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THE SEDIMENTOLOGY OF THE LOWER SILURIAN WHIRLPOOL SANDSTONE,  
IN SUBSURFACE LAKE ERIE, ONTARIO

by

MICHAEL FERGUS JOHNSON

A Thesis submitted to the Department of Earth Sciences

Brock University

in partial fulfillment of the requirements for the degree of  
Master of Science

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Dr. R. J. Cheel

Supervisor

## ABSTRACT

The lower Silurian Whirlpool Sandstone is composed of two main units: a fluvial unit and an estuarine to transitional marine unit. The lowermost unit is made up of sandy braided fluvial deposits, in shallow valleys, that flowed towards the northwest. The fluvial channels are largely filled by cross-bedded, well sorted, quartzose sands, with little ripple cross-laminated or overbank shales.

Erosionally overlying this lower unit are brackish water to marine deposits. In the east, this unit consists of estuarine channels and tidal flat deposits. The channels consist of fluvial sands at the base, changing upwards into brackish and tidally influenced channelized sandstones and shales. The estuarine channels flowed to the southwest. Westwards, the unit contains backbarrier facies with extensive washover deposits. Separating the backbarrier facies from shoreface sandstone facies to the west, are barrier island sands represented by barrier-foreshore facies. The barrier islands are dissected by tidal inlets characterized by fining upward abandonment sequences. Inlet deposits are also present west of the barrier island, abandoned by transgression on the shoreface. The sandy marine deposits are replaced to the west by carbonates of the Manitoulin Limestone.

During the latest Ordovician, a hiatus in crustal loading during the Taconic Orogeny led to erosional offloading and crustal rebound, the eroded material distributed towards the west, northwest and north as the terrestrial deposits of the fluvial Whirlpool. The “anti-peripheral bulge” of the rebound interfered with the peripheral bulge of the Michigan Basin, nulling the Algonquin Arch, and allowing the detritus of the fluvial Whirlpool to spread onto the Algonquin Arch.

The Taconic Orogeny resumed in the earliest Silurian with crustal loading to the south and southeast, and causing tilting of the surface slope in subsurface Lake Erie towards the

southwest. Lowstand terrestrial deposits were scoured into the new slope. The new crustal loading also reactivated the peripheral bulge of the Appalachian Basin, allowing it to interact with the bulge of the Michigan Basin, raising the Algonquin Arch. The crustal loading depressed the Appalachian basin and allowed transgression to occur. The renewed Algonquin Arch allowed the early Silurian transgression to proceed up two slopes, one to the east and one to the west. The transgression to the east entered the lowstand valleys and created the estuarine Whirlpool. The rising arch caused progradation of the Manitoulin carbonates upon shoreface facies of the Whirlpool Sandstone and upon offshore facies of the Cabot Head Formation. Further crustal loading caused basin subsidence and rapid transgression, abandoning the Whirlpool estuary in an offshore setting.

## ACKNOWLEDGEMENTS

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# INTRODUCTION

## ***Purpose of Study***

The Lower Silurian Whirlpool Sandstone has not been the subject of a thorough study in subsurface Lake Erie (figure 1), although in outcrop it has been well documented (Rutka 1986). The goal of this study is to document the sedimentology of the Whirlpool Sandstone in subsurface to provide a basis for interpreting paleoenvironments. The interpretations based on this subsurface study are compared with previously published works on the Whirlpool in outcrop in order to improve our understanding of the lateral relationships between the two areas.

## ***Geology of the Study Area***

During the Early Silurian Period, sedimentation in southern Ontario and the northeastern United States was controlled by three major structural features: the Appalachian Basin, the Michigan Basin, and the Algonquin Arch, which structurally separates the two basins (figure 2; Middleton 1987). The Algonquin Arch was periodically a topographic high that limited types of sedimentation to certain basins: clastics to the Appalachian Basin and carbonates to the Michigan Basin (Liberty and Bolton 1956). The Michigan Basin is an intracratonic basin whereas the Appalachian Basin is a foreland basin (Middleton 1987). The Appalachian Basin formed in response to the crustal loading in the east during the Taconic Orogeny of the middle to late Ordovician Period (Dorsch and Driese 1995). The Whirlpool Sandstone is largely confined to the Appalachian Basin though significant portions stretch onto the Algonquin Arch (Rutka 1986).

The Whirlpool Sandstone is early Silurian in age and is the lowermost formation in the Cataract Group (Medina Group of Northwest New York; figure 3; Liberty and Bolton 1956).



Figure 1. Location of the study area. Wells and cores used in this study were solely from Lake Erie. Boxed area highlights Lake Erie (dark area) in relation to the other Great Lakes. From Benicasa (1996).



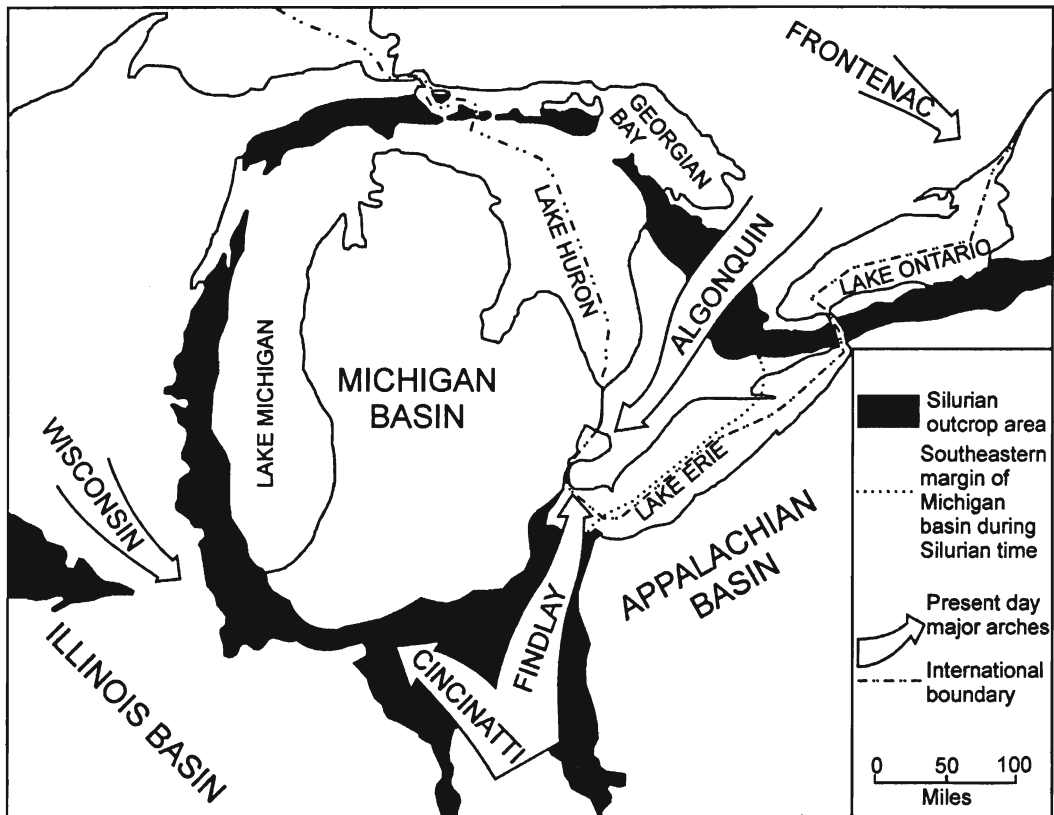


Figure 2. Major basins and arches of southern Ontario and Northeastern United States. The Whirlpool Sandstone is largely limited to the Appalachian Basin although it locally extends onto the Algonquin Arch. Modified from Sanford (1969).

		<i>This Thesis</i>							
		a	a	a	a	a	a,b	c	c
Standard Time Reference		Ohio	Windsor-Sarnia Goderich-Bruce Peninsula	Algonquin Arch	Hamilton-Niagara Peninsula-Eastern Lake Erie	Western New York	Central Pennsylvania	East Tennessee	Central Virginia
Early Silurian	Niagaran	Clinton Group	Fossil Hill	Fossil Hill	Reynales	Reynales	Rose Hill Fm		Rose Hill Fm
		Brassfield Ls			Neagha	Neagha			
	Alexandrian	Cabot Head Shale	Cabot Head Shale	Cabot Head Shale	Cabot Head Shale	Cabot Head Shale	Tuscarora Fm	Brassfield Fm	"Upper" Tuscarora Fm
		Whirlpool	Manitoulin Dolomite	Manitoulin Whirlpool	Manitoulin Whirlpool	Manitoulin Whirlpool			
Late Ordovician	Richmond	Queenston Shale	Queenston Shale	Queenston Shale	Queenston Shale	Queenston Shale	Juniata-Tuscarora Transition	Sequatchie Fm	Juniata Fm
		Kagawong					Juniata Fm		"lower" Tusc.
	Ashgillian	Shale and Limestone (unnamed)	Meaford Dundas	Meaford Dundas	Meaford Dundas	Lorraine	Oswego	Bald Eagle	Reeds-ville
									Martinsburg

Figure 3. Stratigraphic nomenclature of the Late Ordovician to Early Silurian strata in Southern Ontario, Northeastern, and Eastern United States. From: a -- Benincasa 1995; b -- Piotrowski 1981; and c -- Dorsch and Driese 1995.

It disconformably overlies the Late Ordovician Queenston Shale in outcrop and is conformably overlain by either the Manitoulin Formation or by the Cabot Head Formation (Liberty and Bolton 1956). Wherever the Whirlpool Sandstone is overlain by the Manitoulin Formation it belongs to the Cataract Group and wherever the Whirlpool Sandstone is overlain by the Cabot Head Formation (a.k.a. Power Glen Formation) it belongs to the Medina Group (figure 3; Liberty and Bolton 1956). The boundary between the two groups generally runs parallel to the Algonquin Arch (figure 2; Sanford 1969). Where it is part of the Medina Group, the Whirlpool Sandstone forms the basal unit of a thick clastic wedge that was shed from the east and south (figure 4; Piotrowski 1981).

During the late Ordovician, the prograding mudflats of the Queenston Shale (Brogly 1984) filled the Appalachian Basin in southern Ontario and western New York. In central New York and central Pennsylvania the Queenston Shale is replaced by coarser clastic sediments of the Oswego and Juniata formations, respectively (Middleton 1987). In southern Ontario and Western New York the boundary between the Ordovician and Silurian is marked by a regional disconformity termed the Cherokee unconformity (Brett *et al.* 1990). This unconformity can be traced southward into the central Appalachians where it is truncated by the later Tuscarora Unconformity which separates the Tuscarora Formation into separate “lower” (late Ordovician) and “upper” (early Silurian) formations (figure 3; Dorsch and Driese 1995). Piotrowski (1981) stated that in Pennsylvania the unconformity at the end of the Ordovician is not laterally continuous: there is a gradual transition between the late Ordovician Juniata Formation and the overlying early Silurian Tuscarora Formation (figure 4). Benincasa (1996) reported a widespread unconformity at the base of the Tuscarora equivalent Grimsby Formation in subsurface Lake Erie.

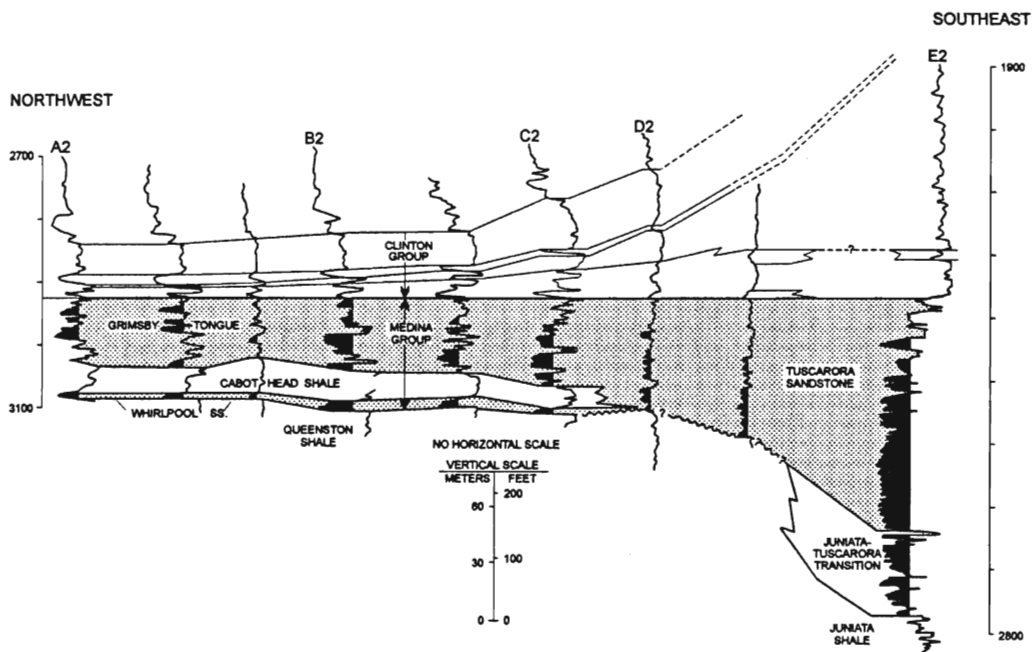


Figure 4. Clastic wedge of the Medina Group and Tuscarora Formation in subsurface Pennsylvania (Southeast end) and subsurface Southern Ontario (Northeast end). From Piotrowski (1981).

The Whirlpool Sandstone is not known to be equivalent with any other formations, though Lumsden and Pelletier (1969) suggested that the Whirlpool Sandstone merges with the Grimsby Formation in western New York State. It has also been suggested that the Whirlpool Formation is laterally equivalent to the lowermost Tuscarora Formation of western New York State and northeastern Pennsylvania (figure 4; Piotrowski 1981).

The Whirlpool Sandstone was first defined by Grabau (1913), based upon the distinctive white, quartz-arenite sandstone sheet exposed near the Niagara River whirlpool in the Niagara Gorge of southern Ontario and western New York. The Whirlpool Sandstone is a clean, fine grained, well sorted, white, locally stained red or brown, quartzose sandstone in outcrop and in subsurface (Rutka 1986). In outcrop in Southern Ontario and western New York State the formation is sheetlike over a wide geographic area (Rutka 1986). It dips to the south extending towards the southwest, south and southeast into subsurface Lake Erie (Sanford 1969), western New York State and Pennsylvania (Piotrowski 1981), and Ohio and northeastern West Virginia (Coogan 1990). In subsurface it is known as a producer of natural gas and/or oil. In outcrop and in subsurface the sandstone normally ranges from 3 m to 6 m in thickness (Rutka 1986, and Sanford 1969).

Prior to Rutka (1986) most studies of the Whirlpool Sandstone were limited and commonly formed parts of larger studies of the entire Medina Group. Most of these studies interpreted that the Whirlpool Sandstone as a sublittoral sand sheet based upon its sheetlike nature and abundant cross-bedding (e.g., Martini 1971).

Rutka (1986) concluded that the Whirlpool Sandstone could be divided into two distinct units: a basal braided fluvial deposit overlain by the deposits of a marine shoreface environment (figure 5). The interpretation of the lower unit, as a northwest flowing braided fluvial system, was based on the sheet-like nature of the entire sandstone, the absence of

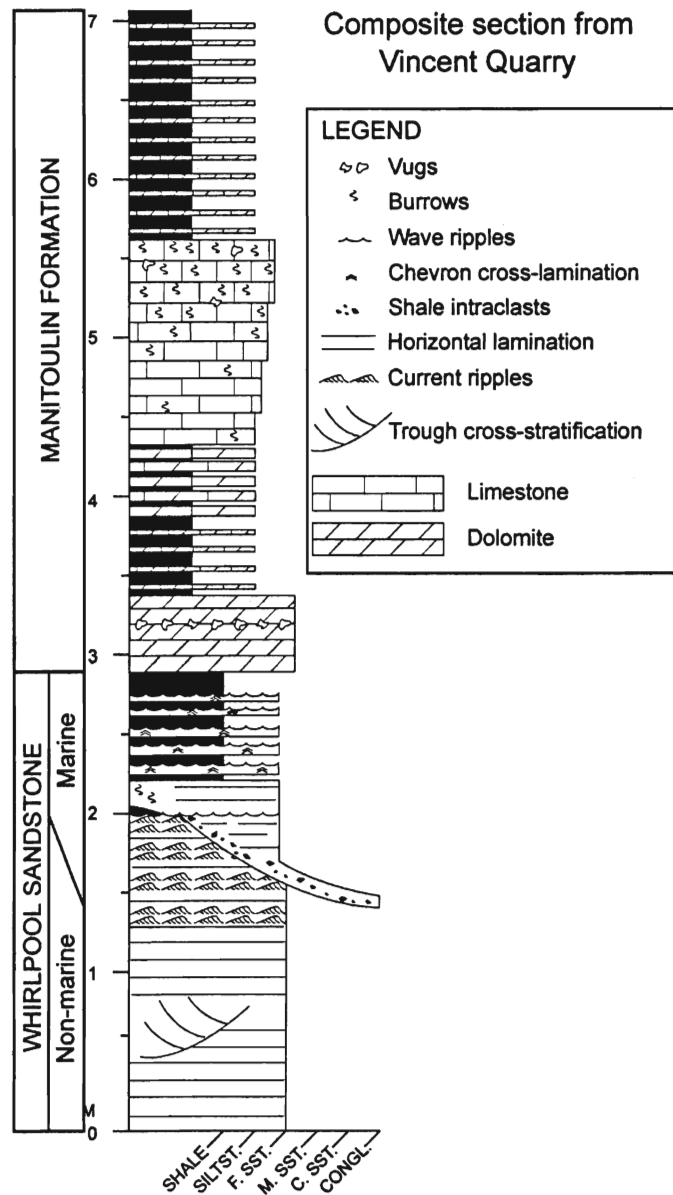


Figure 5. Composite section for the Whirlpool Sandstone at the Vincent Quarry near Georgetown, Ontario. This section displays two distinct portions of the Whirlpool, the lower portion being non-marine (fluvial) and the upper portion being marine (shoreface). This section also displays an erosional surface separating the marine from the non-marine. Modified from Cheel and Middleton (1993).

lateral accretions, unidirectional paleocurrents, sharp and erosive vertical facies boundaries, and considerable lateral variability in the facies.

Rutka (1986) also described the upper unit of the Whirlpool Sandstone as containing some wave formed structures (symmetrical ripples), shallow water fossils, and ichnofossils; this upper unit was interpreted as a shallow marine deposit.

Cheel and Middleton (1993) proposed that tectonic tilting and erosion occurred between deposition of the fluvial and marine units in the Whirlpool Sandstone. An erosional lag of shale clasts occurs on top of the fluvial Whirlpool as well as immediately on the erosional scours (figure 5). According to Cheel and Middleton (1993), the northwest dipping braided fluvial system of Rutka (1986) was tilted towards the northeast as indicated by the orientation of the scours on top of the fluvial Whirlpool. From these scours, the offshore direction was determined to be towards the northeast during deposition of the marine Whirlpool.

In subsurface Lake Erie few studies have examined the Whirlpool Sandstone. Rutka (1986) and Cheel *et al.* (1995) compared core with outcrop exposures, but neither extensively mapped the Whirlpool in subsurface. In subsurface New York State, Pennsylvania and Ohio there have been few published subsurface studies (Piotrowski 1981; Laughrey 1984; Pees 1986; Coogan 1990; and Davis *et al.* 1992). None of these came to the same conclusion as Rutka (1986) and considered the Whirlpool Sandstone to be a sublittoral sand sheet. The studies on core in the American subsurface (Laughrey 1984, and Pees 1986), compared with outcrop work, suggested that there are many textural and structural similarities with the outcrop in southern Ontario and western New York State.

Various Canadian oil and gas companies have explored subsurface Lake Erie for natural gas reservoirs. The border between Canada and the United States dissects Lake Erie. There has been no natural gas exploration on the United States side of the border because of

environmental laws and therefore the available data are restricted to the Canadian side of the border. In contrast, there is an abundance of subsurface data for the Whirlpool Sandstone from beneath the Canadian portion of Lake Erie (figure 6). In subsurface, the Cataract Group includes three gas bearing sandstones: the Whirlpool, Grimsby, and Thorold formations. Even if the Whirlpool Formation is not a target formation in a particular drill hole, it is normally penetrated because of its proximity to the other two formations on the off chance that it may contain hydrocarbons. There are over 1000 wells, with well logs, drilled on Lake Erie that penetrate the Whirlpool Formation and over 650 wells record a Whirlpool thickness greater than 1 m. Many more holes have been drilled but the exploration companies did not run well logs. Wells for the Medina Group are quick to drill, taking generally less than a week from spud to completion, including wireline logging and drill stem testing.

Wells producing from the Whirlpool can easily exceed flow rates of 100 mcf/day. For example, well Long Point 23-20 8-Y had a flow rate of almost 6000 mcf/day. Other nearby wells reached flow rates of more than a million cubic feet of natural gas per day. Porosity in the Whirlpool Sandstone can reach 24% in some zones, though it is normally much less. A better understanding of the Whirlpool Sandstone in subsurface will lead to new exploration opportunities. The Whirlpool Sandstone in subsurface Lake Erie is an insignificant producer of oil, which is beneficial because provincial laws forbid production of oil from subsurface Lake Erie (Mike Hunter of the Ontario Ministry of Natural Resources, personal communication). Wells that produce oil must be plugged and abandoned which some drillers refer to as “running liquid casing”.



