42-28-19 N
COUNTY:	Haldimand	LONGITUDE:	79-58-11 W
LOT, CONC.,TWP:	Lake Erie		

Core 678:

WELL NAME:	Anschutz	BLOCK/TRACT:	21-W
	Lake Erie 21-W	LATITUDE:	42-45-45 N
COUNTY:	Haldimand	LONGITUDE:	79-37-29 W
LOT, CONC.,TWP:	Lake Erie		

Core 676:

WELL NAME:	Anschutz	BLOCK/TRACT:	23-Y
	Haldimand 23-Y	LATITUDE:	42-45-30 N
COUNTY:	Haldimand	LONGITUDE:	79-29-30 W
LOT, CONC.,TWP:	Lake Erie		

Core 552:

WELL NAME:	Consumers 32265	COORD:	975.4S:57.9E
COUNTY:	Welland		
LOT, CONC.,TWP:	9, III, Wainfleet		

Core 512:

WELL NAME:	Consumers 32273	COORD:	597.4S:70.1E
COUNTY:	Welland		
LOT, CONC.,TWP:	32, III, Humberstone		

Core 677:

WELL NAME:	Anschutz	BLOCK/TRACT:	5-X
	Lake Erie 5-X	LATITUDE:	42-50-45 N
COUNTY:	Welland	LONGITUDE:	79-13-44 W
LOT, CONC.,TWP:	Lake Erie		

Core 240:

WELL NAME:	Consumers 31841	BLOCK/TRACK:	27-G
	Lake Erie 27-G	LATITUDE:	42-48-33 N
COUNTY:	Welland	LONGITUDE:	79-08-45 W
LOT, CONC.,TWP:	Lake Erie		

<u>OGS (Corbetton) Core</u>:

WELL NAME:	Deep Hole No.1 Corbetton		
COUNTY:	Dufferin		
LOT,CONC.,TWP:	251, II, Melancthon	GRID REF:	NU514874

APPENDIX 2

PALEOCURRENT DATA

APPENDIX 2

PALEOCURRENT DATA

This appendix lists all the paleocurrent readings obtained for this study. Readings were obtained from a variety of directional features--trough cross-laminations, rib-and-furrow structures, parting lineations, planar tabular cross-laminations, symmetrical ripples, current crescents, inclination direction of fold axes, and large troughs--using methods outlined in Potter and Pettijohn (1963) and Collinson and Thompson (1982). All numbers listed below are actual paleocurrent directions, except those for parting lineations and symmetrical ripple crests; these are given as trends. Because the Whirlpool's regional dip is less than 1 degree (to the south or southwest), no additional treatment of the data (restoration to original horizontal positions) was required.

Statistics--mean azimuth (theta), vector magnitude (R), consistency (L), and Chi-square and Rayleigh Tests--and rose diagrams (Fig. 4-42 to 4-44) were calculated using a program written by Dr. G.V. Middleton. The values for the Rayleigh Test are the probabilities for rejecting the null hypothesis (that the sample does not differ from a normal distribution). The number of degrees of freedom for the

Chi square test is two.

DUNTROON

Lower Whirlpool

a) ripple cross-laminations

320	339	theta = 340
339	348	R = 4.9
355		L = 97.9%
		Chi square = 9.59
		Rayleigh Test = 0.992
		n = 5

b) parting lineations

355-175	356-176	theta = 353-173
350-170	353-173	R = 5.9
353-173	348-168	L = 99.5%
		Chi square = 11.31
		Rayleigh Test = 0.997
		n = 6

Upper Whirlpool

symmetrical ripple crestline trends

312-132
341-161

drift direction = 67

Statistics for all Duntroon readings (lower Whirlpool):

theta = 347
R = 10.8
L = 98.4%
Chi square = 21.31
Rayleigh Test = 0.999
n = 11

LAVENDER

Lower Whirlpool

ripple cross-laminations

245	243
260	

PRIMROSE

Lower Whirlpool

ripple cross-laminations

325
320
325

CANNINGS FALLS

Lower Whirlpool

a) trough cross-laminations

262	246
270	225
229	

theta = 246
R = 4.8
L = 95.3%
Chi square = 9.08
Rayleigh Test = 0.989
n = 5

b) ripple cross-laminations

270
267
288

Upper Whirlpool

symmetrical ripple crestline trends

305-125	316-136	330-150
305-125	354-174	325-145
316-136	324-144	003-183
341-161	305-125	

drift direction = 229

Cannings Falls - symmetrical ripples cont'd.

theta = 325-145
R = 8.8
L = 80.0%
Chi square = 11.61
Rayleigh Test = 0.999
n = 11

Statistics for all Cannings Falls readings (lower Whirlpool)

theta = 257
R = 7.5
L = 93.7%
Chi square = 14.06
Rayleigh Test = 0.999
n = 8

CATARACT

Lower Whirlpool

a) trough cross-laminations

310	325	310	300	322
325	294	025	350	310
300	310	309	244	272
260	345	030	031	323
262	261	331		

theta = 313
R = 18.1
L = 78.8%
Chi square = 28.53
Rayleigh Test = 0.999
n = 23

b) ripple cross-laminations

321
316

Upper Whirlpool

symmetrical ripple crestline trends

015-195	349-169	350-170
358-178	354-174	295-115
345-165	360-180	015-195

Cataract - symmetrical ripples cont'd.

theta = 355-175
R = 6.9
L = 76.8%
Chi square = 7.25
Rayleigh Test = 0.995
n = 9

Statistics for all Cataract readings (lower Whirlpool):

theta = 314
R = 20.1
L = 80.4%
Chi square = 32.34
Rayleigh Test = 0.999
n = 25

THE JOLLEY CUT

Lower Whirlpool

a) trough cross-laminations

159	132	theta = 197
230	177	R = 8.0
170	175	L = 80.0%
215	225	Chi square = 12.81
222	260	Rayleigh Test = 0.998
		n = 10

b) ripple cross-laminations

285	275	theta = 271
275	281	R = 11.6
271	277	L = 96.7%
280	273	Chi square = 22.42
282	273	Rayleigh Test = 0.999
237	240	n = 12

c) planar tabular cross-laminations

Jolley Cut cont'd.

Upper Whirlpool

symmetrical ripple crestline trends

334-154	008-188	350-170
015-195	018-198	015-195
010-190	340-160	343-163
350-170	358-178	338-158
360-180	345-165	360-180
350-170	357-177	005-185
346-166	358-178	360-180
010-190	358-178	002-182

drift directions = 070
270

theta = 357-177
R = 22.0
L = 91.5%
Chi square = 24.97
Rayleigh Test = 1.000
n = 24

Statistics for all lower Whirlpool Jolley Cut readings (minus planar tabular cross-lamination readings):

theta = 242
R = 15.8
L = 71.6%
Chi square = 22.59
Rayleigh Test = 0.999
n = 22

KENILWORTH AVENUE

Lower Whirlpool

low-angle cross-laminations

305
125

Kenilworth Avenue cont'd.

Upper Whirlpool

a) trough or planar tabular cross-laminations

326
355
320

b) symmetrical ripple crestline trends

302-122
309-129 drift direction = 034
298-118

BALL FALLS

Lower Whirlpool

a) trough cross-laminations

005	007	003	004	008
015	012	014	033	175
189	190	194	185	195
200	195	196	219	210
215	203	210	210	212
206	205	240	235	225
230	230	227	240	238
225	239	226	236	254
247	248	246	273	270
278	263	278	275	277
280	275	261	270	267
265	280	261	284	281
290	296	300	292	282
299	289	293	293	287
283	285	298	295	291
284	300	294	287	307
315	308	303	324	333
333	341	345	352	355
360	349	344		

theta = 273
R = 58.1
L = 62.5%
Chi square = 72.62
Rayleigh Test = 1.000
n = 93

Balls Fall cont'd.

b) ripple cross-laminations

260	250	277	269	255
260	250	253	280	291
295	290	286	290	318
321	328	319	328	310
328	330	323	329	320
310	275			

theta = 295
R = 23.9
L = 88.6%
Chi square = 42.36
Rayleigh Test = 1.000
n = 27

c) planar tabular cross-laminations

207
195

d) low-angle cross-laminations

334
356

e) inclination of fold axes

320

Statistics for all lower Whirlpool Balls Falls readings (minus low-angle and planar tabular cross-laminations):

theta = 279
R = 80.8
L = 67.4%
Chi square = 108.94
Rayleigh Test = 1.000
n = 120

NIAGARA GLEN

Lower Whirlpool

a) trough cross-laminations

270	265	312	328	343
242	273	293	323	316

Niagara Glen - trough cross-laminations cont'd.