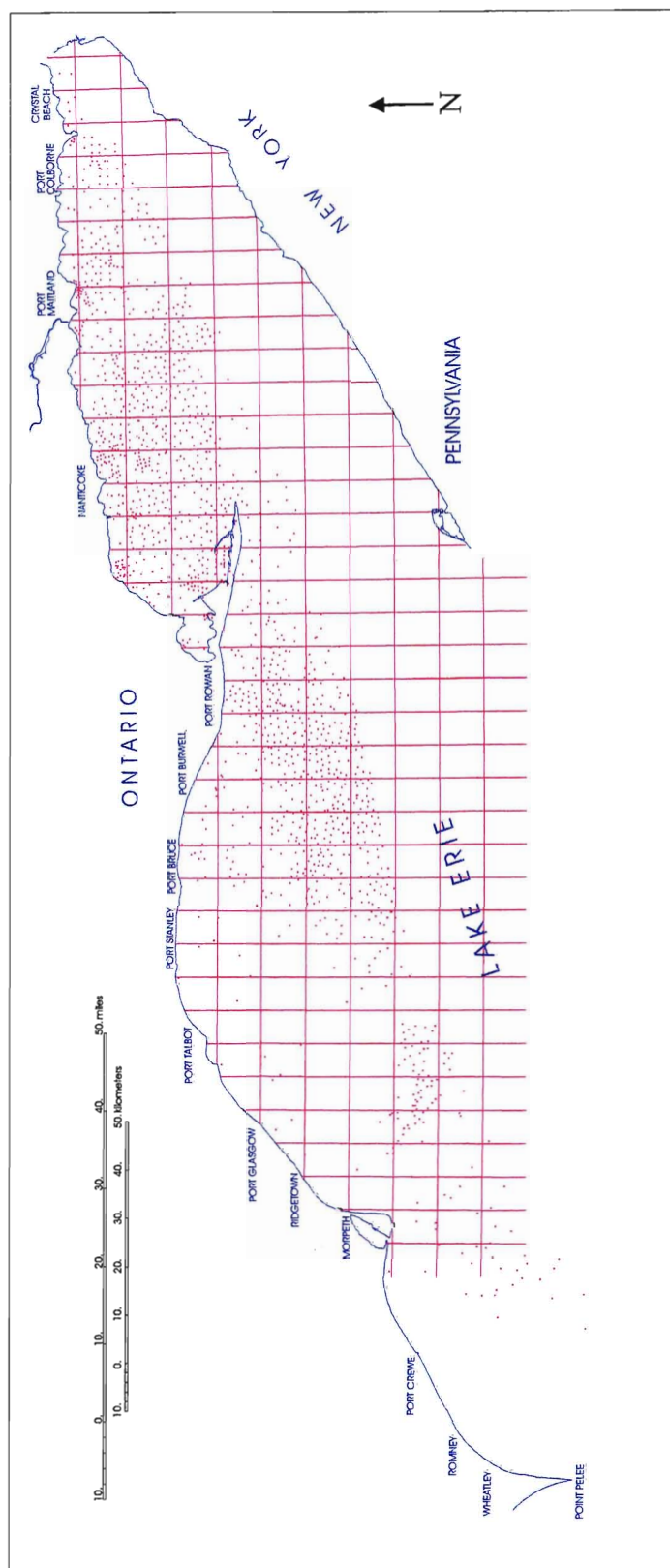


Figure 6. Well location map for Lake Erie. Most wells pierce the Medina Group.

## METHODS

All raw data obtained for this thesis were derived from well logs and core at the Ontario Ministry of Natural Resource's Petroleum and Core Laboratory, London, Ontario. By law, any company that drills a well in Ontario for exploration or development purposes must forward samples of well cuttings, copies of well logs (if well logs were run) and a representative set of slabs of core (if coring was performed) to the Ontario Ministry of Natural Resources. The material remains confidential for one year after completion or plugging of the well, thereafter becoming available to the public. Data from all subsurface Lake Erie wells are present, with only a few instances where a company failed to forward information to the lab.

In many cases companies did not run geophysical logs on wells drilled. In other cases, wells were not drilled completely through the Medina Group so the physical characteristics of the Whirlpool Sandstone were not recorded. In some cases holes were not drilled far enough into the Queenston Shale, preventing logging tools from fitting past the Queenston-Whirlpool contact, thus the Whirlpool may not have been logged.

Gamma-ray, neutron porosity, and density porosity logs were primarily used during the course of this study. Formation tops that are most crucial to the thesis are the Thorold-Grimsby formations, the Whirlpool Sandstone and Queenston Shale (figure 7). The Thorold-Grimsby top was relatively easy to pick, and was based upon the change of sandstones and shales of the Thorold and Grimsby formations into the carbonates of the overlying Reynales Dolomite (figure 7). The Queenston Shale top was also easy to pick on well logs where the high radioactivity of the Queenston Shale contrasted sharply with the clean sandstones of the Whirlpool Formation (figure 7).

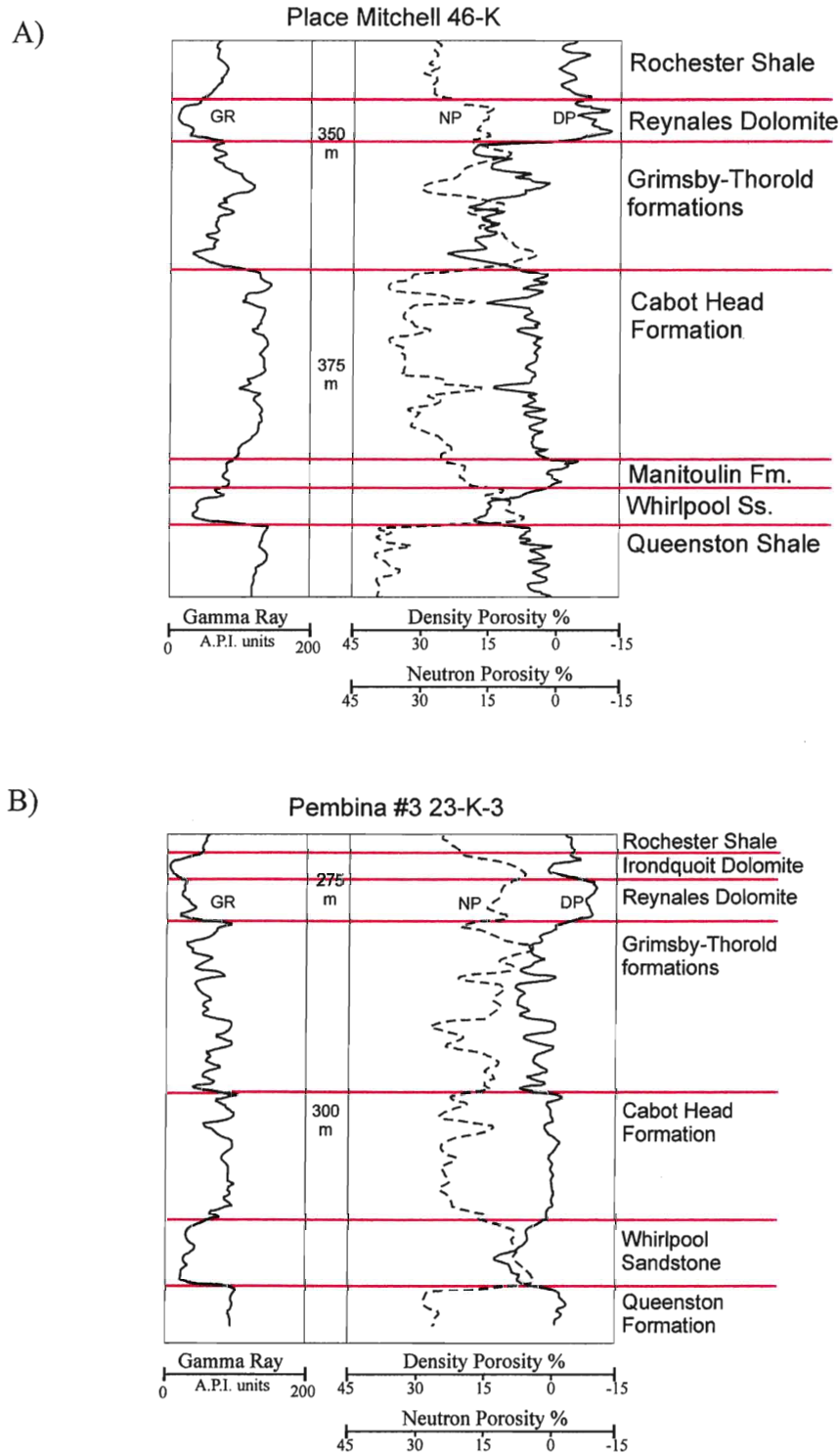


Figure 7. Typical gamma-ray (GR), neutron porosity (NP), and density porosity (DP) log sections of the Cataract Group. A) Whirlpool Sandstone and Manitoulin Formation: notice the sharp decrease in porosity of the Manitoulin Formation in the density porosity log where overlying the Whirlpool Sandstone. B) Whirlpool Sandstone and Cabot Head Formation: the contact between the Whirlpool Sandstone and Cabot Head Formation is generally based on shale content as shown in the gamma-ray log above. Both sections show how the Whirlpool Sandstone sharply contrasts with the underlying Queenston Formation.

The top of the Whirlpool Formation was more difficult to pick on well logs but could generally be picked based upon sandstone content. The Whirlpool Sandstone is largely clean sandstone whereas the overlying units are either shales or carbonates. The denser Manitoulin Formation carbonates could be differentiated from the Whirlpool by density porosity logs (figure 7a). The Whirlpool Sandstone can be differentiated from the Cabot Head Formation by an increase in radioactivity on the gamma-ray logs (figure 7b). Comparisons between core and neighbouring well logs helped clear up any confusion. Cross-sections also helped in separating shaly Whirlpool Formation from shaly Cabot Head Formation sandstones.

The “township” of Lake Erie is divided into numerically designated blocks (figures 6 and 8) which are then divided into 25 alphabetically labeled tracts. The tracts are subsequently divided into quarters designated by numbers one to four (figure 8). Not all wells are identified by the quarter in which they were drilled. This led to some confusion when more than one well has been drilled in the same tract. In such cases, the latitude and longitude were needed to differentiate which well logs belonged to which well on a map provided by Pembina Resources.

Mapping of the Whirlpool Sandstone consisted of two parts. The first part was the construction of an isopach map of the Whirlpool Sandstone (figure 9). A map provided by Pembina Resources and a second map from Telesis Oil and Gas were combined and used as the base map, showing all the well locations on Lake Erie. The Whirlpool Formation is almost exclusively sand, and a total sand thickness map was not attempted, as it would not differ much from the isopach map. The isopach map was used to select the cross-sections used in this study. A second map was constructed by isolating the different units of the Whirlpool Sandstone in order to better understand their geometry.

**LIBRARY ENDOWMENT FUND**  
**STATEMENT OF INTEREST INCOME BY SOURCE**  
**1998 - 1999**

<u>Source</u>	<u>Capital</u>	<u>%</u>	<u>Income</u>
General	\$ 98,317.48	26.92	\$ 4,505.00 *[4,862.00]
Alumni	6,516.00	1.78	322.00
Hull	2,113.82	0.58	105.00
Matheson	905.71	0.25	45.00
Bickle	6,311.73	1.73	313.00
Reed	1,048.18	0.29	52.00
Hogan	3,315.45	0.91	164.00
Fox	30,688.17	8.40	1,517.00
Ormsby	1,503.56	0.41	74.00
BUSU	1,338.78	0.37	67.00
Martynuk	48,681.77	13.33	2,407.00
Osterbind	10,319.81	2.83	511.00
Runnalls/Standring	1,431.69	0.39	70.00
Megannety	13,014.29	3.56	1,000.00 *[643.00]
Special borrowers	125,245.40	34.30	6,195.00
Gibson	3,237.98	0.89	161.00
TeleGrad	6,118.83	1.68	303.00
Clark	<u>5,055.62</u>	<u>1.38</u>	<u>249.00</u>
	<u>\$365,164.27</u>	<u>100.00</u>	<u>\$18,060.00</u>

\* Adjustment made to provide \$1,000.00 for Megannety donation.

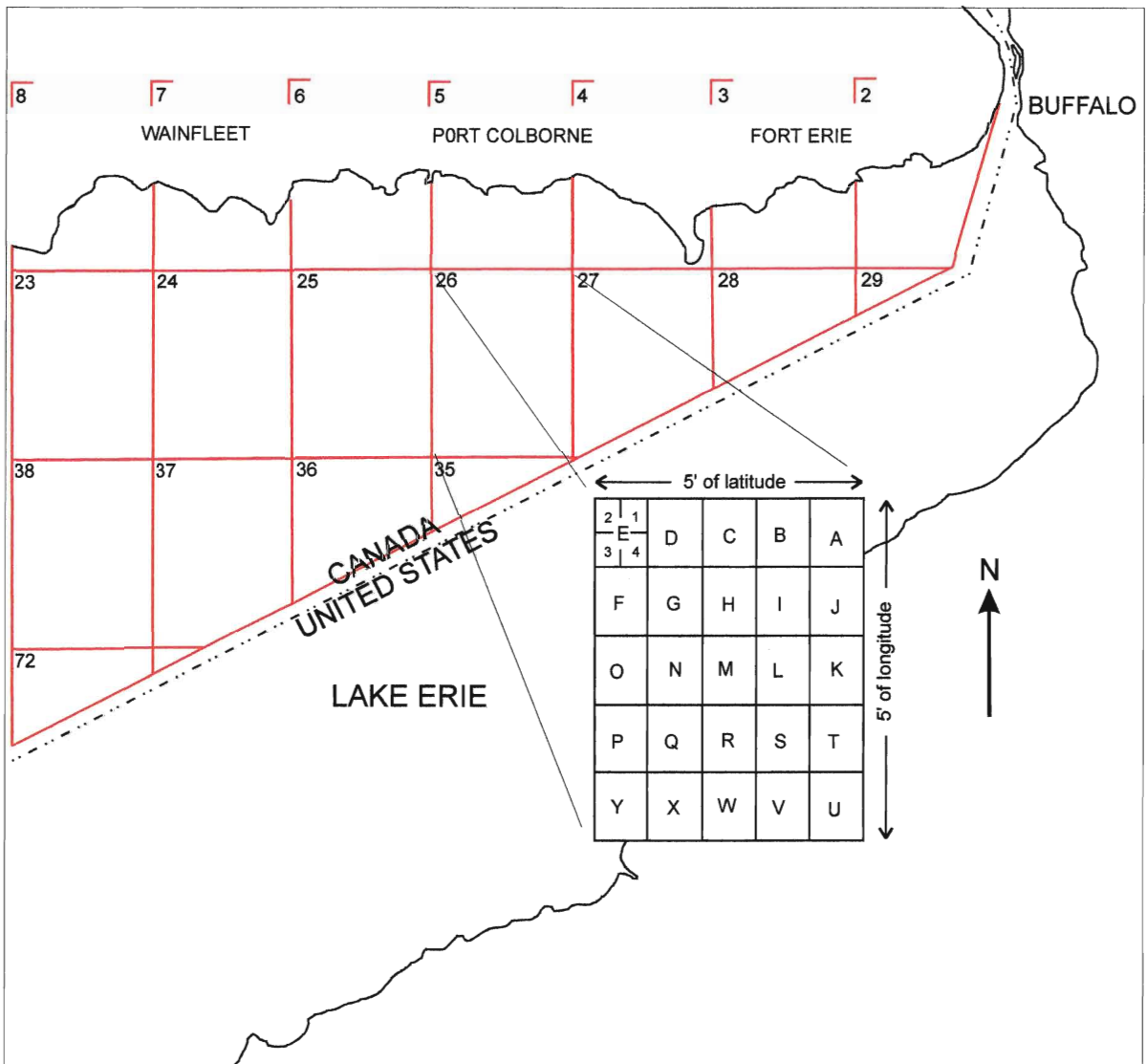


Figure 8. Block, tract and quarter system used in locating wells on Lake Erie. Each numbered block is broken down into 25 tracts denoted by letters of the alphabet. Each tract can then be broken down into 4 quarters denoted by numbers 1 to 4. For the full block breakdown of the relevant study area please see map 1. No exploration drilling occurs on the United States side of the border so those block numbers are absent from this diagram. Modified from Booth-Horst *et al.* (1982).

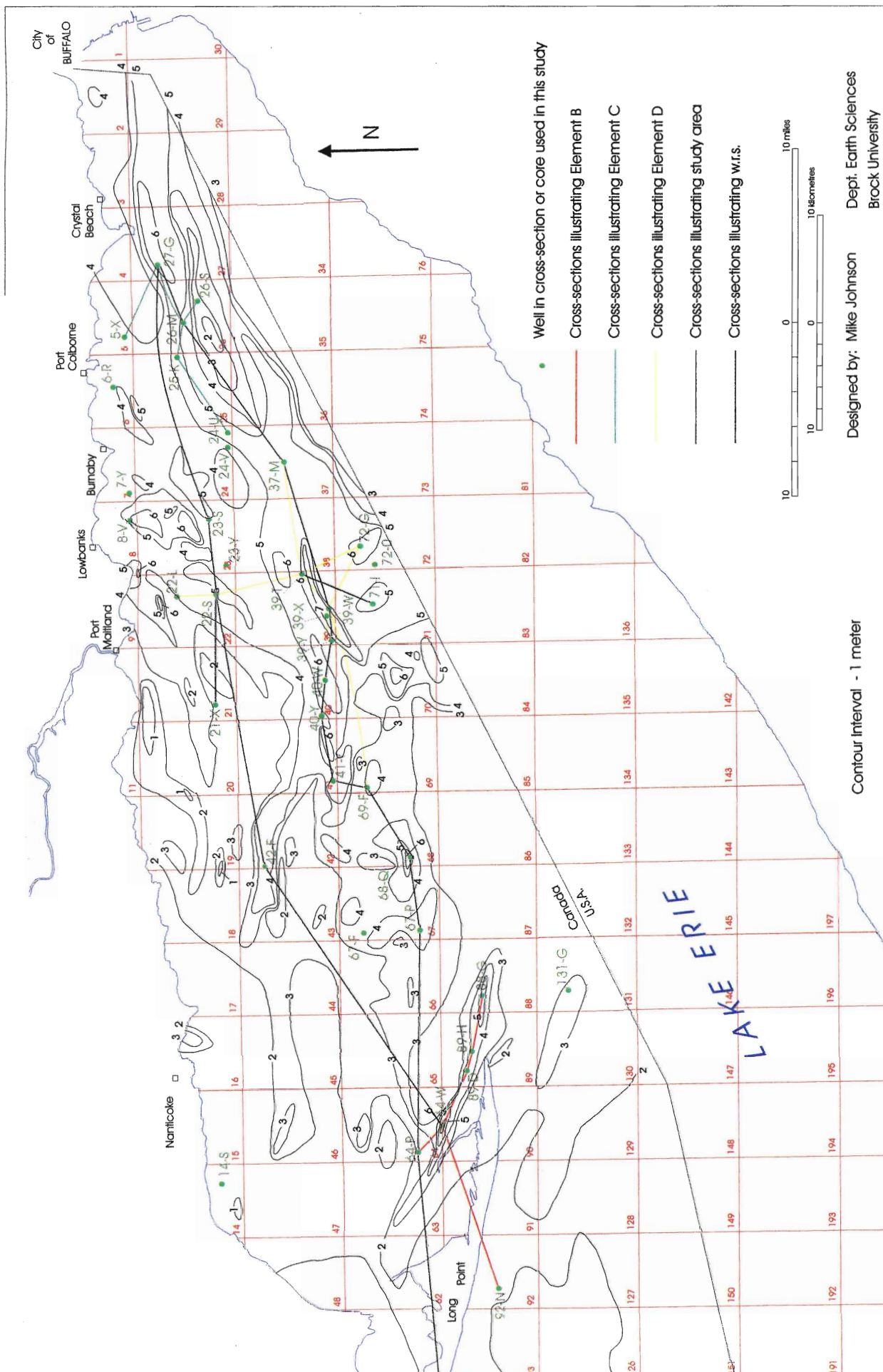


Figure 9. Isopach map of the Whirlpool Sandstone in subsurface Lake Erie. Cores used in the study and wells used in the cross-sections are highlighted in green..



# Subsurface Lake Erie Whirlpool Sandstone Isopach Map

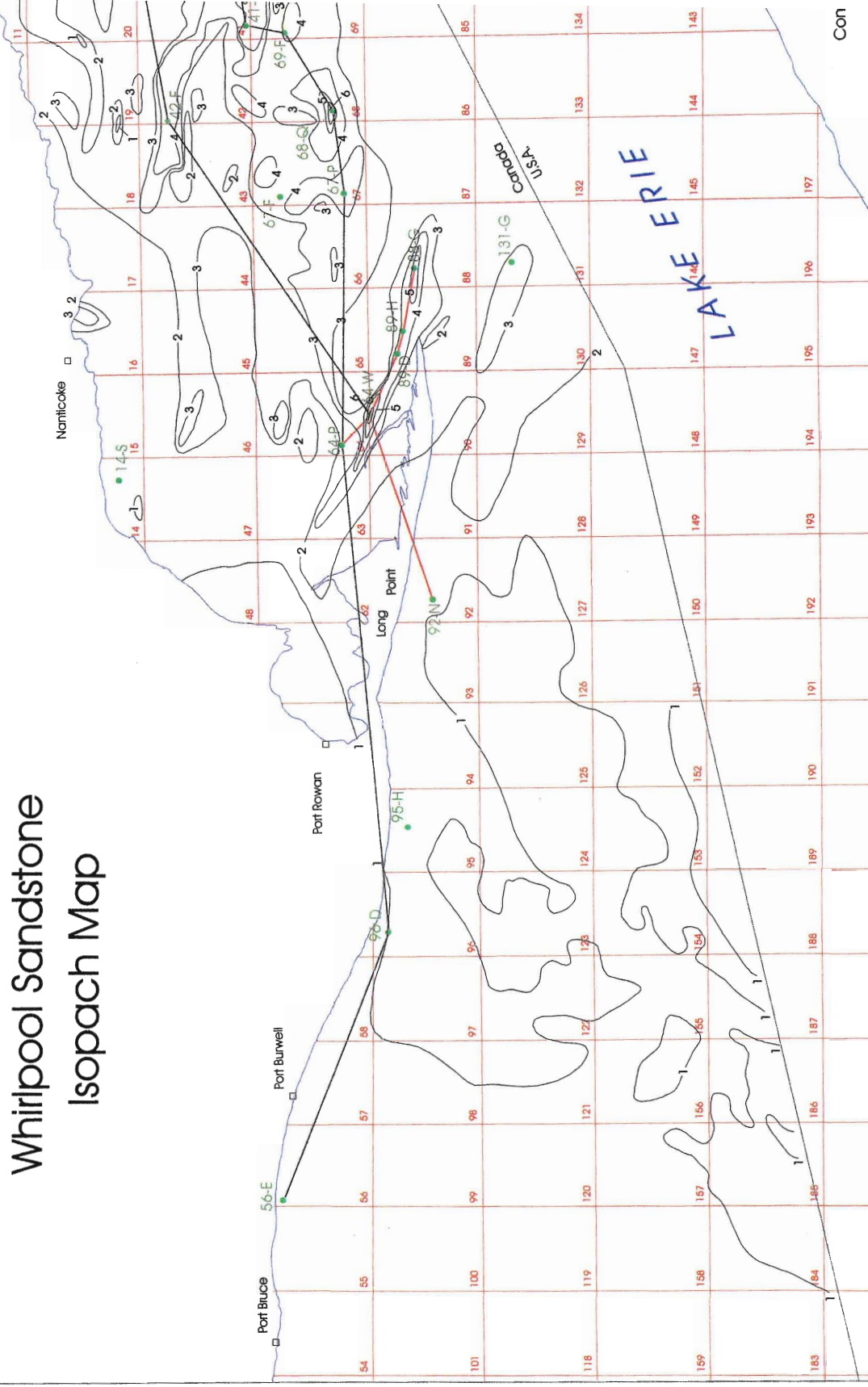


Figure 9. Isopach map of the Whirlpool Sandstone in subsurface Lake Erie and wells used in the cross-sections are highlighted in green..



A total of 33 cores of the Whirlpool Sandstone from subsurface Lake Erie were logged. Many other cores of the Whirlpool Sandstone exist, however, either the responsible exploration company did not send the core slabs to the core lab or the core box had been previously mishandled and dropped, thereby making any accurate description impossible.

All cross-sections presented in this study used the base of the Reynales Dolomite as the datum. The base of the Reynales Dolomite appears to be a flat surface (Benincasa 1996) and is thought to be a good datum.

Palynological analyses were performed on two shale samples obtained from the Whirlpool Sandstone. The methods used and results are available in appendix 1 (Parkins 1997).

## RESULTS

### *Facies and Facies Descriptions*

The Whirlpool Sandstone is the formation of interest. Of lesser importance, but also described below, are the Queenston Shale, Manitoulin Limestone, and Cabot Head Shale. The strata have been broken down into elements (figure 10) as based upon geometries noted on the isopach map (figure 9) and cross-sections. An element is a facies association.

The Queenston Shale is described as Element A.

Four main elements of the Whirlpool Sandstone and related strata are identified and delineated on figure 10 as Elements B to E. The first element consists of northwest-southeast trending thicks, one of which is present immediately west of Long Point, and another that extends through blocks 43 and 42. The facies associated with these thicks are grouped into Element B.

The second element in the Whirlpool Sandstone (figure 10) consists of the long northeast-southwest trending thicks in the eastern portion of the study area. These are best displayed east of the 37 block, though they can be traced westwards towards Long Point. Facies related to this element are grouped into Element C.

The third element in the Whirlpool Sandstone (figure 10) consists of lobate bodies within some of the northeast-southwest trending thicks appearing first south of Port Maitland, and towards the west. The most notable lobate form occurs in block 68. These lobate bodies trend northeast-southwest, similar to the orientation of Element C. Facies related to these lobate bodies are grouped in Element D.

The fourth element (figure 10) is characterized as a thin (< 4m) sheet of Whirlpool Sandstone that does not display any particular trending thicks. The Manitoulin and Cabot

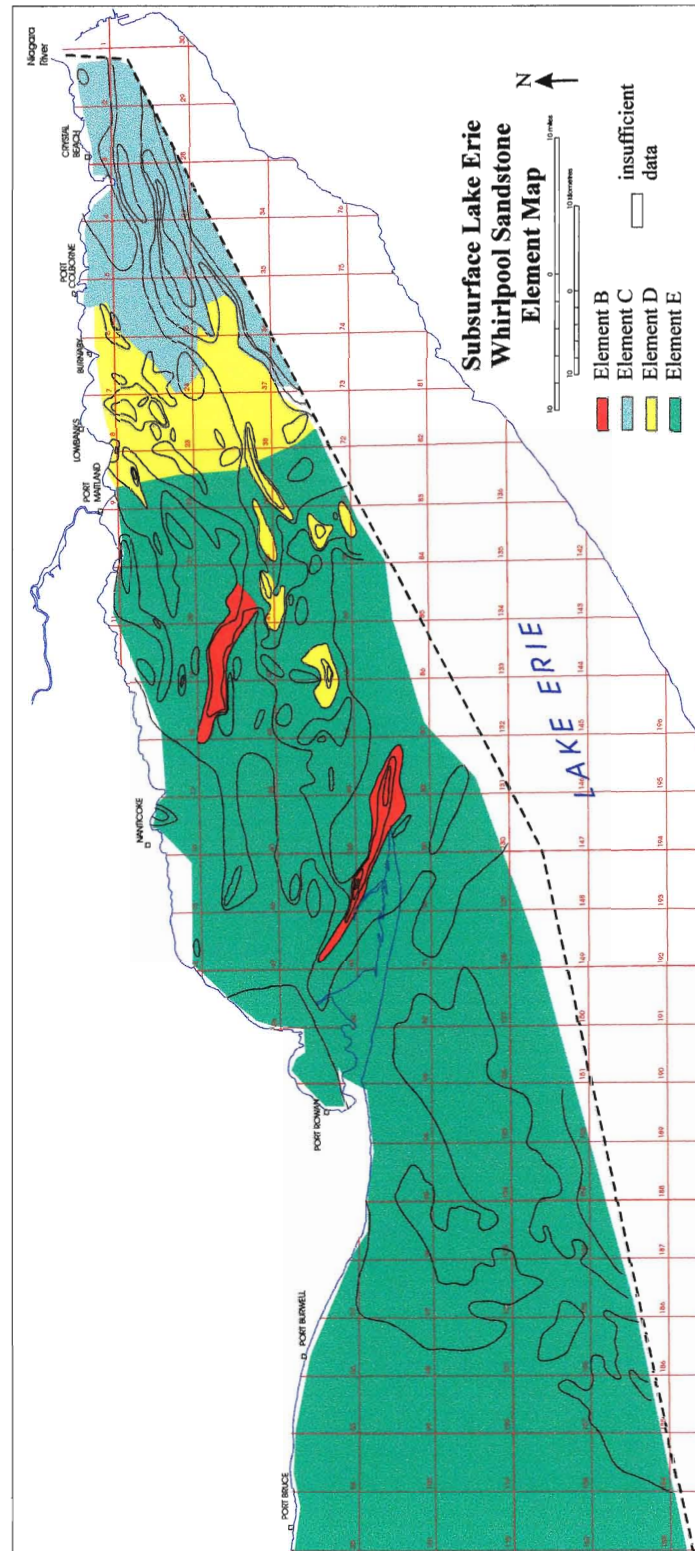


Figure 10. Elements of the Whirlpool Sandstone and related strata. From the isopach map (figure 9).

Head Formations are included in this element. Facies related to this sheet are grouped in Element E.

## **Element A -- Queenston Shale**

### **Facies A**

Facies A consists of red, silty, blocky shale. Bedding and other structures are difficult to discern. Most of the shale is red, but the uppermost portions are almost always altered green; the green zone ranges from a few centimetres (figure 11a) to over a metre in thickness. Trace fossils are never observed. The core from this unit is normally in poor condition (figure 11a). The top is always sharp and eroded (figure 11a), with one possible exception, core 96-D which appears somewhat gradational. The top of the shale is locally “cracked” and infilled with white quartzose sandstone when overlain by the Whirlpool Sandstone. Even when overlain by the Manitoulin Limestone the infill to these cracks remains mostly white, quartzose sandstone, but is calcareous. The cracks and infill can appear up to 92 cm in length, though are normally less. Apparent mud diapirs locally protrude into the lowermost portions of the overlying Whirlpool Sandstone (figure 11b).

## **Element B**

### **Facies B1**

Facies B1 is normally white to grey, locally stained light brown, cross-bedded sandstone with no shale. There is no visible bioturbation.

Planar tabular cross-bedded sandstone is common in Facies B1. The sands are quartzose, unfossiliferous, well sorted and mostly fine grained, but locally medium grained. In some instances rounded or angular shale clasts are present. Cross-bed sets range in thickness from 2 cm to 30 cm; most are in the range of 20 cm to 30 cm in thickness. Locally these sets

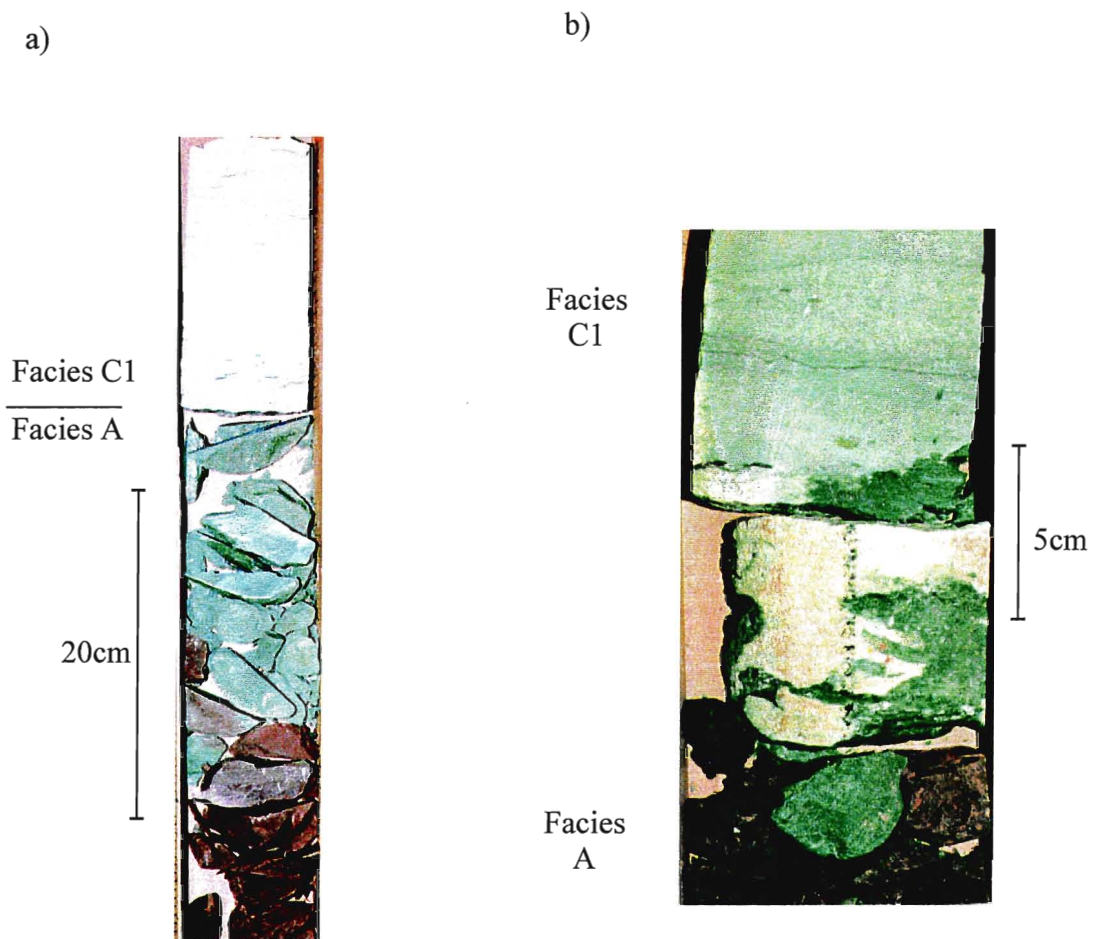


Figure 11. Facies A (Queenston Shale) tops. a) Facies A is topped by a green weathered unit and is erosively overlain by Facies C1 of the Whirlpool Sandstone. Notice the poor condition of Facies A. From well Pembina East Lake Erie 26-M-1a. The Queenston-Whirlpool contact is at -142.29m; b) Mud diapirs of Facies A intruding into Facies C1. Notice the abrupt facies change between the two units. From well Pembina East Lake Erie 26-S-1b. The Queenston-Whirlpool contact at -157.11m

fine upwards. The sets also appear to be sharp or even erosionally based. Multiple sets of planar tabular cross-bedded sandstone are normally stacked to form parasetts.

Trough cross-bedded sandstone is also present in Facies B1. Trough cross-beds appear as sets ranging from 5 cm to 42 cm in thickness. Sands are quartzose, unfossiliferous, well sorted and mostly fine grained, but locally medium grained. Locally, shale clasts lie along cross-bed foresets. The shale clasts are normally well rounded. Rare angular shale clasts are most likely mud chips. Like the planar tabular cross-bedded sandstone, the trough cross-bed sets commonly occur stacked, forming parasetts. Locally, cross-bed sets fine upwards. The bases of sets are erosional and are locally lined by a shale clast lag.

Horizontally laminated to low angle cross-bedded sandstone in Facies B1 is uncommon and forms units ranging up to 50 cm thick. The bases of such units are erosional. The sand is well sorted, unfossiliferous, quartzose and fine grained. Angular shale clasts can be found in some instances and these shale clasts are most likely mud chips. In one instance, the horizontal lamination is associated with heavy mineral sheets (figure 12a).

Shale clast conglomerate occurs locally in Facies B1. The units occur largely as a thin (normally 5 cm thick, but locally thicker) layer of rounded shale clasts, approximately 1 cm in diameter (figure 12b). The clasts are supported by a matrix of well sorted, fine to medium grained sandstone. The clasts commonly form a lag deposit over a scoured boundary, but locally the conglomerate forms the base of a set of unfossiliferous, trough cross-bedded sandstone. In some cases, the unit forms as abundant subrounded shale clasts in trough cross-stratified sandstone approximately 25 cm thick.

This facies is found in cores 42-F, 64-P, 64-W, 89-D, and 89-H.

## **Facies B2**

Current ripple cross-laminated sandstone dominates Facies B2. The composition of the

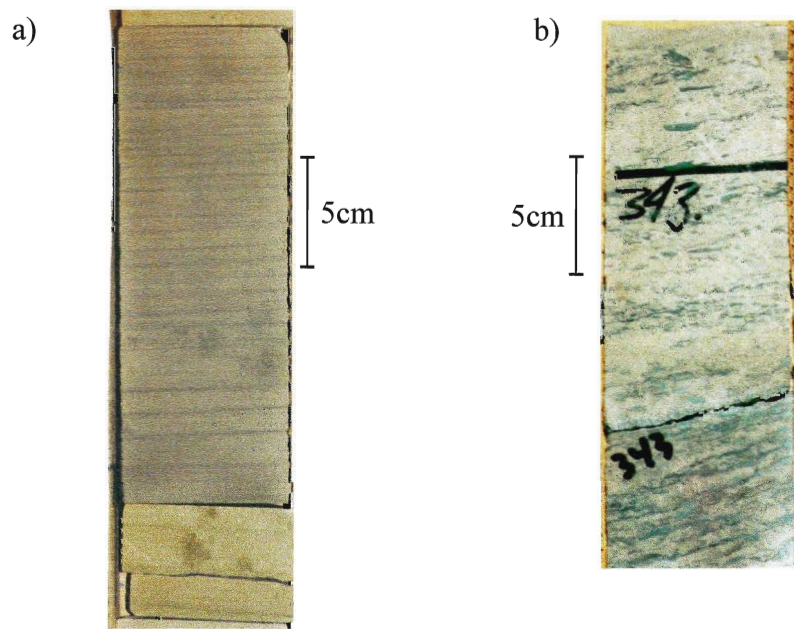


Figure 12. Facies B1. a) Horizontally laminated sandstone with heavy mineral laminae. From well Pembina Lake Erie 64-W-4, core interval -260.00m to -259.66m; b) Shale clast conglomerate in a trough cross-bedded sandstone matrix. From well Pembina #2 Lake Erie 42-F-2, core interval -162.60m to -162.37m.

sandstone is quartzose and unfossiliferous and the grain size ranges from very fine to fine grained sand with minor silt. Sets were approximately 1 cm thick. The current ripples are commonly associated with shale beds that interbed with the current rippled sandstone (figure 13); commonly the shales gradationally overlying the sandstone. The current rippled sandstone commonly consists of many sets of ripple cross-lamination stacked to form larger parasetts. The base of the current ripple cross-laminated sandstone is normally sharp.

Shale and siltstone are minor components of Facies B2. Beds are always very thin, the thickest measured 5 cm. The shale is unfossiliferous and bioturbation and desiccation cracks are never present in this facies. Shale locally forms the cap of a fining upward sequence associated with the current rippled sandstone. A shale sample from well Pembina Lake Erie 64-W-4, depth 259.14 m below sea level, was found to contain spores and spore-like palynomorphs and no known marine palynomorphs (appendix 1, Parkins, 1997).

Facies B2 is present in cores 42-F, 64-W-4, 89-H, and 89-H-2.

## **Element C**

### **Facies C1**

In general, Facies C1 is lithologically similar to Facies B1 and Facies C2 with some significant textural differences. The sandstones of Facies C1 are normally better cemented, normally coarser grained (though there can be some overlap), and greyer in colour, due to a higher lithic fragment content (well displayed in well Anschutz Lake Erie 8-V). Overall, this facies is quartzose and unfossiliferous, well sorted and mostly medium grained, but locally fine grained. Facies C1 is present in cores 5-X, 6-R, 7-Y, 8-V, 21-X, 22-S, 26-S, 26-M, 27-G, 67-F, 67-P, 69-F, and 72-O.

Planar tabular cross-bedded sandstone is common in Facies C1, locally containing



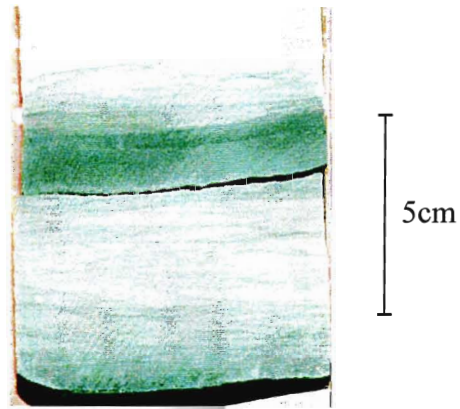


Figure 13. Sandstone and shale of Facies B2. From well Pembina Lake Erie 89-H-2, core interval -275.85m to -275.71m.

rounded shale clasts. Sets range from 10 cm to over 50 cm. Such units are sharp based and locally erosionally scoured. Trough cross-stratified sandstone also appears in Facies C1 (figure 14). Sets vary in thickness from less than 10 cm to almost 50 cm. The sets are invariably erosionally based and locally contain rounded shale clasts.

Shale clast conglomerates are commonly associated with Facies C1. The conglomerates are normally 2 cm to 14 cm thick, matrix supported, and associated with trough cross-bedded sandstone (figure 14). The shale clasts are angular to rounded. The sandy matrix is normally well sorted, quartzose, unfossiliferous, and is medium grained. The shale clast conglomerate is concentrated at the bases of scours.

Horizontal laminated sandstone is preserved locally in Facies C1 in quartzose, well sorted, unfossiliferous, fine to medium grained sand. Units are up to 17 cm thick and contain common erosional surfaces. Heavy mineral sheets are rare.

Massive sandstone is rare in Facies C1, being present in only one core. The sandstone is quartzose, well sorted, unfossiliferous and fine to medium grained. It contains erosional surfaces defining units approximately 10 cm thick. There are no apparent original bedding surfaces defining any internal forms of cross-stratification.

## **Facies C2**

Planar tabular cross-bedded sandstone is a common feature in Facies C2. The sand in this unit is unfossiliferous, quartzose, well sorted, and normally fine grained, uncommonly medium grained. Sets range in thickness from 9 cm to almost 40 cm. Locally, sets are stacked to form parasetts, although parasetts are less common than in Facies B1. Planar tabular cross-beds are periodically erosionally based. The presence of rounded to angular shale clasts lying on foresets was recorded but is uncommon. Sets commonly fine upward, and less commonly coarsen upwards. In one instance, rhythmic shale laminae appeared

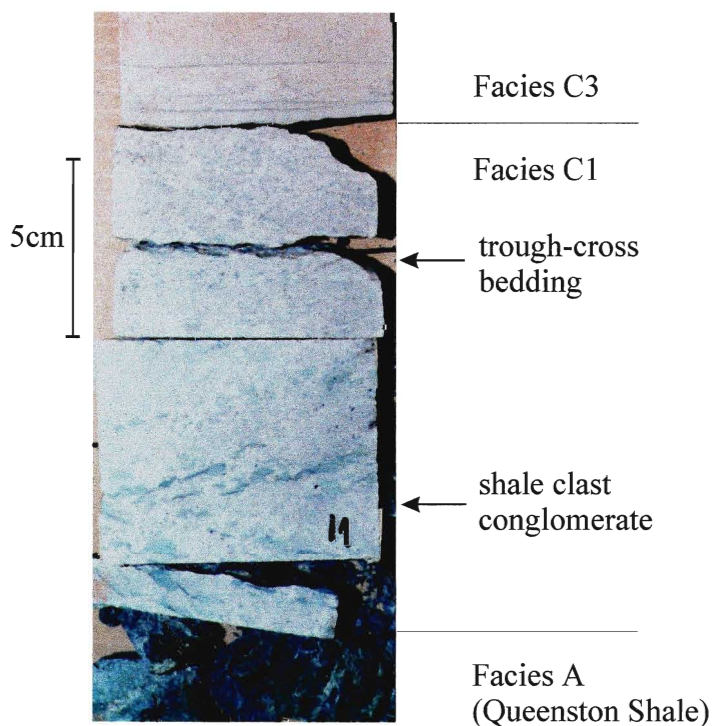


Figure 14. Shale clast conglomerate in a trough cross-bedded sandstone matrix of Facies C1 forming the base of the Whirlpool Sandstone. It is immediately overlain by trough cross-bedded, medium grained sandstone of Facies C1. This is further overlain by what appears to be curled shale laminae in sandstone, commonly seen in Facies C3. From well Pembina Lake Erie 21-X-2, Facies A (Queenston) top at -142.16m.

draping foresets in core 26-M-1a (figure 15a). The shale laminae bound thick-thin alternations of sand packages. Rare bioturbation is locally present and consists of small *Paleophycus*.

Trough cross-bedded sandstone is very common in Facies C2. The sands are well sorted, quartzose, unfossiliferous, and are normally fine grained, though they can uncommonly reach medium grain size. In one instance the sands are glauconitic (well Con Amoco 13102 Lake Erie 96-D). The sets range from 3 cm to 30 cm in thickness, but most range from 10 cm to 25 cm thick. Like the planar tabular cross-bedded unit described above, these sets are stacked to form parasetts. Locally, the sets fine or coarsen upwards. Rounded to angular shale pebbles locally line the foresets. The bases of the sets are erosional and can have up to 5 cm of relief visible in core. Rare bioturbation is locally present in the trough cross-beds and consists of *Paleophycus*.