307	225	252	256	264
256	247	260	255	269

theta = 277
R = 17.1
L = 85.2%
Chi square = 29.05
Rayleigh Test = 0.999
n = 20

b) ripple cross-laminations

250
254

c) parting lineations

280-100	272-092	283-103
284-104	281-101	280-100
280-100	258-078	

theta = 277-097
R = 7.7
L = 96.2
Chi square = 11.61
Rayleigh Test = 0.999
n = 8

Statistics for all Niagara Glen readings (lower Whirlpool):

theta = 275
R = 26.8
L = 89.3%
Chi square = 47.85
Rayleigh Test = 1.000
n = 30

THE WHIRLPOOL

Lower Whirlpool

a) trough cross-laminations

275	320	320	315	315
283	283	280	285	280
310	335	315	275	312
298	306	308	315	354
329	336	321	310	303

The Whirlpool - trough cross-laminations cont'd.

308	292	350	308	313
313	280	277	287	325
291	275	308		

theta = 305
R = 35.6
L = 93.7%
Chi square = 66.76
Rayleigh Test = 1.000
n = 38

b) ripple cross-laminations

300	290	055	323	315
335	325	323	333	331
280	274	273	272	333
343	336	336	335	290
300	295	290	295	

theta = 313
R = 20.9
L = 87.0%
Chi square = 36.33
Rayleigh Test = 1.000
n = 24

c) parting lineations

245-065

d) planar tabular cross-laminations

275	305
290	260
230	

theta = 272
R = 4.5
L = 90.2%
Chi square = 8.14
Rayleigh Test = 0.983
n = 5

e) current crescents

354

Statistics for all The Whirlpool readings (lower Whirlpool)
(minus planar tabular cross-laminations)

theta = 307
R = 56.8
L = 90.2%

Chi square = 102.60
Rayleigh Test = 1.000
n = 63

WHIRLPOOL STATE PARK

Lower Whirlpool

a) trough cross-laminations

340	343	275	275	267
253	235	260	300	300
307	254	274	215	284
274	261	310	305	358

theta = 284
R = 16.5
L = 82.5%
Chi square = 27.22
Rayleigh Test = 0.999
n = 20

b) ripple cross-laminations

320	292	293	301	295
280	296	301	288	288
240	231	229	280	295
286	285	280	285	297
278	281	284	285	287
316	210	289		

theta = 283
R = 25.6
L = 91.5%
Chi square = 46.86
Rayleigh Test = 1.000
n = 28

c) parting lineations

303-123
295-115

d) planar tabular cross-laminations

279	275
298	315

theta = 292
R = 3.8
L = 96.1%
Chi square = 7.39
Rayleigh Test = 0.975

Statistics for all Whirlpool State Park readings (lower Whirlpool):

theta = 284
R = 44.0
L = 88.1%
Chi square = 77.56
Rayleigh Test = 1.000
n = 50

DEVIL'S HOLE

Lower Whirlpool

a) trough cross-laminations

074	082	049	060	055
244	059	084	013	054
055	314	240	239	190
297	075	079	340	

theta = 47
R = 7.3
L = 38.3%
Chi square = 5.58
Rayleigh Test = 0.939
n = 19

b) ripple cross-laminations

353	340
345	

c) planar tabular cross-laminations

225	215
245	220
221	212

theta = 223
R = 5.9
L = 98.3%
Chi square = 11.59
Rayleigh Test = 0.997
n = 6

d) current crescents

340

Statistics for all Devil's Hole readings (lower Whirlpool) (minus planar tabular cross-lamination readings):

theta = 30
R = 9.1
L = 41.5%
Chi square = 7.57
Rayleigh Test = 0.977
n = 22

ARTPARK

Lower Whirlpool

a) trough cross-laminations

188	045	330	340	305
307	003	030	295	002
028	318	317	028	350
335	332	015	055	080
325	335	324	348	312
040	032	350	280	275
214	233	309	303	360
005	315	344		

theta = 340
R = 25.8
L = 67.9%
Chi square = 35.00
Rayleigh Test = 1.000
n = 38

b) ripple cross-laminations

310	020
007	359
004	346
347	015
002	356
358	

theta = 357
R = 10.5
L = 95.4%
Chi square = 20.02
Rayleigh Test = 0.999
n = 11

Statistics for all Artpark readings (lower Whirlpool):

theta = 345
R = 35.9
L = 73.3%
Chi square = 52.69
Rayleigh Test = 1.000
n = 49

QUARRY LAKE

Lower Whirlpool

a) trough cross-laminations

295	240	100	080	255
195	330	312	235	280
053	035	235	255	261
345	020	015	008	018
040	043	355	328	060
074	310	295	310	

theta = 337
R = 11.8
L = 40.8%
Chi square = 9.65
Rayleigh Test = 0.992
n = 29

b) ripple cross-laminations

250
274

c) planar tabular cross-laminations

077	090
078	095
090	

theta = 086
R = 4.9
L = 99.2%
Chi square = 9.84
Rayleigh Test = 0.993
n = 5

Statistics for all lower Whirlpool Quarry Lake readings (minus planar tabular cross-lamination readings):

theta = 328
R = 12.5
L = 40.2%
Chi square = 10.04
Rayleigh Test = 0.993
n = 31

LOCKPORT

Lower Whirlpool

a) trough cross-laminations

032	027	222	255	245
265	254	306	330	002
023	056	072	073	052
088	052	075	059	060
050	072	061	025	037
033	036	020	266	280
280	033	074	093	290
257	270	340	284	205
345	280	285		

theta = 5
R = 15.9
L = 37.1%
Chi square = 11.82
Rayleigh Test = 0.997
n = 43

b) ripple cross-laminations

337

Upper Whirlpool

symmetrical ripple crestline trends

336-156	010-190	347-167
355-175	358-178	354-174
350-170	354-174	355-175
338-158	360-180	355-175
320-140	294-114	295-115
295-115	300-120	

drift directions = 072
070

theta = 341-161
R = 11.2
L = 66.1%
Chi square = 16.15
Rayleigh Test = 0.999
n = 17

Statistics for all Lockport readings (lower Whirlpool):

theta = 3
R = 16.8
L = 38.3%
Chi square = 12.88
Rayleigh Test = 0.998
n = 44

<u>MEDINA</u>

<u>Lower Whirlpool</u>

a) ripple cross-laminations

280	282	270

b) parting lineations

322-142

Statistics for all Medina readings (lower Whirlpool):

theta = 288
R = 3.8
L = 94.1%
Chi square = 7.09
Rayleigh Test = 0.971
n = 4

APPENDIX 3

PALEOCURRENT STATISTICS

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PALEOCURRENT STATISTICS

This appendix provides the statistics for the various rose diagrams shown on the the regional paleocurrent maps in chapter 4 (Figs. 4-42, 4-43, and 4-44) and for the rose diagrams accompanying the Whirlpool and Whirlpool State Park bedding plane maps (Figs. 4-24 and 4-25).

The following abbreviations are used: txl, for trough cross-laminations; rxl, for ripple cross-laminations; and pl, for parting lineations.