Horizontal to low angle, laminated sandstone is common in Facies C2 (figure 15b). These quartzose, unfossiliferous, well sorted sands are very fine to medium grained, with fine grain size dominating. Rounded shale clasts are present in some instances. Units range from 2 cm to 78 cm in thickness and contain many erosional surfaces. Over the erosional surfaces are normally medium grained sand lags that fine upwards into fine grained sandstone.

Convolute stratification is present in Facies C2 as a very fine to fine grained quartzose sandstone. Associated structures include ball and pillow structures and forms of fluid injection. In core CPOG Haldimand #1 Lake Erie 131-G-4, the convoluted sandstone displayed fluid injections of fine and very fine grained sandstone into medium grained sandstone (figure 15c). This unit rarely displays any forms of bioturbation, but when present consist of rare, small *Paleophycus*. Beds range from 13 cm to 94 cm in thickness. Original

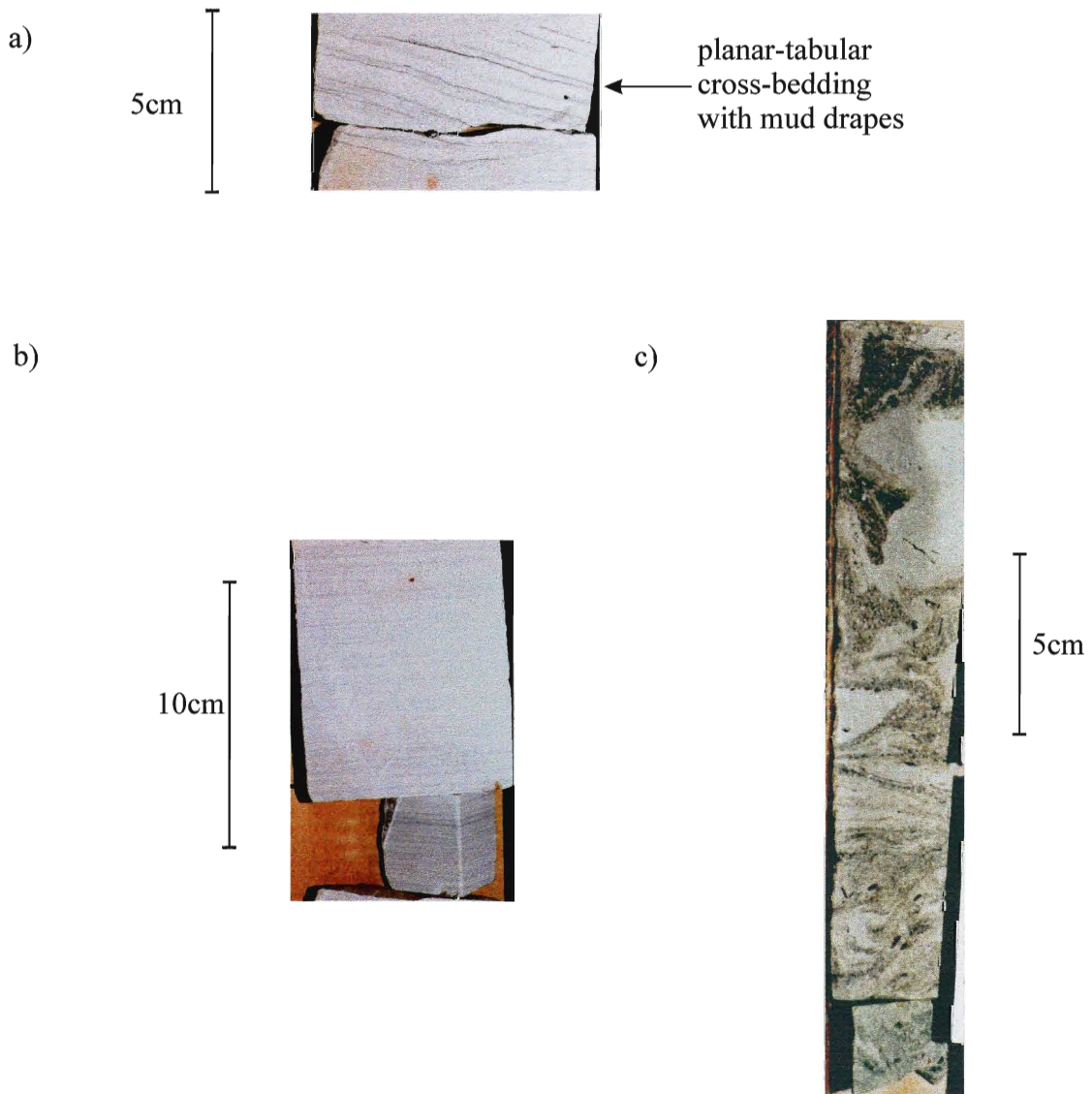


Figure 15. Facies C2. a) Planar-tabular cross-bedding with mud drapes on the foresets. From well Pembina East Lake Erie 26-M-1a, core interval -147.21m; b) Horizontally laminated sandstone. From well Pembina East Lake Erie 26-M-1a, core Interval -156.14m to -155.85m; c) Convoluted sandstone with injection of fine grained sand into a medium grained sandy body. From well CPOG 131-G, core interval -338.04m to -337.93m.

bedding is normally not preserved, but in two cases the original bedding appeared to be trough cross-bedded.

This facies is observed in cores 5-X, 6-R, 7-Y, 8-V, 21-X, 22-S, 23-S, 24-V, 26-M, 26-S, 27-G, 67-F, 67-P, 69-F, 96-D, and 131-G.

### **Facies C3**

Facies C3 consists entirely of coarsely interlayered sandstone with or without shale, and lenticular, wavy and flaser bedded sandstone and shale, and is very common in the Whirlpool Sandstone. Facies C3 is quite variable, locally containing entirely sandstone (figure 16a), whereas in other locations Facies C3 consists of over 30% shale (figure 16b). The sands are unfossiliferous, quartzose, well to moderately sorted, and range in size from very fine to medium grained. The coarsely interlayered sandstone includes sand beds anywhere from 1 cm thick to 17 cm thick. These beds normally fine upward and are erosionally based. Less commonly the beds coarsen upwards. Rounded shale clasts are present locally. Ripple cross-laminated beds are associated with the sands at some locations and horizontal lamination is uncommon in the sand beds. Silty shales are normally interbedded or interlaminated with the sand beds. These shale beds are commonly internally horizontally laminated and can be up to 5 cm thick. The shales never contain fossils. Sun cracks, and less commonly syneresis cracks, are visible in the shales (figure 16b). The sun cracked shale beds normally take the form of curled shale clasts lying on sand beds, the curled edges almost exclusively pointing upward (figure 16c). In other cases the interbedded and interlaminated sandstone and shale appear lenticular in form (figure 16d). Rare bioturbation is associated with this unit, normally as isolated burrows of *Planolites* or *Paleophycus* found largely in the shales and less commonly in the sandy beds. A shale sample from this unit (well 64-P, from -240.52m above mean sea level) was found to contain mostly spores and spore-like

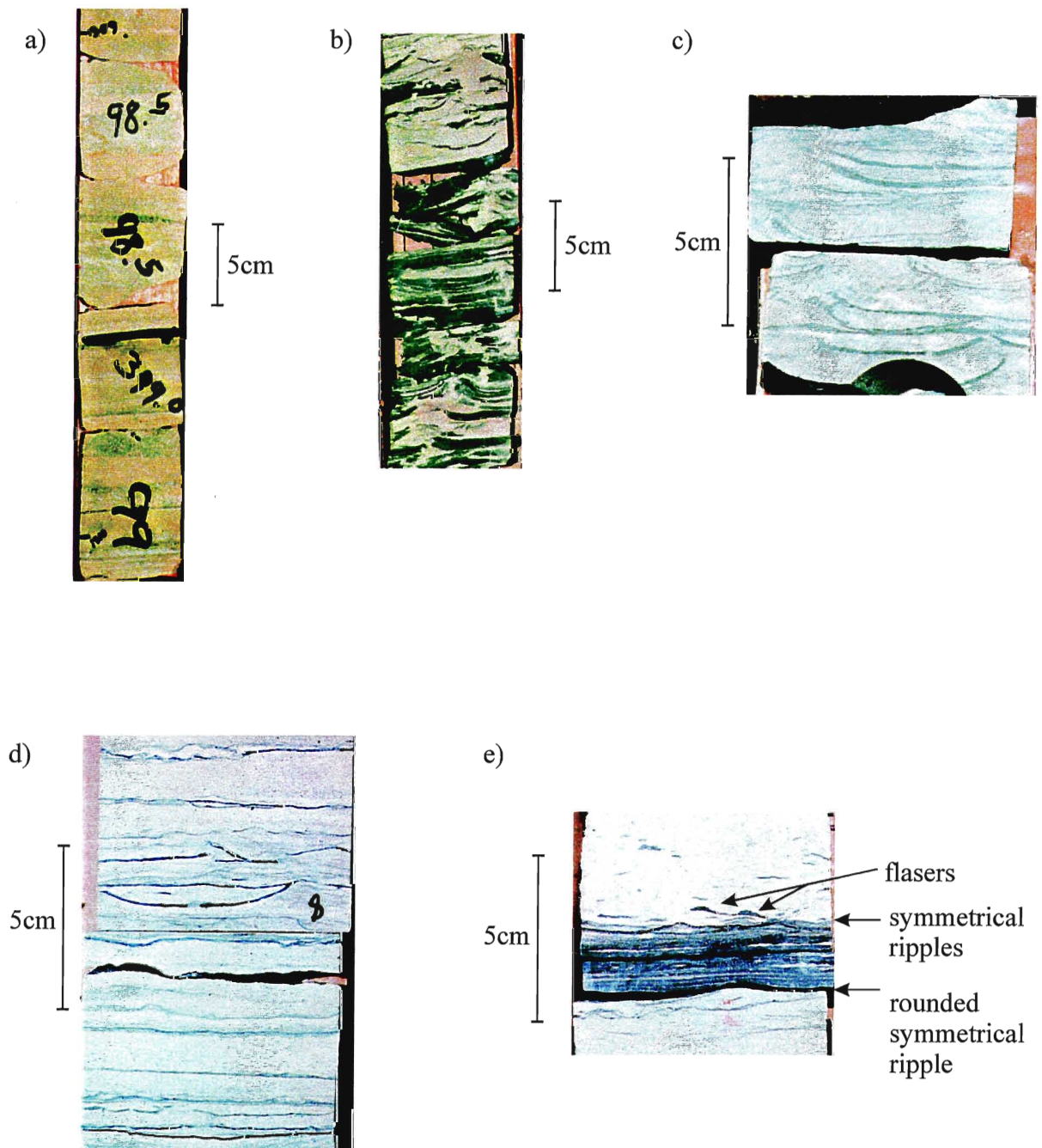


Figure 16. Facies C3. a) Coarsely interlayered sandstone. This is an end member of the unit consisting of 100% sand and no shale. Discrete sandstone beds are centimetres in thickness and normally fine upwards. From well Pembina Lake Erie 67-F-4, core interval -218.32m to -217.75m; b) Coarsely interlayered sandstone and shale. A shalier version of figure 15a. There are abundant suncracks in the shales. A shale sample for a palynological analysis was taken from this unit. From well Pembina #2 Lake Erie 64-P, core interval -240.72m to -240.14m; c) Curled shale laminae. From well Pembina Lake Erie 89-H-2, core interval -275.17m; d) Lenticular shale laminae. From well Pembina Lake Erie 21-X-2, core interval -140.87m to -141.00m; e) Preserved symmetrical ripples and flasers. From well Pembina East Lake Erie 26-S-1b, core interval -156.41m.



palynomorphs, with minor acritarchs and scolecodonts (appendix 1, Parkins, 1997).

Lenticular, wavy and flaser bedded sandstone and shale occur less commonly in Facies C3 than the coarsely interlayered sandstone and shale described in the previous paragraph. The sands are quartzose and unfossiliferous, fine to very fine grained and well sorted. Beds are generally thin, less than 5 cm. Primary structures in the sandstone include thin planar tabular and trough cross-beds, asymmetrical current ripples, and symmetrical ripples, the symmetrical ripples have sharp and rounded crests (figure 16e). Locally draped over the foresets are shale laminae or beds. Bedding ranged from lenticular, with thick sand lenses in shale, to cross-bedding with flasers, depending upon the amount of shale present. Locally very little shale is present and the ripple cross-laminae appears to have a high rate of climb. Associated with this unit are syneresis cracks. Bioturbation is rare and mostly consists of small *Planolites* burrows. Where overlain by the carbonates of the Manitoulin Formation, this unit is calcareous.

This facies is found in core 5-X, 6-R, 7-Y, 8-V, 21-X-2, 23-S, 24-V-1, 26-M-1A, 26-S-1B, 27-G, 39-W, 39-Y, 42-F, 51-A, 56-E, 64-P, 64-W, 67-F-4, 67-P-2, 69-F, 71-I-3, 72-O-1, 89-D, and 89-H-2.

## **Element D**

### **Facies D1**

Facies D1 is characterized by a fining upward pattern, normally from cross-bedded sandstone into bioturbated sandstones and shales.

Planar tabular cross-bedding is common in Facies D1. The sands are quartzose, locally fossiliferous, well sorted, and fine to medium grained. Sets range from 8 cm to 30 cm thick and may fine upwards. In one core evidence for current reversals can be recognized in changing directions of foreset dips from one set to the next. The foresets are normally graded



in some instances (figure 17a). Locally, there is rare bioturbation, the trace fossils being *Skolithos* or *Paleophycus*.

Trough cross-bedding commonly occurs in Facies D1 (figure 17b). The sands are quartzose, unfossiliferous, well sorted, and fine to medium grained. Sets range from 15 cm to 35 cm in thickness and are locally stacked to form parasetts over 1.5 m thick. Sets have erosional bases and locally contain angular shale clasts or a lag of rounded shale clasts.

Horizontal to low angle laminated sandstone is present in Facies D1. The sands are quartzose, unfossiliferous, well sorted, and fine grained. Sets range from a few centimetres to over half a metre. Rare bioturbation is locally present in this unit, consisting of *Paleophycus* and *Bergauria*. The trace fossils are very small, the *Bergauria* always less than 0.5 cm in width.

Ripple cross-laminated sandstone occurs in Facies D1. The sands are quartzose, unfossiliferous, well sorted, and fine grained. The cross-laminated sets are less than 1 cm thick and appear as climbing ripples in some instances and include mud drapes over foresets, suggestive of thin flasers. They are locally associated with the horizontal and low-angle laminated sandstone.

Convolute sandstone appears in Facies D1. It is formed in a well sorted, fine grained (with minor mud), quartzose, and unfossiliferous sandstone. Original structures have been erased by the formation of ball and pillow structures along with large flame structures (figure 17c).

Interbedded sandstones and shales, similar to those of Facies D2, are found in Facies D1 (figure 18a). The lower contact is generally gradational with the previously described cross-bedded units in this facies. The beds of sand are normally fine grained, quartzose, unfossiliferous, and locally glauconitic (figure 18a). The sand beds show rare horizontal to

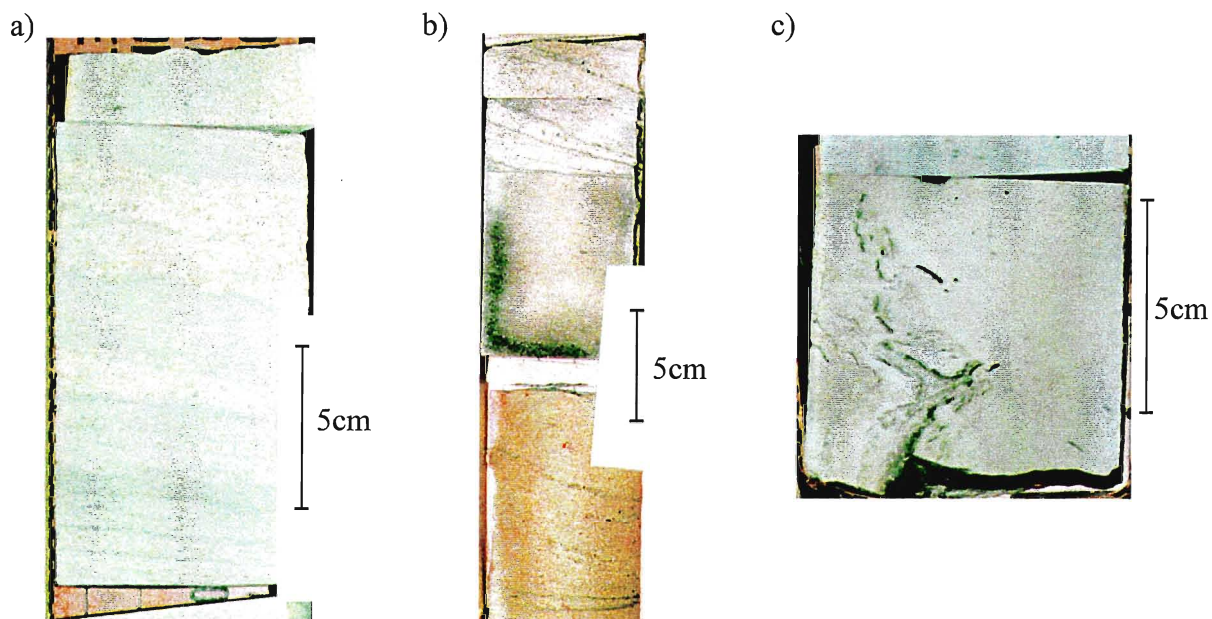


Figure 17. Facies D1. a) Planar tabular cross-bedding with graded foresets. From well Pembina #3 39-Y, core interval -211.17m to -210.88m; b) Trough cross-bedded sandstone. From well Pembina #2a LE 68-Q-2a, core interval -246.60m to -246.19m; c) Flame structure in convolute bedding. From well Pembina #2a LE 68-Q-2a, core interval -243.70m.

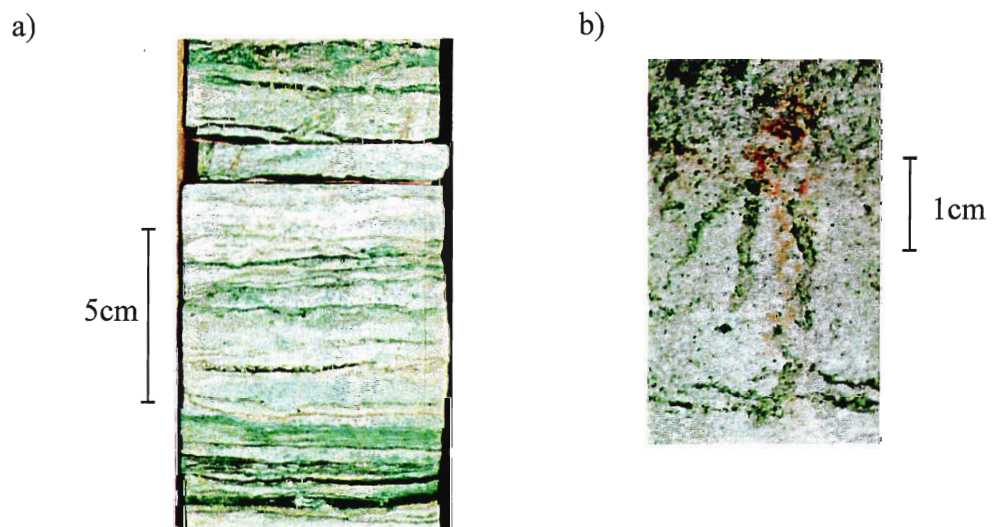


Figure 18. Facies D1. a) Glaucconitic sandstone and shale. From well Pembina #3 LE 39-W, core interval -216.94m to -216.74m; b) *Skolithos* ichnofauna. From well Pembina #3 LE 39-W, core interval -215.74m.

low angle lamination and are normally strongly bioturbated, including *Skolithos* (figure 18b), *Arenicolites*, *Bergauria*, and *Paleophycus*. The shales are normally on the order of several centimetres thick, dark grey in colour, well bioturbated and locally contain syneresis cracks. Trace fossils in the shales include *Planolites* and a “nested” form of *Teichichnus*, where the trace normally consists of two spreiten, the upper limit of spreiten being four.

This facies is found in cores 23-Y, 39-T, 39-W, 39-Y, and 68-Q.

## **Facies D2**

Interbedded sandstone and shale is common in Facies D2. The proportion of shale normally varies from approximately half the unit (figure 19a) to almost the entire unit (figure 19b), although rarely sandstone forms thick beds interbedded with thin shale beds. The sandstone is quartzose and ranges from very fine to fine grained and beds can be several centimetres thick. This particular unit is normally horizontal to low angle laminated and locally wavy bedded, although ripple cross-lamination is locally present within the sand beds. The sandstone beds fine upwards in some instances. The sands are normally moderately bioturbated and the trace fossils in the sands are commonly *Ophiomorpha*, *Arenicolites*, *Teichichnus*, and *Paleophycus*, and much less commonly *Skolithos*, *Diplocraterion* (figure 20a), *Gyrolithes*, and *Helminthopsis*. The trace fossils are generally small in size, normally less than 1 cm across, the *Ophiomorpha* are the largest forms, exceeding 1 cm across. The shales are normally black or dark grey, horizontally laminated, and range up to several centimetres in thickness. They are normally moderately bioturbated by *Chondrites* (figure 20b), *Planolites*, *Paleophycus* and a “nested” form of *Teichichnus*. In some cases a *Teichichnus* dominated suite is present in black shale (figure 19b). As in the sandy portion of the unit, the trace fossils are generally limited to a small size. In one instance, the bioturbation intermixed the sand and shale beds (Anschutz Lake Erie 23-Y).

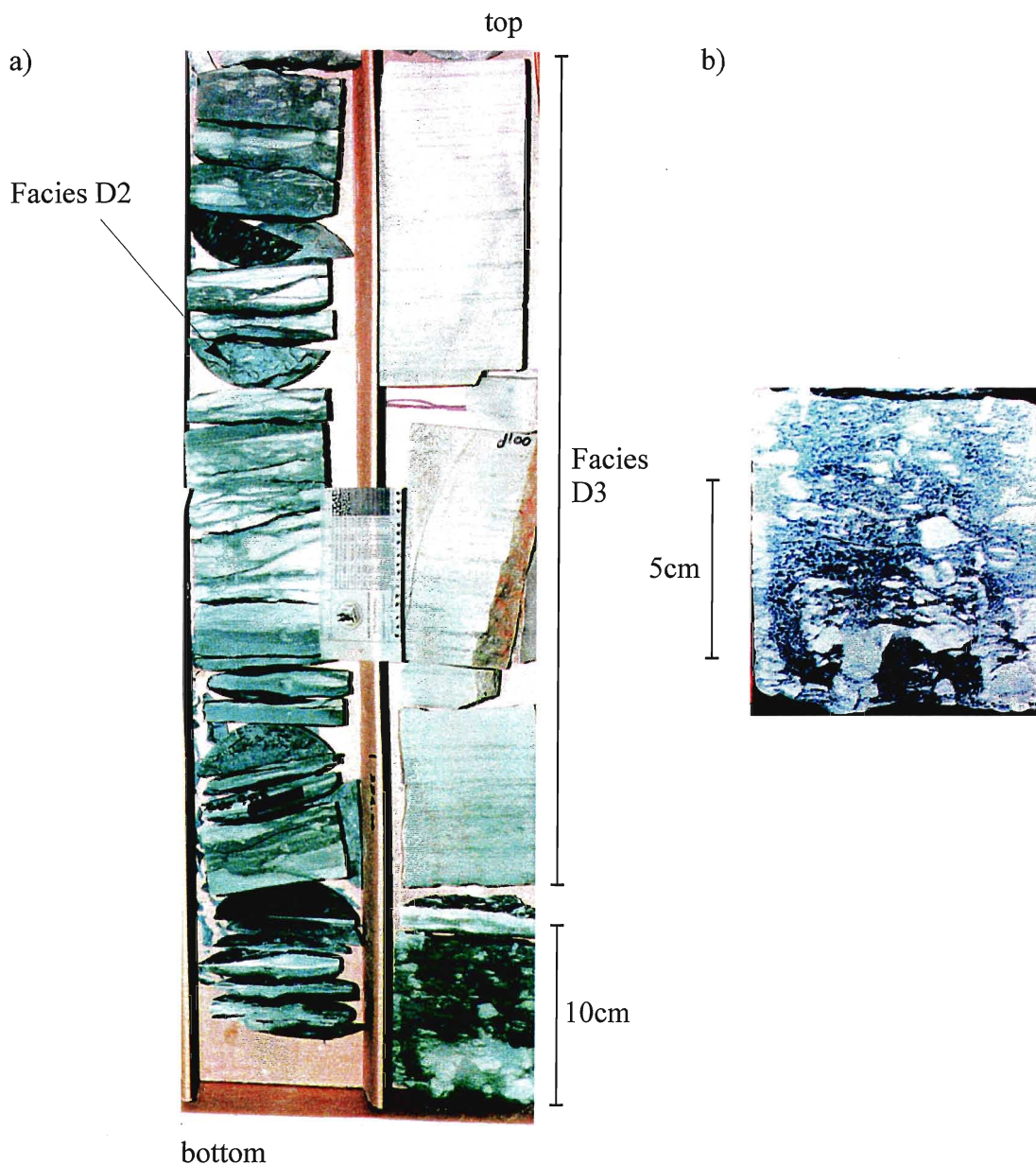


Figure 19. Facies D2. a) Interbedded sandstone and shale with a low diversity ichnofossil assemblage. Capping the sequence is a horizontally laminated sandstone with heavy mineral laminae from Facies D3. From well Pembina East Lake Erie 39-T-2, core interval -204.10m to -203.42m. b) *Teichichnus* dominated ichnofossil assemblage in shale. From well Pembina East Lake Erie 39-T-2, core interval -203.52m to -203.42m.



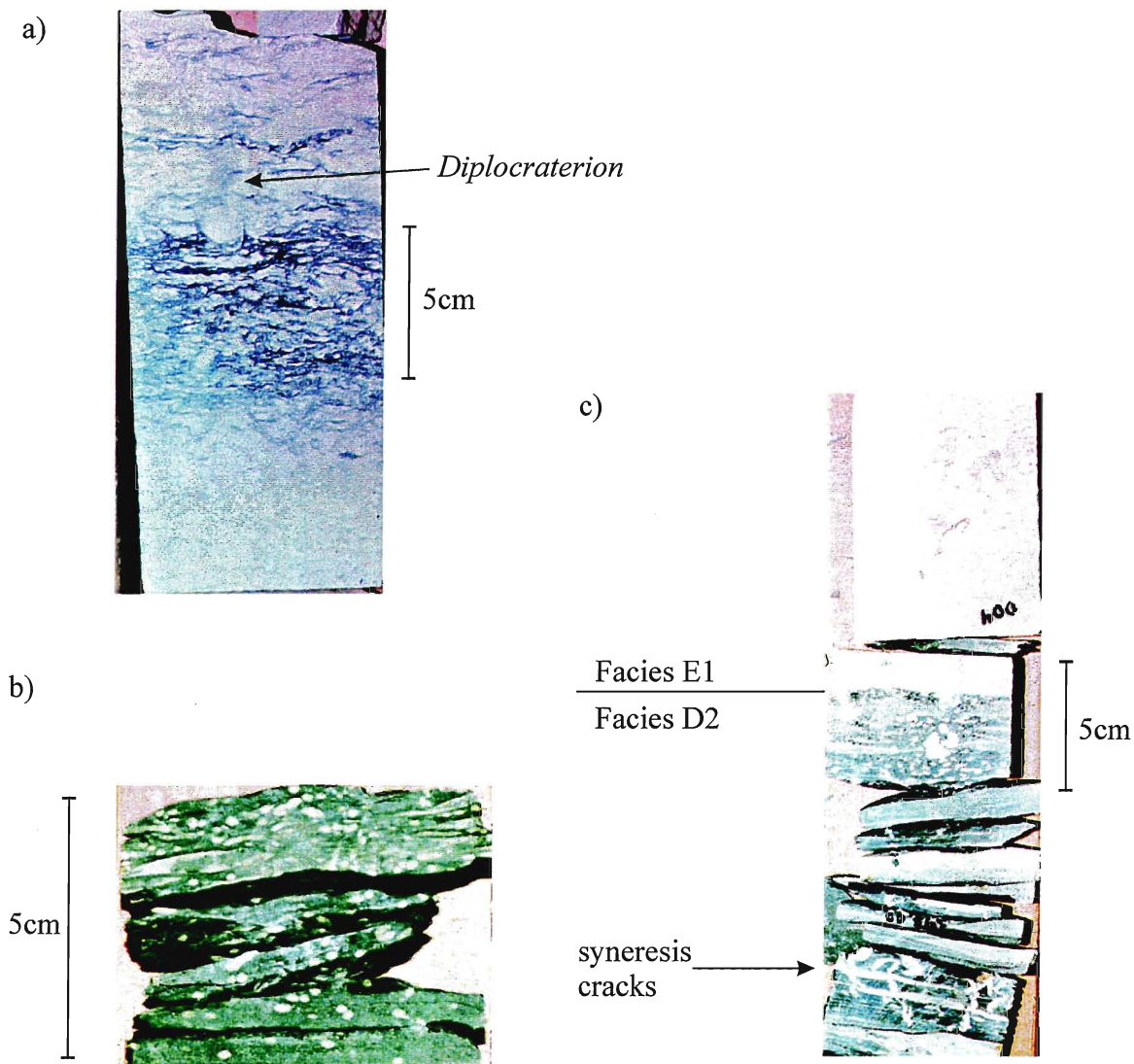


Figure 20. Facies D2. a) Large *Diplocraterion* in bioturbated sandstone. From well Pembina East Lake Erie 21-X-2, core interval -140.89m to -140.70m. b) Low diversity ichnofossil assemblage consisting of *Chondrites*. From well Pembina #2 Lake Erie 64-P, core interval -239.87m to -239.79m; b) Well formed syneresis cracks in shale with a low diversity ichnofossil assemblage. This is sharply overlain by a bioturbated sandstone of Facies E1. From well Pembina Lake Erie 69-F-2, core interval -159.97m to -159.88m.

Shell material is absent. The shales commonly contain syneresis cracks (figure 20c).

Trough cross-bedded, planar tabular cross-bedded to low angle cross-bedded, and low angle laminated sandstone and silty sandstone is also part of this facies. The sand in the unit is quartzose and is normally fossiliferous. Sandstone intraclasts are common. The foresets are draped with silty shale laminae, giving the foresets a lenticular appearance. The sets are erosionally based and up to 29 cm thick, but mostly less than 15 cm thick. The sets locally fine upwards from a very fine grained sandstone into a silty sandstone. Bioturbation occurs locally near the tops of the sets and consists of *Skolithos*, *Planolites*, and *Teichichnus*, where the *Teichichnus* burrows consist of two spreiten.

Horizontally laminated to planar tabular cross-bedded sandstone also appears in this facies. The sands are well sorted, fine to medium grained and quartzose. The entire sequence locally fines upwards. Shell fragments and glauconite is locally present and heavy mineral laminae are very common. The sets of horizontal laminae are approximately 4 cm thick and fine upwards. The planar tabular cross-bedded sets are up to 7 cm thick and form thick amalgamated sets approximately 1 m in thickness. Bioturbation is rare in these units, but *Paleophycus* is present locally. Shale laminae or thin shale beds are also locally present. Also present are weak to strong convolute bedding, water escape flame structures, and an instance of one overturned soft sediment fold, which helps to differ this unit from the similar Facies D3.

This facies is found in cores 5-X, 6-R, 7-Y, 8-V, 21-X-2, 22-S, 23-S, 23-Y, 26-M-1A, 39-T-2, 39-W, 39-Y-3, 42-F-2, 69-F-2, 71-I-3, and 72-O.

### **Facies D3**

Horizontal to low angle laminated sandstone forms the entirety of Facies D3. The unit consists of a well sorted, fine to medium grained, quartzose sandstone. Bedding is dominated

by horizontal to low angle lamination (figure 19a). There are numerous erosion surfaces in these units, normally accompanied by a shell fragment lag or, less commonly, a shale clast lag. In general, shell fragments are common in this unit. Heavy mineral sheets are locally present (figure 19a). Only two instances of bioturbation were noted, one being a single *Paleophycus* and the other single *Teichichnus* and *Thalassinoides* traces, both found burrowing into the facies from an the overlying unit. The base of the facies is always sharp. This facies is normally associated with Facies D2, commonly overlying it and in one instance (well 39-W) interbedded with it. Where it exists, it always caps the Whirlpool Sandstone.

This facies is found in cores 22-S, 39-T-2, 39-W, 39-Y, and 72-O-1.

## **Element E**

### **Facies E1**

Bioturbated sandstone is very common in Facies E1. The sandstone is quartzose and very fine to fine grained and commonly has a minor amount of mud. Locally, the sandstone is calcareous and, throughout the Whirlpool in subcrop, the calcite content increases westwards. Shell fragments are rarely preserved except in the western part of the study area. The sandstone is normally completely bioturbated (figure 21), rarely preserving primary structures. Where primary structures are preserved the sandstone appears to be hummocky cross-stratified. Trace fossil forms are robust and normally include *Planolites*, *Teichichnus*, *Chondrites*, *Paleophycus*, *Rhizocorralium*, *Skolithos*, and *Zoophycos*. Less commonly found were *Helminthopsis*, *Asterosoma*, and *Gyrolithes*.

Cross-bedded sandstone of Facies E1 occurs in one core only (Pembina #2 Lake Erie 42-F). The sands are quartzose and fine grained and contain some abraded shell material. Planar tabular cross-beds are present with sets up to 9 cm in size. Rare, well developed *Paleophycus* occurs in this unit.



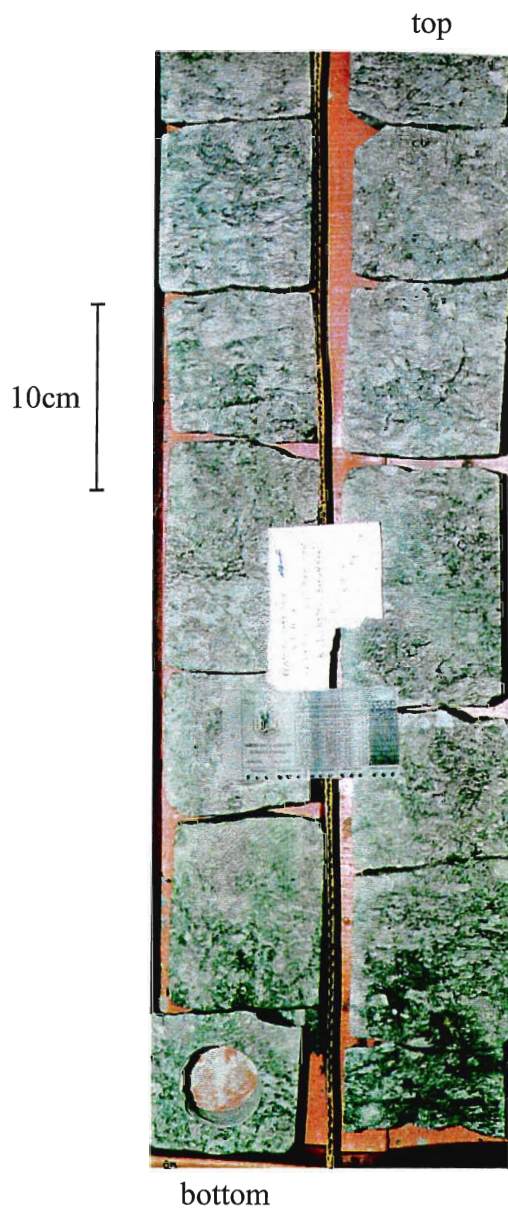


Figure 21. Facies E1. Bioturbated sandstone with a high diversity, high density ichnofossil assemblage. From well Pembina Lake Erie 89-H-2, core interval -274.59m to -273.32m.

Found in cores 14-S, 42-F, 64-P, 64-W, 67-F, 67-P, 69-F, 89-D, 89-H, 131-G.

## **Facies E2 (Manitoulin Formation)**

Interbedded and interlaminated shale and limestone make up Facies E2 (figure 22a). Shale beds are up to several centimetres thick but are generally much thinner. The limestone is dark grey and contains abundant shell fragments and crinoid ossicles as well as dark grey pellets and glauconitic pellets. Both shale and carbonate can be heavily bioturbated. Calcareous sandstone is present instead of shale in some instances. Westwards, away from the majority of the Whirlpool Sandstone, the proportion of shale decreases and the entire unit becomes limestone.

Found in cores 14-S, 51-A, 56-E, 95-H, and 96-D.

## **Facies E3 (Cabot Head Formation)**

Interbedded sandstone and shale forms an important part of this facies. It is always sharp based when overlying the Whirlpool Sandstone. The sandstones are well sorted, fine to very fine grained and quartzose. The sandstone beds are hummocky cross-stratified and the sets are up to a few centimetres thick (figure 22b). The sandstone beds locally contain rounded shale clasts and are bioturbated by the ichnofossils *Teichichnus*, *Paleophycus* or *Thalassinoides*. Escape traces are commonly found within the sandstone beds. Beds are sharp based and fine upwards into shale beds. The shale beds are commonly heavily bioturbated, containing the ichnogenera *Planolites*, *Teichichnus*, *Zoophycos*, *Rhizocorallium*, *Asterosoma*, *Anconichnus*, *Chondrites* and *Helminthopsis*, but, in other instances the shales appear massive. The shales and sandstones locally contain shell fragments and/or crinoid ossicles. The sandstones and shales are locally calcareous or locally glauconitic, similar to the carbonate unit described previously.

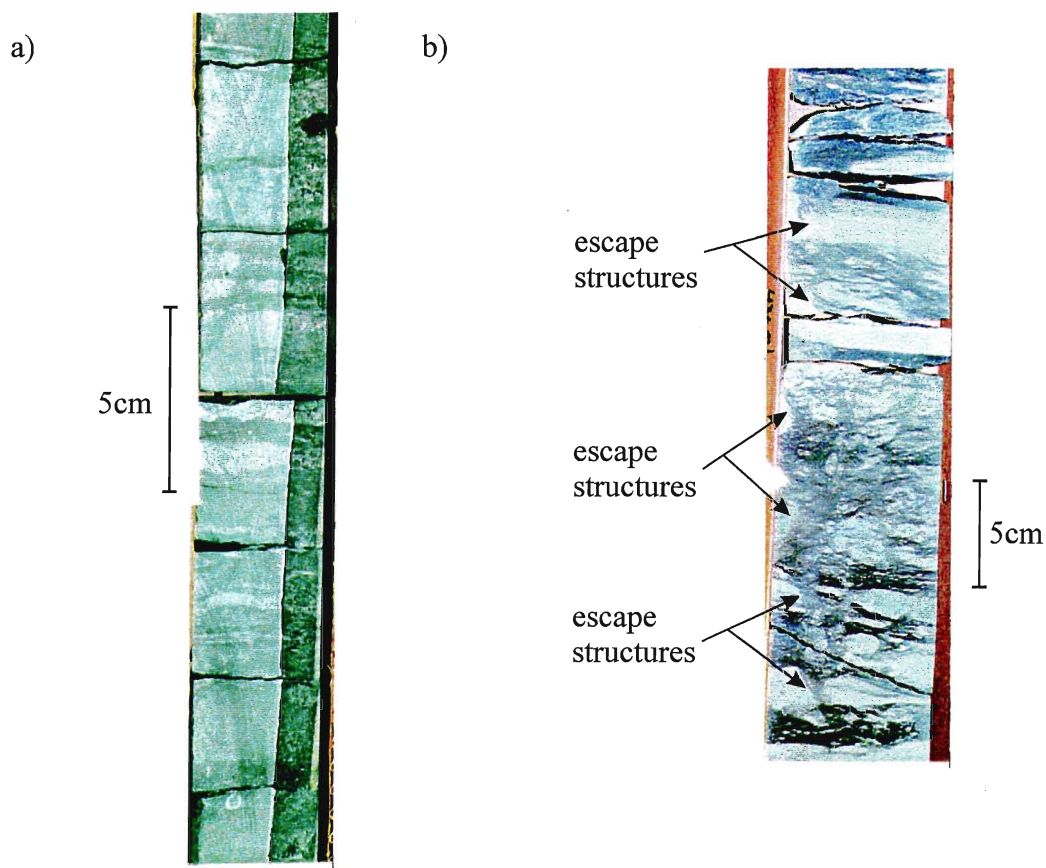


Figure 22. Facies E2 and E3. a) Interbedded and interlaminated limestone and shale of Facies E2 (Manitoulin Formation). From well Cons. Amoco Lake Erie 13076, core interval -303.19m to -302.87m; b) Interbedded sandstone and shale of Facies E3 (Cabot Head Formation). Notice the abundant escape structures. From well Pembina Lake Erie 72-O-1, core interval -255.39m to -255.05m.

A massive or bioturbated shale is included as part of the Cabot Head Formation. It is sharp based where overlying the Whirlpool Sandstone. Trace fossils in the bioturbated shale are normally *Zoophycos*, *Planolites*, *Chondrites*, and *Teichichnus*. The massive shale may also be bioturbated, but trace fossils may be difficult to see because of a lack of sand to fill the burrows.

## ***Facies in Well Logs***

Gamma-ray logs and density-porosity logs were most commonly used in this study. When referring to the density porosity logs, low porosity indicates a porosity between 0 and 6 percent, moderate porosity indicates a porosity between 6 and 12 percent, high porosity indicates a porosity between 12 and 18 percent, and very high porosity is anything over 18 percent.

### **Element A**

As discussed above, the Queenston Shale (Facies A) is very easy to pick based on the gamma ray logs (figure 7) where the radioactive shales contrast with the cleaner units above. The density porosity of the facies is always very low (approximately 0%).

### **Element B**

Facies B1 and B2 are detected using gamma-ray logs and density porosity logs. The facies occur interbedded with each other and distinguishing them on well logs is difficult. Generally, Element B, when dominated by Facies B1, appears as a clean sandstone on the gamma-ray logs with a moderate to high porosity (figure 23). An increase in the radioactivity suggests higher shale content due to the presence of Facies B2. A serrated appearance in the gamma-ray log may indicate interbedding of Facies B1 and B2.

### **Element C**

Facies C1, C2 and C3 are detected through the use of gamma-ray and density porosity well logs. Facies C1 is invariably clean sandstone and this is reflected in the gamma-ray logs (figure 24a). The density porosity log of Facies C1 normally has low to moderate porosity (figure 24a), although it can show local development of high porosity.

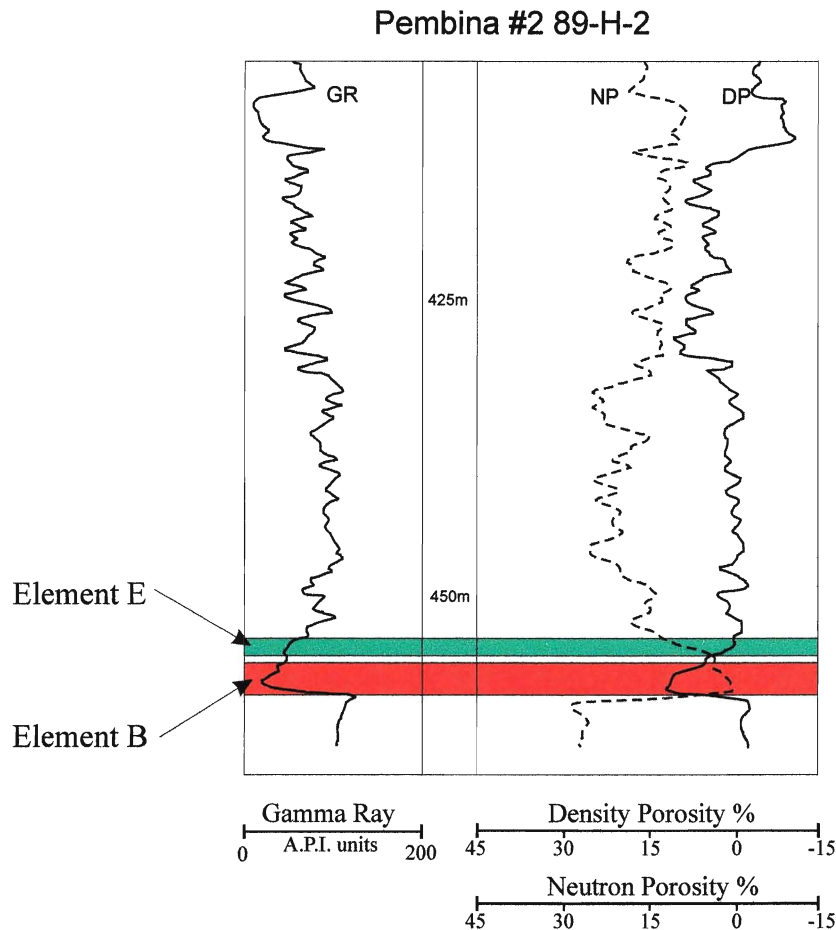


Figure 23. Elements B and E in well logs. Because of the clean, sandy nature of Element B (red fill) in the gamma-ray logs, this section is probably composed largely of Facies B1. Element B also has a moderately high porosity in the density porosity curve. Element E (green fill) is a muddy sandstone in gamma-ray logs with a low porosity in density porosity logs and represents Facies E1.