TROUGH CROSS-LAMINATIONS (FIGURE 4-42)

Cannings Falls:

theta = 246	Chi square = 9.08
R = 4.8	Rayleigh Test = 0.989
L = 95.3%	n = 5

Cataract:

theta = 313	Chi square = 28.53
R = 18.1	Rayleigh Test = 0.999
L = 78.8%	n = 23

Jolley Cut:

theta = 197	Chi square = 12.81
R = 8.0	Rayleigh Test = 0.998
L = 80.0%	n = 10

Balls Falls:

theta = 273	Chi square = 72.62
R = 58.1	Rayleigh Test = 1.000
L = 62.5%	n = 93

Niagara Glen:

theta = 277	Chi square = 29.05
R = 17.1	Rayleigh Test = 0.999
L = 85.2%	n = 20

The Whirlpool:

theta = 305	Chi square = 66.76
R = 35.6	Rayleigh Test = 1.000
L = 93.7%	n = 38

Whirlpool State Park:

theta = 284	Chi square = 27.22
R = 16.5	Rayleigh Test = 0.999
L = 82.5%	n = 20

Devil's Hole:

theta = 47	Chi square = 5.58
R = 7.3	Rayleigh Test = 0.939
L = 38.3%	n = 19

Artpark:

theta = 340	Chi square = 35.00
R = 25.8	Rayleigh Test = 1.000
L = 67.9%	n = 38

Quarry Lake:

theta = 337	Chi square = 9.65
R = 11.8	Rayleigh Test = 0.992
L = 40.8%	n = 29

Lockport:

theta = 5	Chi square = 11.82
R = 15.9	Rayleigh Test = 0.997
L = 37.1%	n = 43

Regional Paleocurrent Pattern:

theta = 302	Chi square = 177.28
R = 173.9	Rayleigh Test = 1.000
L = 51.0%	n = 341

ALL PALEOCURRENTS FOR LOWER WHIRLPOOL (FIGURE 4-43) (minus readings from low-angle and planar tabular cross-laminations and inclination direction of fold axes.)

Duntroon:

theta = 347	Chi square = 21.31
R = 10.8	Rayleigh Test = 0.999
L = 98.4%	n = 11

reading components: 5 rxl
6 pl

Cannings Falls:

theta = 257	Chi square = 14.06
R = 7.5	Rayleigh Test = 0.999
L = 93.7%	n = 8

reading components: 5 txl
3 rxl

Cataract:

theta = 314	Chi square = 32.34
R = 20.1	Rayleigh Test = 0.999
L = 80.4%	n = 25

reading components: 23 txl
2 rxl

Jolley Cut:

theta = 242	Chi square = 22.59
R = 15.8	Rayleigh Test = 0.999
L = 71.6%	n = 22

reading components: 10 txl
12 rxl

Balls Falls:

theta = 279
R = 80.8
L = 67.4%

Chi square = 108.94
Rayleigh Test = 1.000
n = 120

reading components: 93 txl
27 rxl

Niagara Glen:

theta = 275
R = 26.8
L = 89.3%

Chi square = 47.85
Rayleigh Test = 1.000
n = 30

reading components: 20 txl
2 rxl
8 pl

The Whirlpool:

theta = 307
R = 56.8
L = 90.2%

Chi square = 102.60
Rayleigh Test = 1.000
n = 63

reading components: 38 txl
24 rxl
1 pl

Whirlpool State Park:

theta = 284
R = 44.0
L = 88.1%

Chi square = 77.56
Rayleigh Test = 1.000
n = 50

reading components: 20 txl
28 rxl
2 pl

Devil's Hole

theta = 30
R = 9.1
L = 41.5%

Chi square = 7.57
Rayleigh Test = 0.977
n = 22

reading components: 19 txl
3 rxl

Artpark:

theta = 345	Chi square = 52.69
R = 35.9	Rayleigh Test = 1.000
L = 73.3%	n = 49

reading components: 38 txl
11 rxl

Quarry Lake:

theta = 328	Chi square = 10.04
R = 12.5	Rayleigh Test = 0.993
L = 40.2%	n = 31

reading components: 29 txl
2 rxl

Lockport:

theta = 3	Chi square = 12.88
R = 16.8	Rayleigh Test = 0.998
L = 38.3%	n = 44

reading components: 43 txl
1 rxl

Medina:

theta = 288	Chi square = 7.09
R = 3.8	Rayleigh Test = 0.971
L = 94.1%	n = 4

reading components: 3 rxl
1 pl

Regional Paleocurrent Pattern:

theta = 301	Chi square = 356.50
R = 295.2	Rayleight Test = 1.000
L = 60.4%	n = 489