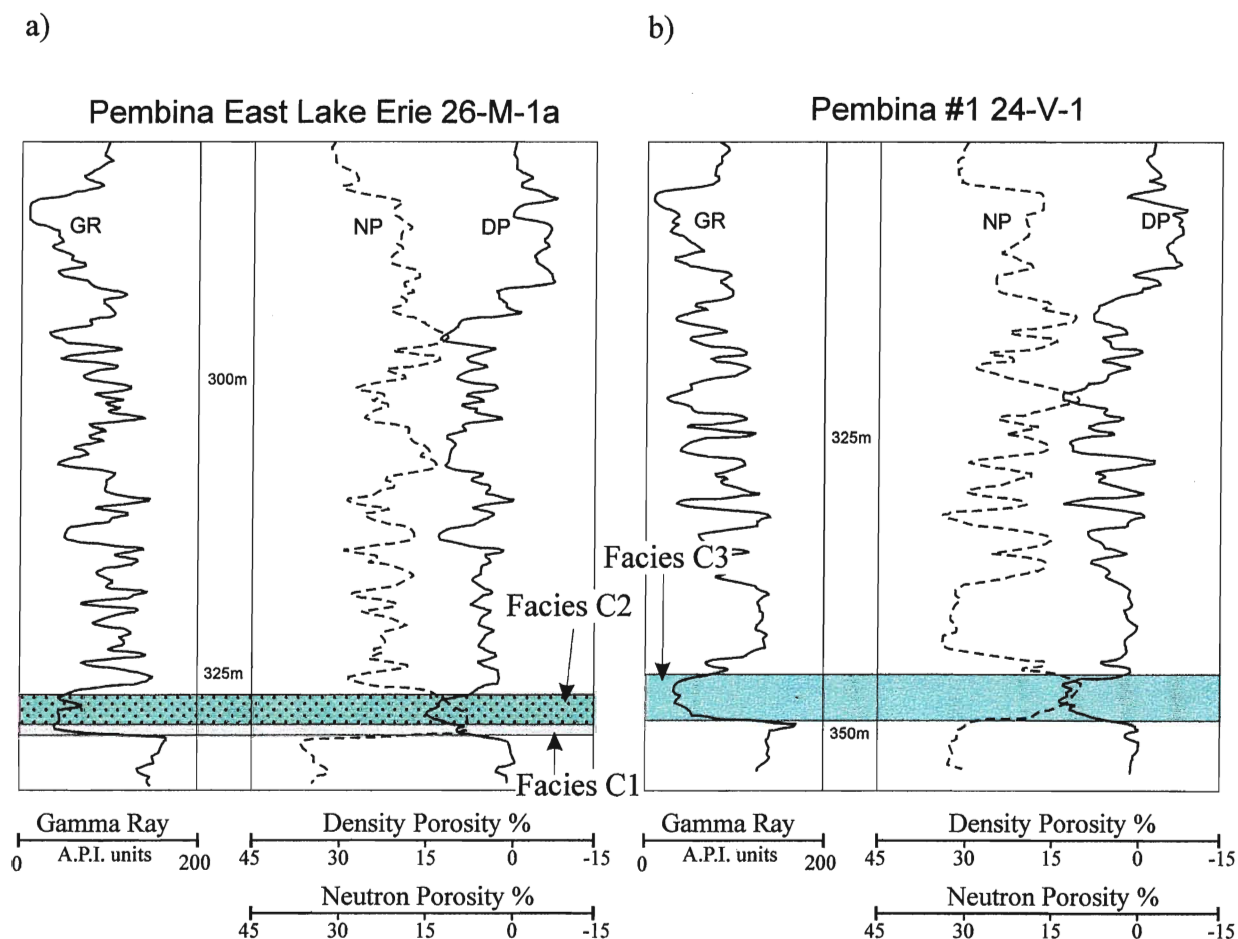


Figure 24. Element C in well logs. a) Facies C1 (grey fill) is a clean sandstone in gamma-ray logs with relatively low porosity in the density porosity log. Facies C2 (speckled blue-green fill) is a clean sandstone in the gamma-ray log and has moderate porosity in the density porosity log. b) Facies C2 (blue-green fill) is a clean sandstone in this example with a moderate porosity in the density porosity log.

Facies C2 is clean sandstone and this is reflected in gamma-ray logs (figure 24a). Density porosity is normally moderate to high, distinguishing it from typical low porosity Facies C1. This facies has very similar characteristics to Facies B1 in well logs. A serrated curve associated with this facies may indicate interbedding with Facies C3.

Facies C3 is a clean sandstone to interbedded sandstone and shale, and as such, makes gamma-ray logs ineffective in distinguishing this facies. Density porosity is normally moderate to low, depending on the shale content (figure 24c). Where this facies is sandy, it is similar to Facies B1 and C2.

#### **Element D**

Facies D1 varies from clean sandstone to interbedded sandstone and shale. Facies D1 normally contains an internal sequence of cross-bedded sands that fines upwards into bioturbated units. This sequence can be recognized on gamma-ray logs as a fining upward sequence of increased radioactivity (figure 25). Where Facies D1 is entirely cross-bedded in core, the fining upward pattern still appears. The density porosity of this facies is generally moderate to high (figure 25) but ranges up to very high porosity. This facies is similar in well logs to Facies B1 and C2, but has a distinctly higher porosity.

Facies D2 is highly variable, from sandstones to shales, and is normally indistinguishable in well logs. Where Facies D2 is a horizontal to low angle laminated sandstone, it is texturally very similar to Facies D3 and indistinguishable from it on well logs.

Facies D3 is clean sandstone and registers as such in gamma-ray logs. This facies has a very low density porosity (approaching 0%; figure 25) and is very similar to a sandy portion of Facies D2, as described above.



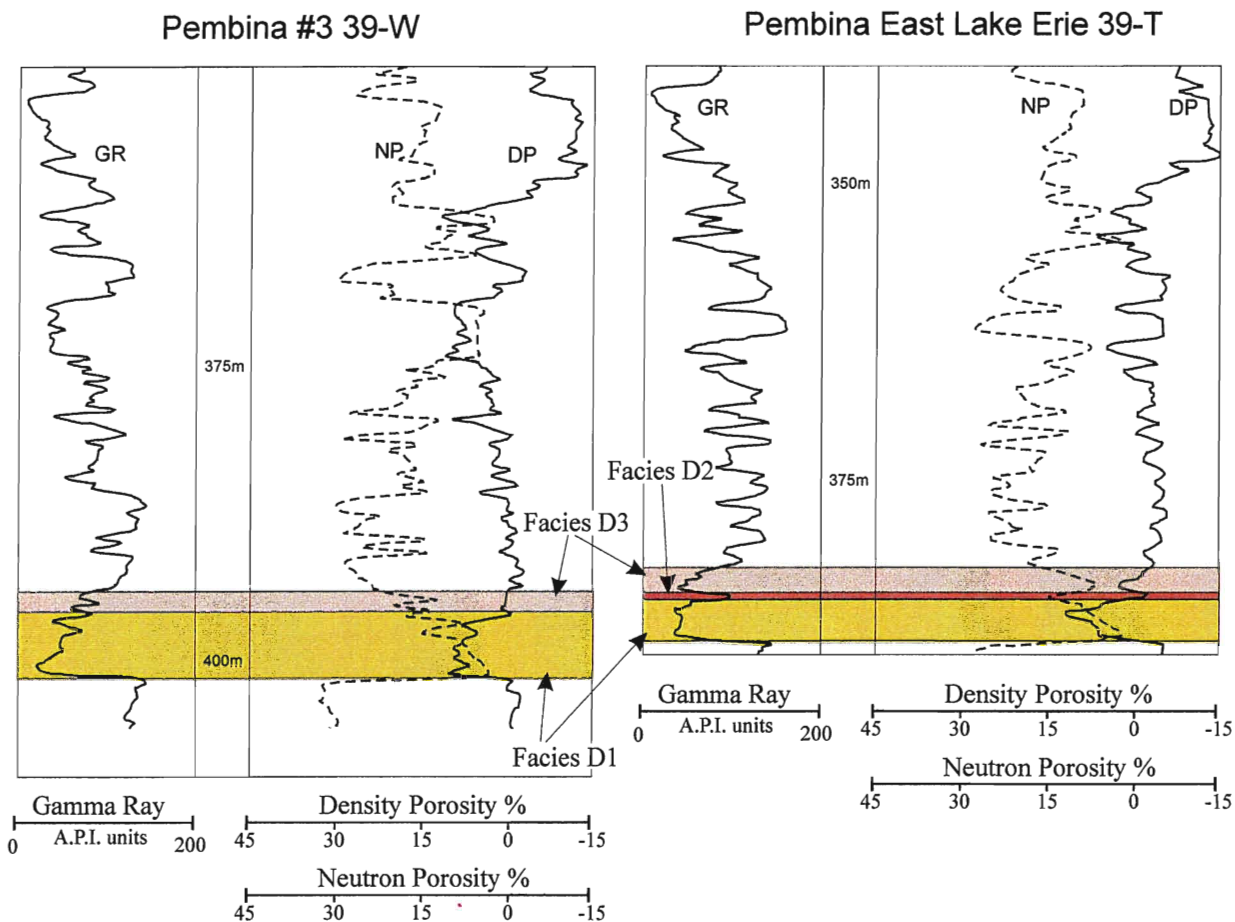


Figure 25. Element D in well logs. Facies D1 (yellow fill) is a clean sandstone in gamma-ray logs and moderately to highly porous in density porosity logs. Element D tends to fine upwards in gamma-ray logs. Facies D2 (dark brown) is a highly variable unit and here exists as a shale. Facies D3 (light brown) is a low porosity sandstone in density porosity logs.

## **Element E**

Facies E1 is shaly sandstone and registers as such on gamma-ray logs. The density porosity of the sandstone is generally low (figure 23). This facies may be confused with Facies C3 and D2, both of which may have a relatively higher shale content and low porosity.

Facies E2 (Manitoulin Formation) is easy to distinguish on well logs. The calcareous nature of these sediments gives the facies a cleaner appearance in the gamma-ray logs. The gamma-ray curve is normally blocky in relatively thick sections. The high density of the facies is apparent as a very low porosity (normally less than 0% density porosity in well logs calibrated for a sandstone reservoir) in the density porosity logs (figure 7).

Facies E3 (Cabot Head Formation) is also relatively easy to distinguish in well logs, though some caution is needed. The unit is normally very shaly and registers as such in gamma-ray logs (figure 7). Sandstones, where present, normally have very low density porosity. This facies can be difficult to discern from a shaley Facies D2.

## **Problems with identifying facies in well logs**

Typical facies responses in well logs are summarized in Table 1.

Facies B1, C2, and D1 can be similar in well logs but can be distinguished using a variety of criteria. Facies D1 tends to have the highest porosity of the three facies and is locally associated with the very low porosity Facies D3. Facies C2 is always associated with Facies C1, which normally has a distinctive response of low density porosity in well logs. Facies B1 has no diagnostic facies associations. Core studies during the course of the project confirmed that host elements identified on figure 10 are characterized by specific facies and facies associations. Therefore, the geometry of the facies and their host elements

**Table 1: Facies and gamma-ray and density porosity well log response.**

<u>Facies</u>	<u>Gamma-ray Response</u>	<u>Density-porosity Response</u>
Facies A	shale	low, ~ 0%
Facies B1	sandstone, serrated curve indicates interbedding between Facies B1 and B2	moderate to high, 6 to 18%
Facies B2	sandstone, sandstone and shale, serrated curve indicates interbedding between Facies B1 and B2	low, 0 to 6%
Facies C1	sandstone, blocky curve	low, 0 to 6%
Facies C2	sandstone, serrated curve indicates interbedding between Facies C2 and C3	moderate to high, 6 to 18%
Facies C3	interbedded sandstone and shale, serrated curve indicates interbedding between Facies C2 and C3	low to moderate, 0 to 12%
Facies D1	sandstone, interbedded sandstone and shale, overall fining upward sequence	high, 12-18% to very high, >18%
Facies D2	shale, interbedded sandstone and shale, sandstone	low, 0 to 6%
Facies D3	sandstone	low, ~0%
Facies E1	sandstone, shaley sandstone	low, 0-6%
Facies E2	limestone, blocky	very low, <0% on sandstone calibrated logs
Facies E3	shale, interbedded shale and sandstone	very low, ~0%

may be the best indicator of which facies is most likely present.

Facies E1, Facies D2, and Facies C3 can be very similar in well logs. Where Facies D2 has locally high shale content, it may be distinguished from the others. If Facies C3 has a high sand content it may be distinguished from Facies E1 on gamma-ray logs and can be distinguished from a sandy Facies D2 by the relatively higher density porosity in Facies C3. Normally, they all have a mix of sand and shale so that they are difficult to distinguish from each other. Geometries and core sections are necessary to distinguish each of the three facies.

## ***Cross-sections and Core Sections***

A legend of symbols used for the core sections is given in figure 26.

### **Element A Geometry**

Element A is a sheet-like shale underlying all the other elements in the study area.

### **Element B Geometry**

Element B comprises two elongate sandstone bodies trending northwest-southeast (figure 10). These bodies are up to 4 m thick, 2 to 4 km wide, and up to 25 km in length. Cross-section 64P-92N (figure 27) cuts across a lobe of Element B just north of Long Point. Here, well 64-W (figure 28) contains a substantial thickness of cross-bedded sandstone of Facies B1 in comparison to the wells adjacent to it, (e.g. well 64-P; figure 29). Immediately overlying Facies B1 in well 64-W (figure 28) is Facies C3. Facies C3 also appears in well 64-P (figure 29) where there is only a thin unit of Facies B1. Facies B1 in well 64-W rests at a lower elevation than the base of the Whirlpool Sandstone in the adjacent wells, and cuts into the underlying Queenston Shale (Facies A). All three Whirlpool Sandstone sections are capped by Facies E1 (figures 28 and 29).










Cross-section 64W-88G (figure 30) lies parallel to and inside the same northwest-southeast trending thick described in the section above, intersecting cross-section 64P-92N (figure 27) at well 64-W. The lower half of the Whirlpool Sandstone contains Facies B1 and Facies B2, as shown in the cores from well 64-W (figure 28). Overlying Element B in each of these cores is Facies C3 (figure 30). The Whirlpool Sandstone is capped by Facies E1.

### **Element C Geometry**












The second set of cross-sections is from the eastern portion of the study area and

## Legend



### Bedding

-  ripple cross-lamination
-  trough cross-bedding
-  planar tabular cross-bedding
-  horizontal lamination
-  low-angle lamination/cross-bedding
-  coarsely interlayered bedding
-  lenticular bedded/laminated
-  symmetrical ripples/wavy bedded
-  hummocky cross-stratification

### Additional Structures/textures

-  curled shale clasts/laminae/beds
-  angular shale clasts
-  rounded shale clasts
-  calclitic
-  shell fragments
-  crinoid ossicles
-  soft sediment deformation
-  glauconitic
-  syneresis/dessication cracks
-  hv min heavy mineral content/laminae
-  curled shale laminae/beds

### Contacts









-  sharp
-  erosional scour

### Stratigraphic Surfaces

- s.b. -- sequence boundary
- t.s. -- transgressive surface
- w.r.s. -- wave ravinement surface
- t.r.s. -- tidal ravinement surface

### Bioturbation

amount

-    -- complete bioturbation
-   -- moderate bioturbation
-  -- weakly bioturbated
- no  but  -- rarely bioturbated/  
ichnogenera -- isolated burrows  
present

### Ichnogenera

- |   |                             |
|---|-----------------------------|
| A   | <i>Anconichnus</i>          |
|    | <i>Arenicolites</i>         |
|    | <i>Astrosoma</i>            |
|    | <i>Bergauria</i>            |
|    | <i>Chondrites</i>           |
|    | <i>Diplocraterion</i>       |
|    | <i>Gyrolithes</i>           |
| H   | <i>Helminthopsis</i>        |
|  | <i>Ophiomorpha</i>          |
|  | <i>Paleophycus</i>          |
|  | <i>Planolites</i>           |
|  | <i>Rhizocorallium</i>       |
|  | <i>Skolithos</i>            |
|  | <i>Teichichnus</i>          |
|  | <i>Teichichnus</i> (nested) |
|  | <i>Thalassinoides</i>       |
|  | <i>Zoophycos</i>            |

Figure 26. List of symbols for the core sections present in this study.

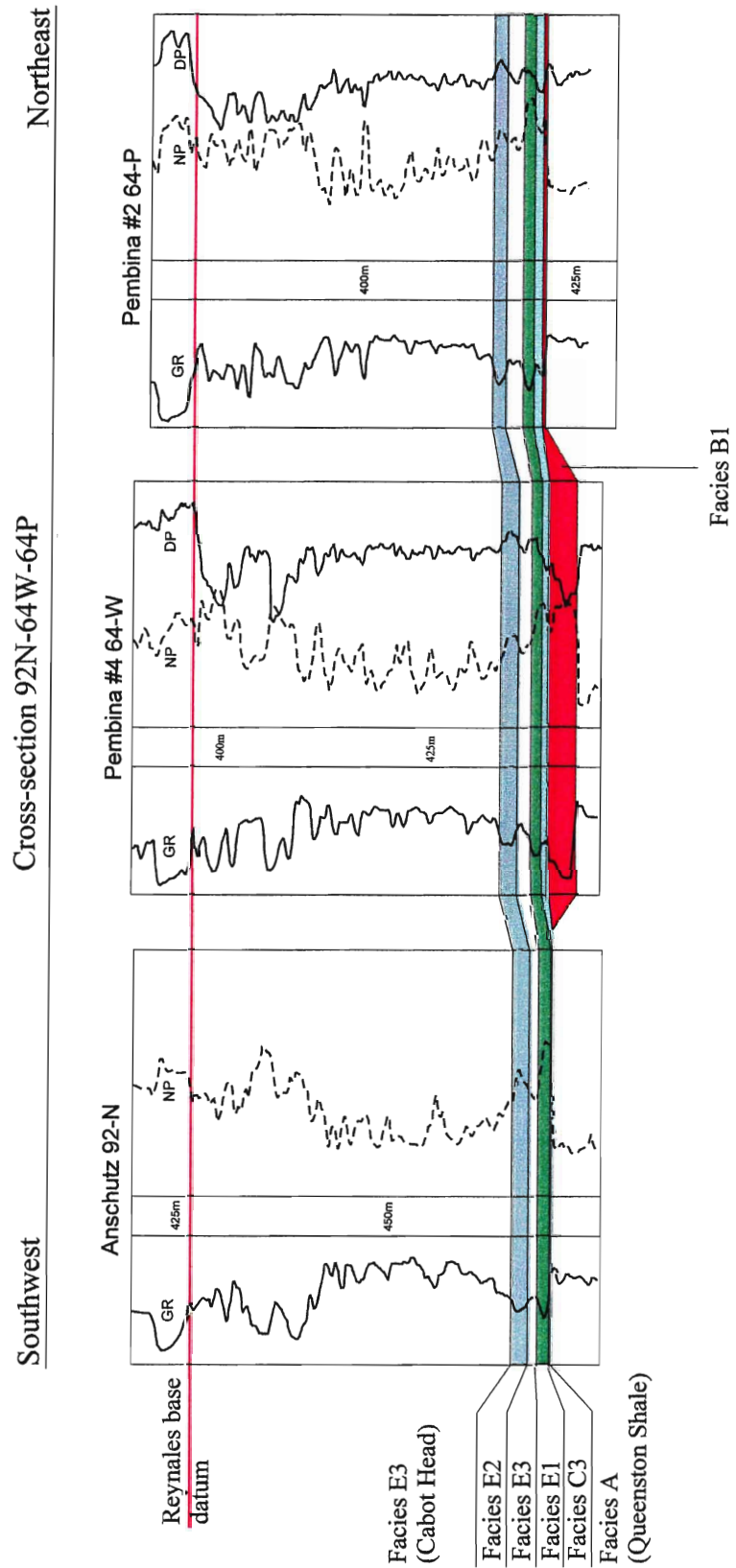


Figure 27. Cross-section dissecting a northwest-southeast trending thick. Facies B1 is concentrated in erosional lows incising the Queenston Formation. Facies B1 is overlain by Facies C3 which in turn is overlain by Facies E1.

Well Name: Pembina Lake Erie 64-W-4  
 Block Number: 64-W-4  
 K.B. elevation: 180.4m a.m.s.l.

Subsea elevation

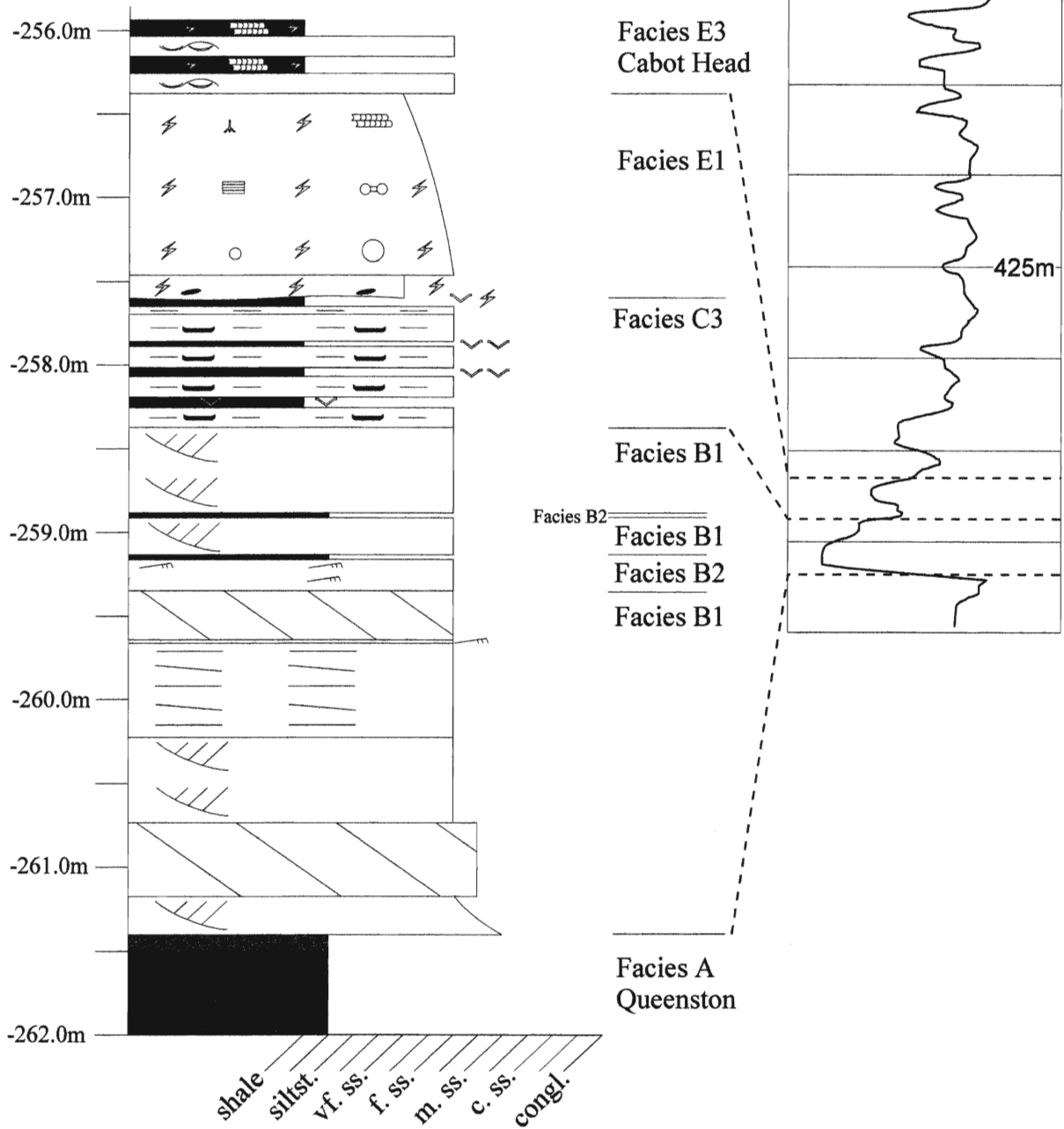


Figure 28. Core of the Whirlpool Sandstone from well 64-W-4. Notice the abundant Facies B1 in the lower portion of the unit. Element B is overlain by Facies C3, which in turn is overlain by Facies E1.



Well Name: Pembina #2 LE 64-P  
 Block Number: 64-P  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation

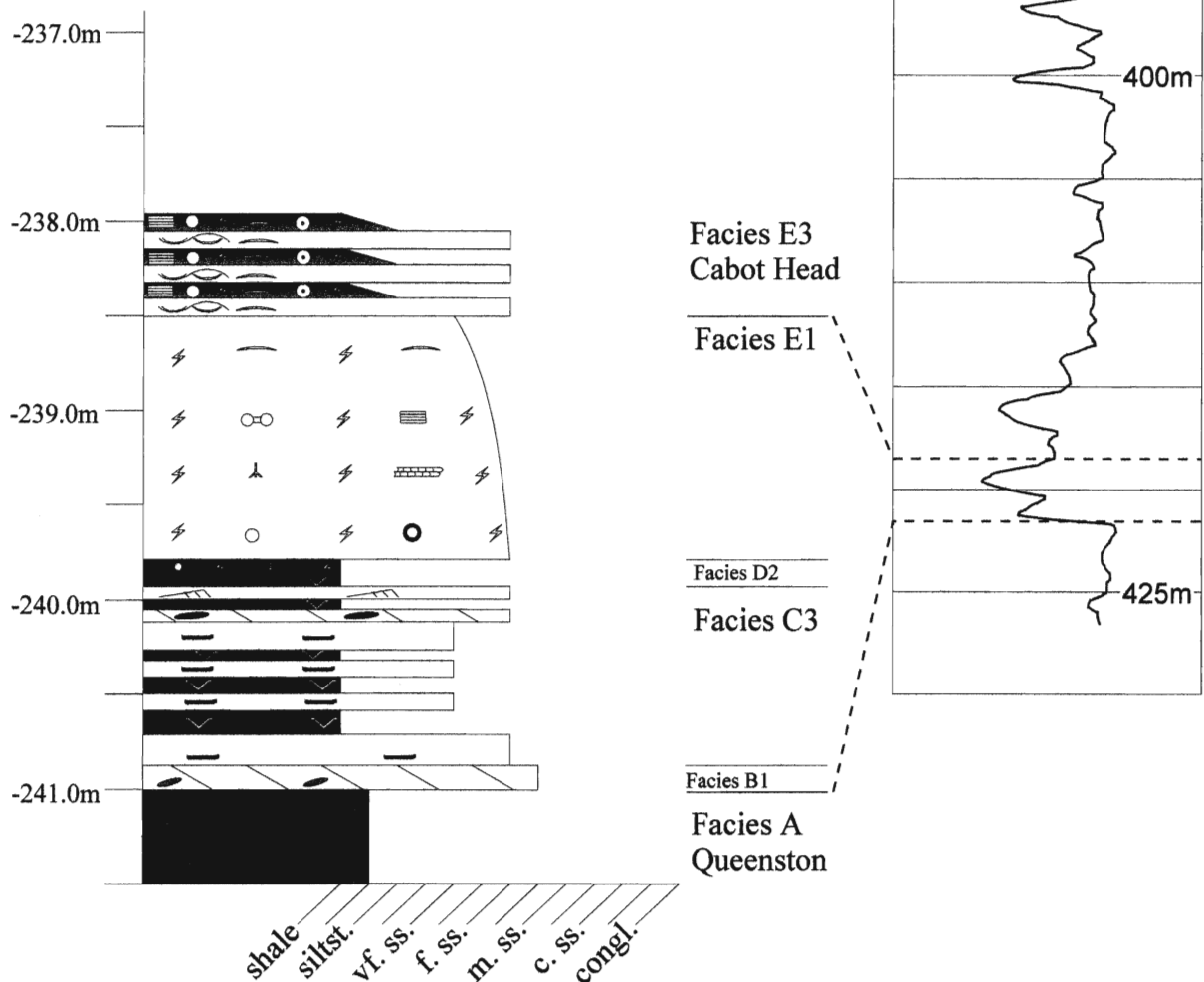


Figure 29. Core of the Whirlpool Sandstone from well 64-P. Notice the very small amount of Facies B1. Notice the general sequence in the Whirlpool of Facies B1 into Facies C3, into a very thin Facies D2, and finally into Facies E1. Also notice the presence of *Zoophycus* in Facies E1.

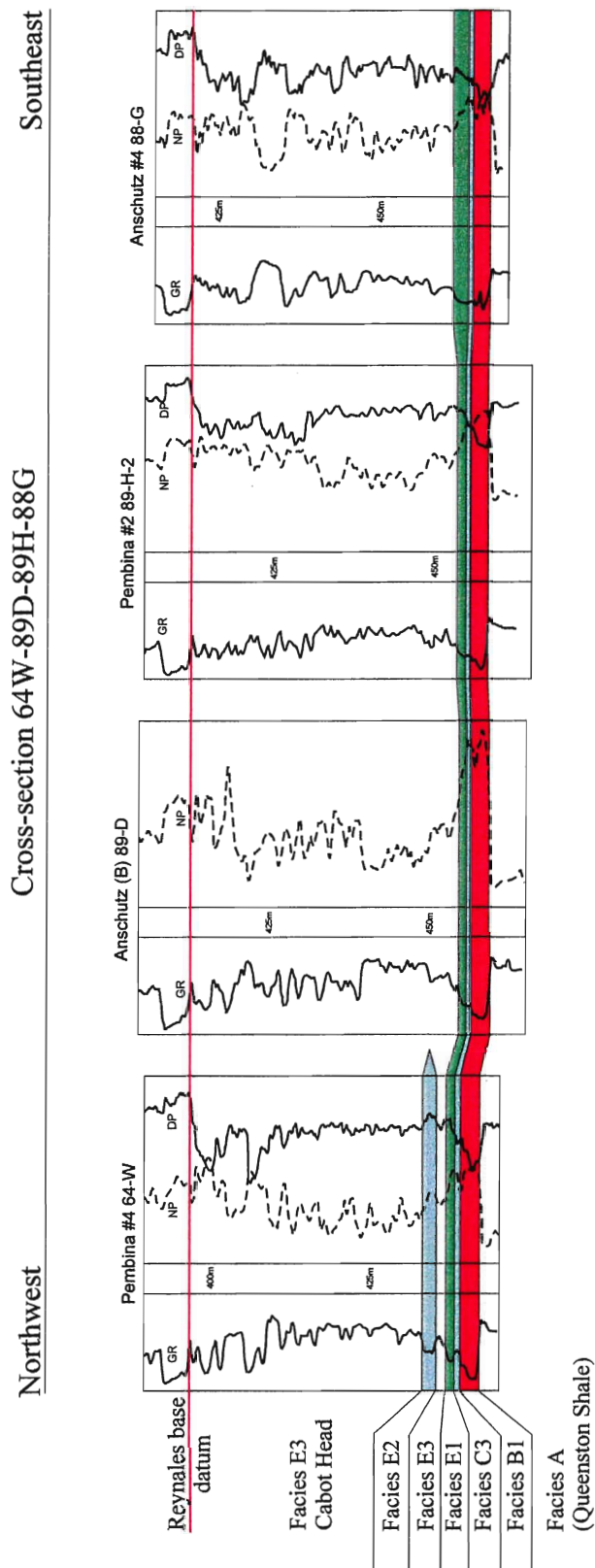


Figure 30. Cross-section illustrating a northwest-southeast trending thick lengthwise. Facies B1 forms the base of the sequence. Facies B1 is overlain by Facies C3, which is subsequently overlain by Facies E1.

illustrates the southwest-northeast trending thicks of Element C on the element map (figure 10). Element C was initially distinguished from Element B by their near orthogonal orientations. However, the facies descriptions of Elements B and C provide other distinguishing characteristics. Element C contains rare bioturbation whereas Element B has none. The palynology of shales suggests that Element C has at least a partial marine contribution, with the presence of acritarchs and scolecodonts, whereas Element B contains no evidence of marine influence, lacking marine palynomorphs (appendix 1, Parkins 1997).

Cross-section 5X-26S (figure 31) lies perpendicular to one of the thicker sections of Element C and largely displays Facies C1, C2, and C3. Core from well 27-G (figure 32) displays sandy, Facies C1 and C2 that sits structurally lower than in surrounding wells. Core from well 26-S (figure 33) in the thinner portions of the same area displays abundant Facies C3. Wells 5-X and 26-S appear to sit structurally higher than wells 27-G and 26-M (figure 31). Facies C1 appears to incise Facies A.

Cross-section 24U-27G (figure 34) lies parallel to and centred in one of these thicker southwest-northeast trending units on the element map (figure 10). Each of the well logs displays a Whirlpool Formation that is thick and composed of clean sand. The base of the Whirlpool Formation appears to slope to the west. Core from well 27-G (figure 32) is largely composed of the cross-bedded sandstone of Facies C1 and C2. Facies C1 forms the base of the southwest-northeast trending thicks, changing into Facies C2 upwards in the section (figure 34). Facies C1 and C2 dominated areas are up to 6 m thick, up to 4 km wide, and 30 km long.

## **Element D Geometry**

Identification of Element D was originally based upon lobe-like portions of the Whirlpool Sandstone in subsurface Lake Erie (figure 10). Cross-section 69F-37M (figure 35) lies

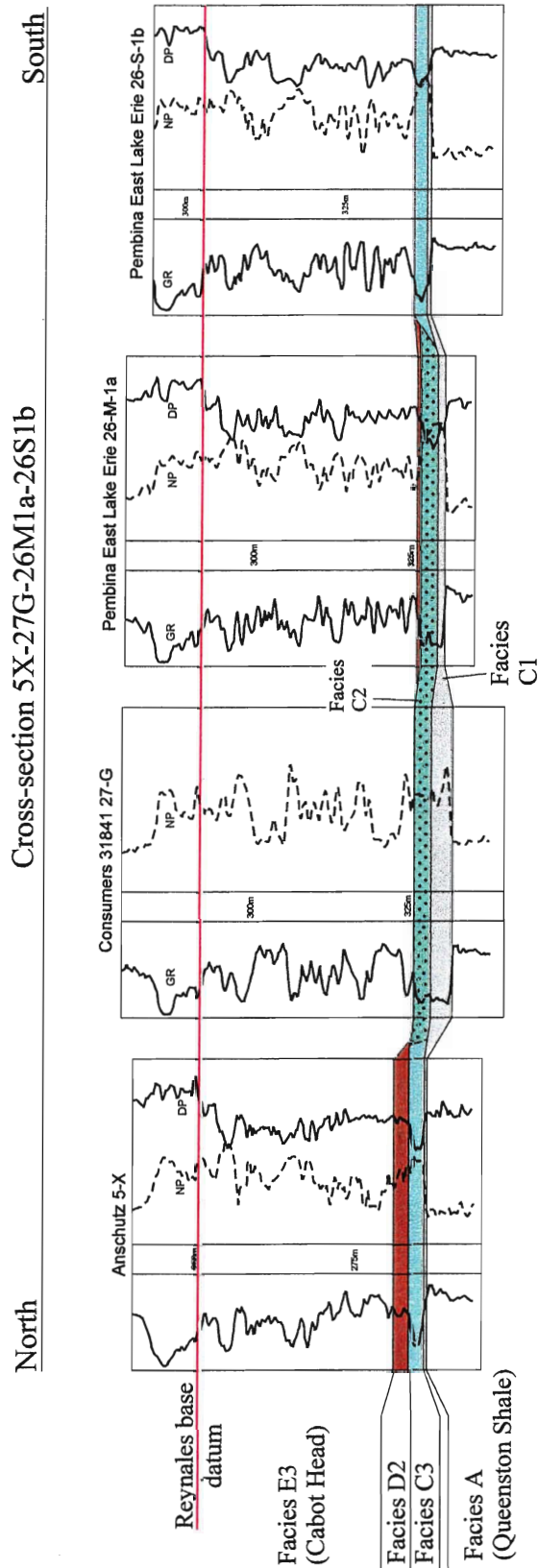


Figure 31. Cross-section perpendicular to the main trend of Element C. Facies C1 and Facies C2 are concentrated in structural lows, interpreted to represent incision. In the vertical section, Facies C2 caps Facies C1. Facies C3 lies on structurally elevated areas.

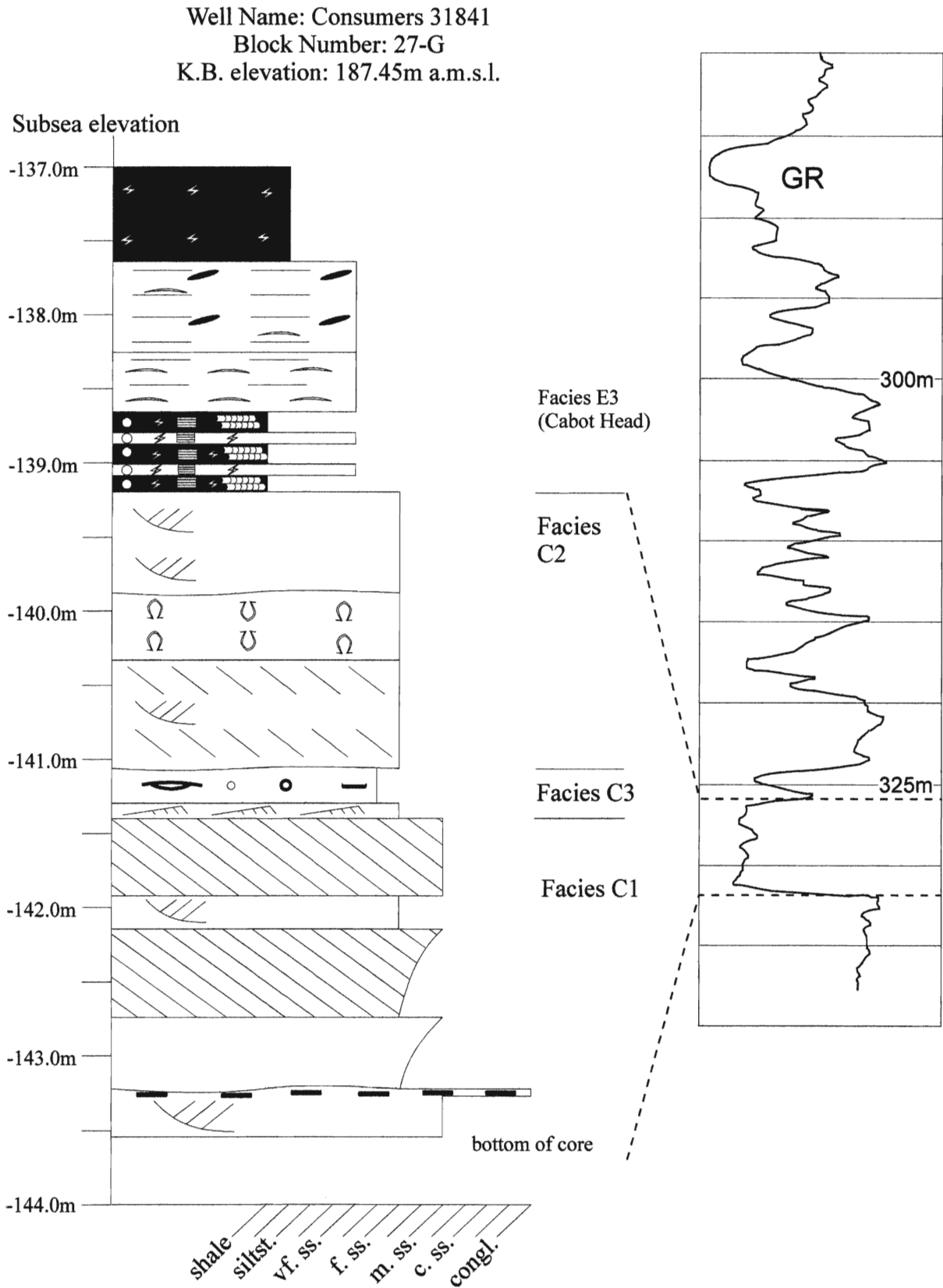


Figure 32. Core section of Whirlpool Sandstone for well 27-G. Notice the abundant cross-bedding. Notice the vertical sequence of Facies C1 being succeeded by Facies C2.

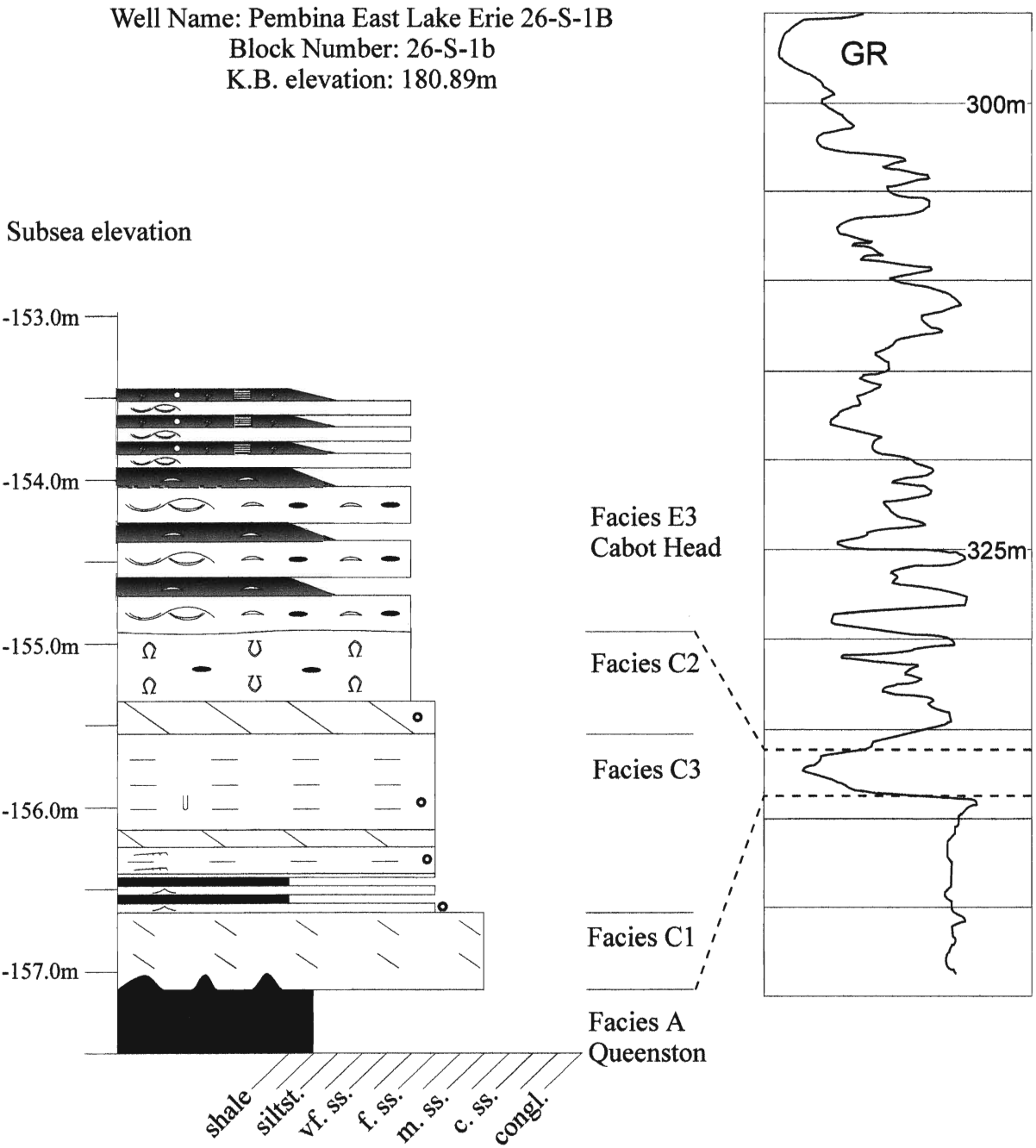


Figure 33. Core of the Whirlpool Sandstone from well 26-S-1b. The section contains abundant Facies C3.