SYMMETRICAL RIPPLES (FIGURE 4-44)

Cannings Fall:

theta = 325-145	Chi square = 11.61
R = 8.8	Rayleigh Test = 0.999
L = 80.0%	n = 11

<u>Cataract:</u>

theta = 355-175	Chi square = 7.25
R = 6.9	Rayleigh Test = 0.995
L = 76.8%	n = 9

<u>Jolley Cut:</u>

theta = 357-177	Chi square = 24.97
R = 22.0	Rayleigh Test = 1.000
L = 91.5%	n = 24

<u>Lockport:</u>

theta = 341-161	Chi square = 16.15
R = 11.2	Rayleigh Test = 0.999
L = 66.1%	n = 17

<u>Regional Pattern of Symmetrical Ripple Crestline Orientations:</u>

theta = 345-165	Chi square = 60.34
R = 46.1	Rayleigh Test = 1.000
L = 69.8%	n = 66

<u>THE WHIRLPOOL BEDDING PLANE MAP (FIGURE 4-24)</u>

theta = 309	Chi square = 87.07
R = 47.6	Rayleigh Test = 1.000
L = 91.5%	n = 52

<u>WHIRLPOOL STATE PARK BEDDING PLANE MAP (FIGURE 4-25)</u>

theta = 285	Chi square = 84.79
R = 47.8	Rayleigh Test = 1.000
L = 88.6%	n = 54

APPENDIX 4

MICROFOSSIL EXTRACTION TECHNIQUE

APPENDIX 4

MICROFOSSIL EXTRACTION TECHNIQUE

The following describes a technique used by Dr. J. Legault (pers. comm., 1985) for the extraction of palynomorphs from sandstone and shale samples. The procedure, which is based on that described by Barss and Williams (1973), is simple and yields very good results. It is probably best to work with four samples at a time; that is, start four samples one day, and another four, the next. Allow about two weeks to complete 20 samples.

EXTRACTION PROCEDURE

1. Wash and brush sandstone or shale samples to remove contaminants. With a hammer, crush samples into small pieces, less than 1 cm in size.

2. Place 10 to 15 g (25 to 30 g for sandstone samples) of each sample into large beakers (600 ml or 1 L; glass beakers can be used). If sample sizes are small, test tubes may be used.

3. Add distilled water barely to cover. (Deionized water may be better to use, as it would insure that no present day pollen that is present in the aquifer is added to the sample.)

4. Add 10 to 20% HCl in small quantities at a time, waiting 1/2 to 1 hour between additions to allow the reaction to subside. Agitate with a stirring rod. Control any violent reactions with acetone. Continue adding HCl in this manner until there is no further reaction. This may take 6 to 24 hours.

5. Pour off clear acid and wash to neutralize. This is a washing-settling-decanting procedure that involves adding distilled water to fill the beaker (thoroughly agitate mixture with stirring rod), allowing the particles time to settle (about 1/2 hour), and decanting the clear water. This procedure should be done at least three times. (If samples are in a test tube, a centrifuge would speed up this procedure.) Use a litmus paper to test for neutrality.

6. Transfer samples to 600 ml plastic beakers and place in a plastic tub (a safety precaution).

7. Add just enough HF (~47%) to cover samples and stir with a plastic rod. Control any violent reactions with acetone. Cover beakers with a plastic lid and let stand for about 24 hours or longer, stirring every hour where practical. After last agitation, allow to settle and pour off the clear acid. (If drainage pipes in the lab are not made of plastic, collect the HF in a plastic bucket and neutralize with calcium carbonate before pouring down the drain.) If there is still much unbroken material, repeat

acid treatment.

8. Wash to neutralize in order to remove any fluoride ions. Do the washing-settling-decanting procedure (see step #5) at least 6 times.

9. Transfer samples to 100 ml Pyrex beakers. Add an equal volume of technical grade HCl and let sit for two hours.

10. Wash to neutralize as in step #5 and transfer last wash to 50 ml polypropylene test tubes.

11. Remove as much liquid as possible by centrifuging and decanting. Add nitric acid (1/3 concentrated solution) to the test tubes to 2/3 full. Stir or shake. (If shaking, wear rubber gloves before placing thumb over the tube opening. Residues with pyrite react violently.) Leave for 5 minutes.

12. Wash to neutralize 3 times using a centrifuge (2000 rpm for 2 minutes), filling test tube to 1/2 inch from the top at each wash.

13. Add a few drops of 5% ammonium hydroxide, stir, and let stand for 2 to 3 minutes. Wash to neutralize as in step #5.

14. Heavy liquid separation, using saturated solutions of zinc chloride or zinc bromide, is an optional but very useful step. Zinc chloride is cheaper and is prepared by combining 432 g of ZnCl, 15 ml of HCl, and 90 ml of distilled water. Prepare this the day before to allow sufficient time to cool.

15. Place samples in 50 ml plastic test tubes and add the heavy liquid to 3/4 full. Shake thoroughly or place on a vortex mixer, and then centrifuge for 15 to 20 minutes at 1000 rpm.

16. Remove test tubes and place in a rack. Gently stir the "float" with a toothpick to free any material adhering to the tube walls. If a clean separation between the "float" (microfossils) and "sink" is evident, pour the "float" into one 15 ml test tube. If a separation is not evident, pour the "float" into 2 or 3 test tubes. Discard the "sink" (heavy liquid). Fill the test tubes containing the "float" with distilled water (use a squeeze bottle). This dilutes the solution causing the microfossils to sink. Centrifuge at 2000 rpm for 2 minutes. Decant the supernatent liquid. If two or three test tubes were used, combine the residues. Wash thoroughly two or three times as in step #5.

17. Pour last wash over a sieve. (Sieve size needed depends on the size of the palynomorphs in the samples. Whirlpool palynomorphs are generally greater than 30 microns in size; therefore, a 24 micron sieve was used.) Wet the sieve on both sides before using. Squirt water in a circular motion over the residue to keep the particles in suspension.

18. Place residues in vials, fill with distilled water, add 1 or 2 drops of phenol, cap, and store until ready for making the slides.

SLIDE PREPARATION

1. Transfer residue in the vials to 15 ml test tubes and centrifuge.

2. Put hot plate on low (warm to the touch), place a piece of paper on top, and place coverslips on top of the paper. Do about four samples at a time, making two slides per sample.

3. Add a drop (about the size of a dime) of PVA (polyvinylalcohol) to the coverslips (see below for PVA preparation).

4. Decant water from the test tubes, leaving about 1 to 2 ml of liquid at the bottom, and mix samples on a vortex mixer.

5. Using a Pasteur pipette, add a drop or two of the samples to the PVA on the slides. With a toothpick, mix and spread the mixture over the slide, almost to the edges. (Discard the toothpick after use.)

6. Leave the coverslips on the hot plate until the water has evaporated.

7. When the coverslips are dry, take 7 x 2.5 cm slides (label appropriately) and using a dropper, place enough Elvacite (see Barss and Williams, 1973) on the slide to cover a 2 x 0.5 cm area. (Be careful not to breathe the Elvacite vapour.) Do one slide at a time.

8. Place slide on the hot plate. Invert a coverslip, placing one edge on top of the Elvacite and letting the other edge down slowly. Allow the Elvacite to spread slowly under the coverslip. After it has spread out, press down on the coverslip with two fingers, spreading the Elvacite further and making the slide thinner.

9. Dry slides on a temperature-controlled hot plate at 38 to 40 degrees C for 2 days. Do not go over 40 degrees C, for the Elvacite will crack.

10. Surplus cured Elvacite on the slide edges can be scraped off with a razor.

Preparation of Polyvinylalcohol

10 g of PVA powder, 275 ml of distilled water.

Heat water to 82 degrees C. Slowly add PVA while stirring on a magnetic mixer. Solution will appear milky. Reheat until the solution clears, and then filter while the solution is still hot. Add 1/2 ml of Phenol and mix.