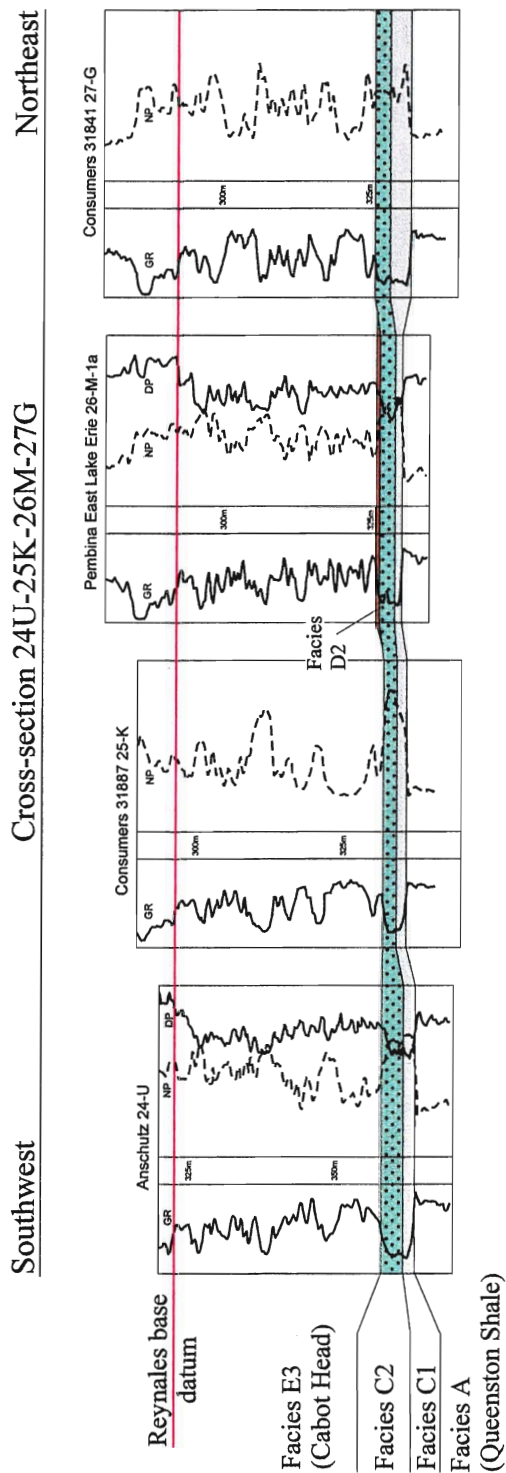


Figure 34. Cross-section displaying contents of a northeast-southwest trending thick. Facies C1 forms the base of the sequence and Facies C2 completes the vertical succession.

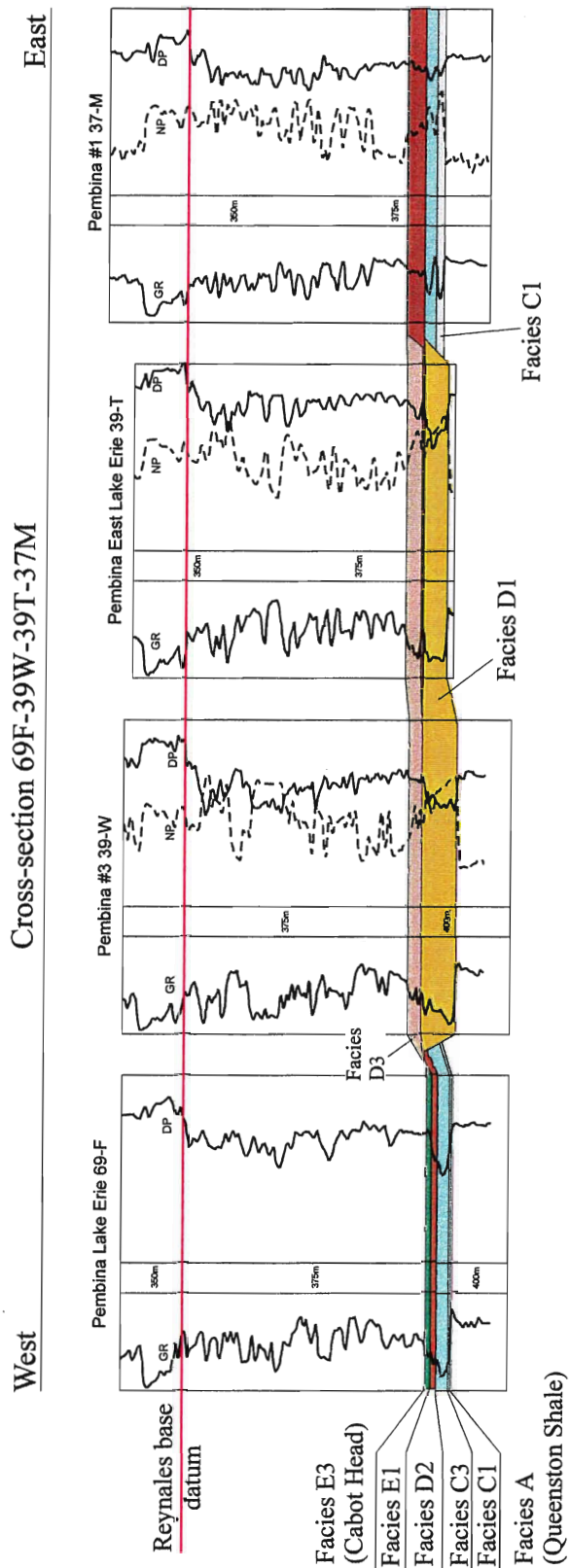


Figure 35. Cross-section displaying a topographic high on top of the Whirlpool Sandstone. The topographic high appears between Facies E1 to the west and Element D to the east. Facies E1 caps the section from well 69-F. East of well 69-F there appears to be no Facies E1. The topographic high appears to be composed of Facies D3. The area immediately behind the topographic high, in well 37-M, is composed of Facies D2.



parallel to a southwest-northeast lobate thick on the isopach map (figure 9). Core from well 69-F is capped by Facies E1 (figure 36). Facies E1 in well 69-F sits structurally lower than the top of the Whirlpool Sandstone in the wells towards the east (figure 35). The top of the Whirlpool Sandstone forms a topographic high at well 39-T (figure 35), composed of positive relief from a thick Facies D3 (figure 37). The topographic high appears to exert considerable sedimentological control on Facies E1 as Facies E1 is absent east of this feature.

Cross-section 72G-22L (figure 38) lies perpendicular to cross-section 69F-37M (figure 35) and intersects it at well 39-T. Figure 38 is meant to display the topographic high along its north-south trend. The topographic high consists of Facies D3 capping the Whirlpool Sandstone (e.g. core from well 39-T; figure 37). This high is approximately 30 km long, 4 km wide, and up to 2 m thick.

A cross-section that spans the entire study area (figure 39) displays the entire Whirlpool Sandstone from beyond its western pinchout to the easternmost portion of the isopach map (figure 9). Of note is that Facies D1 incises Facies C1, C2, and C3. Facies D1 is seen in core from wells 68-Q, 39-Y, and 39-W (figures 40, 41, and 42 respectively). These lobate shaped units of Facies D1 form distinctly isolated scours located west of and at the topographic high described above.

Cross-section 39Y-72G (figure 43) displays, in detail, the incision of Element D into Element C. In core from well 39-Y (figure 41), Facies D1 incises Facies C3. In the neighbouring wells 39-W and 39-X, incision by Facies D1 is much deeper and appears to completely remove Element C (figure 43). Here, Facies D1 is normally capped by Facies D3. The Facies D1 lobes are approximately 2km wide, from 4 to 10 km long, and up to 6m thick.

Well Name: Pembina Lake Erie 69-F-2  
 Block Number: 69-F-2  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation

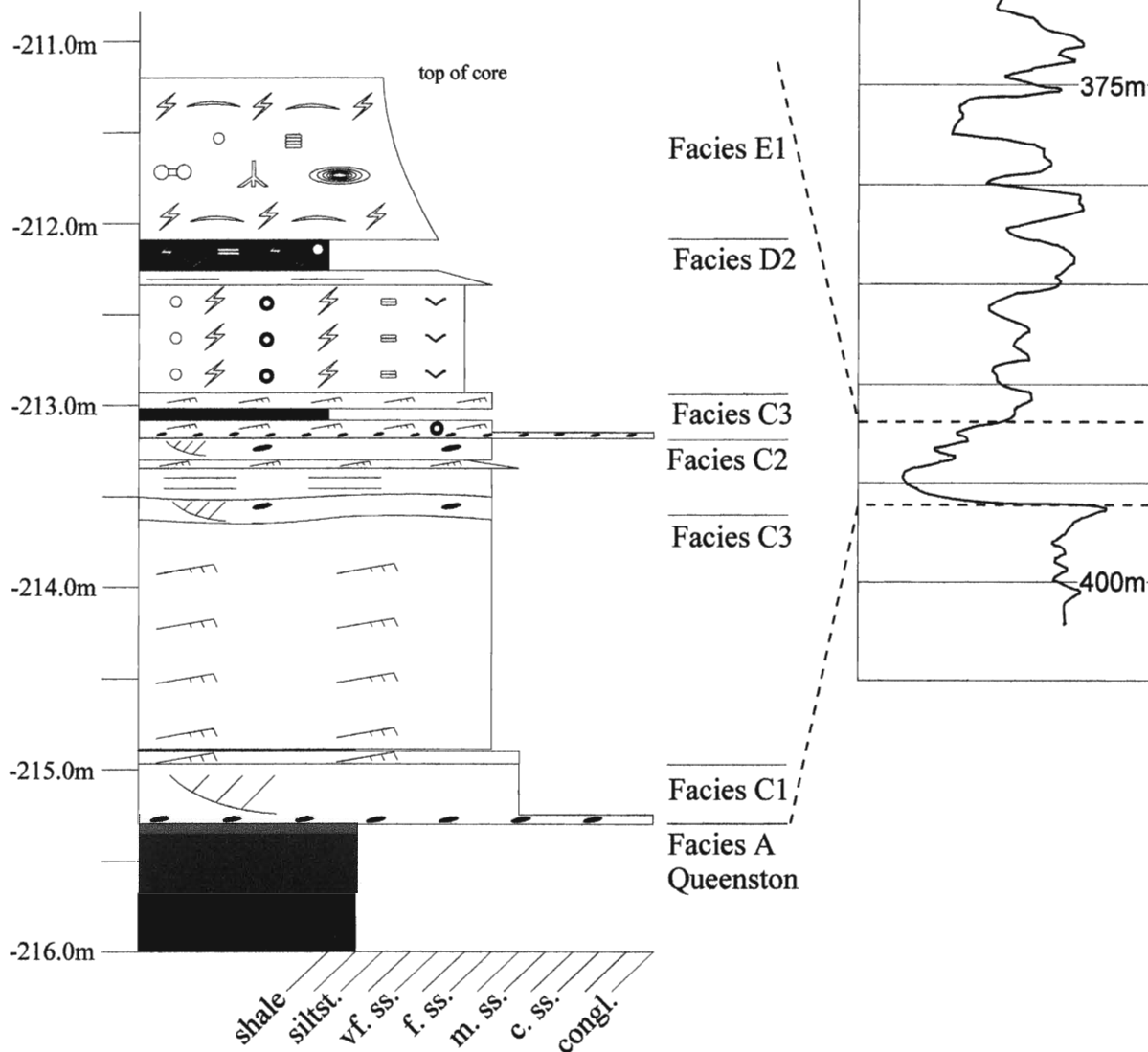


Figure 36. Core of the Whirlpool Sandstone from well 69-F-2. Notice how Facies E1 caps the Whirlpool Sandstone, how Facies E1 overlies Facies D2, and that *Zoophycus* is not present in Facies E1.

Well Name: Pembina East Lake Erie 39-T-2  
 Block Number: 39-T-2  
 K.B. elevation: 180.9m a.m.s.l.

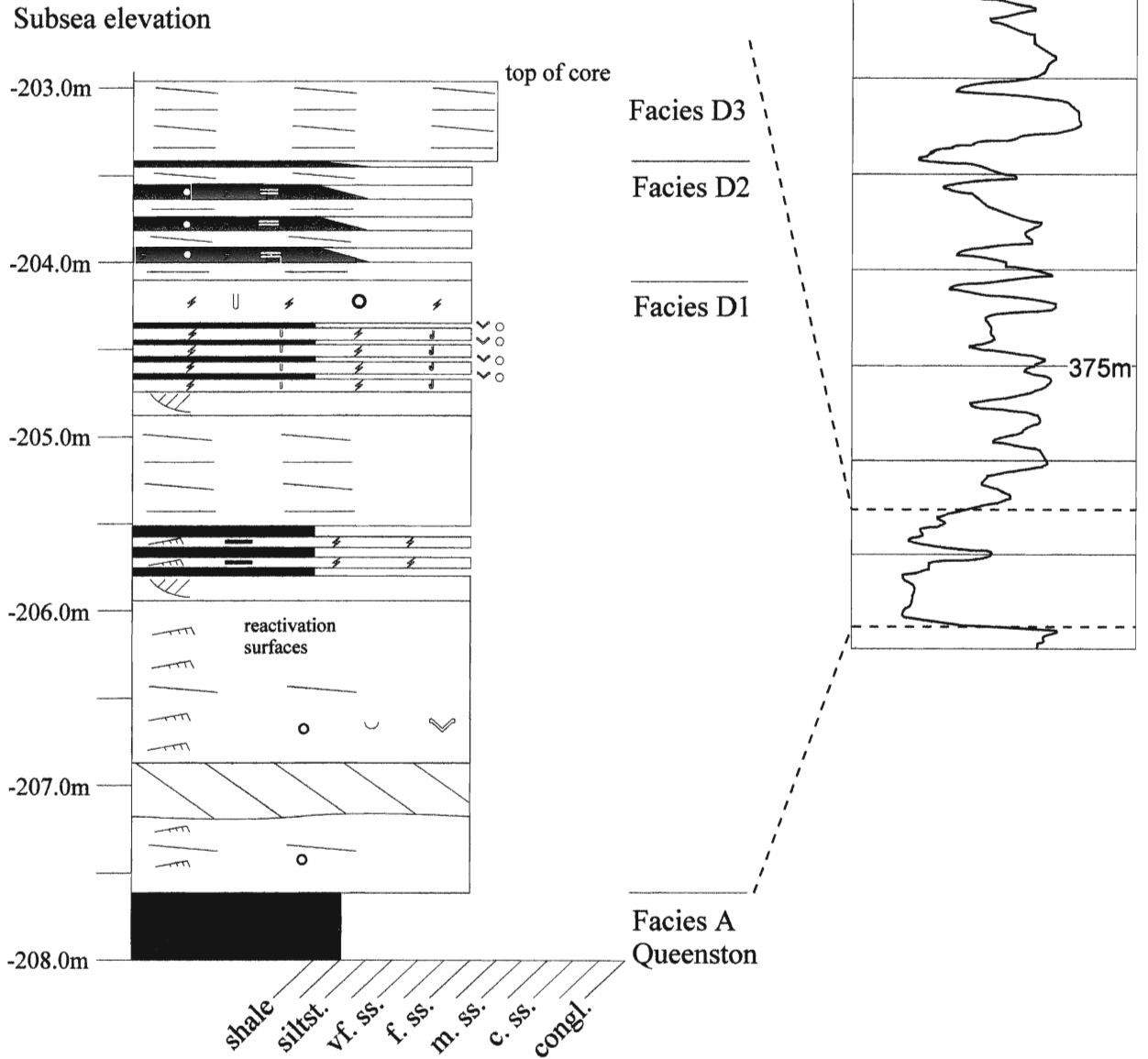
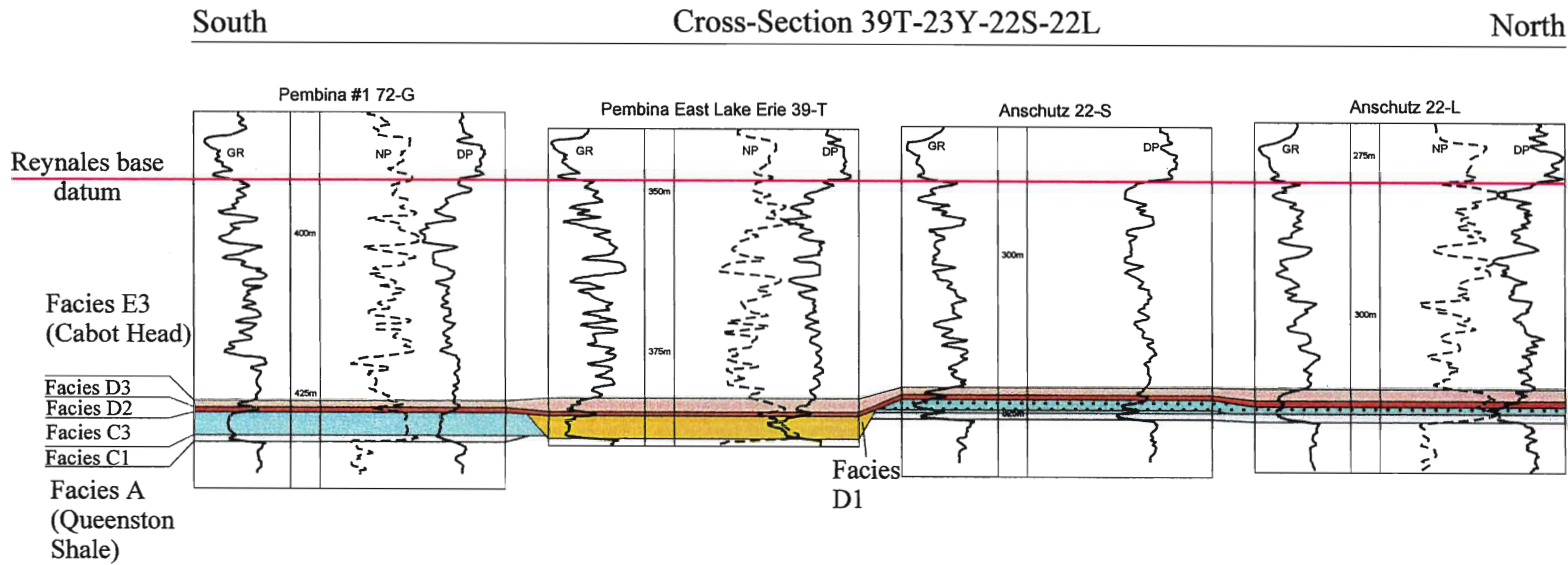


Figure 37. Core of the Whirlpool Sandstone from well 39-T-2. Notice that Facies D3 caps the Whirlpool Sandstone. Also notice that Facies D3 overlies Facies D2.

Figure 38. Cross-section displaying the topographic high lengthwise. The topographic barrier is capped by Facies D3. Facies D3 overlies Facies D2.



West

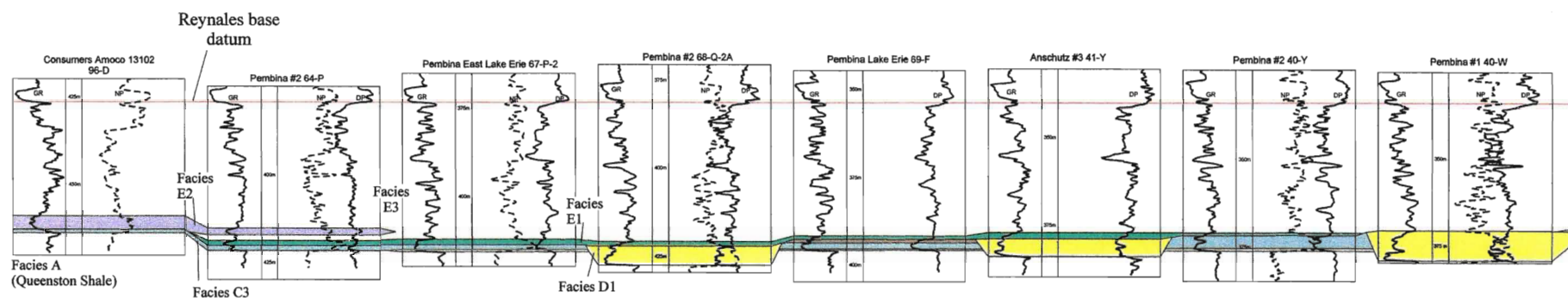
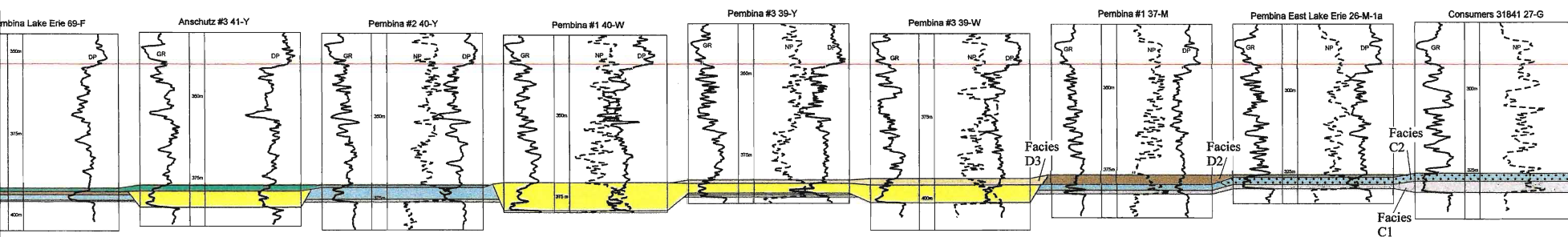


Figure 50. Study area wide cross-section. Notice how Facies D1 (yellow fill) replaces Element C material in discrete units from west to east; how Facies E1 (green fill) drapes Elements C and D west of well 40-W; how Facies C2 or C3 (speckled blue fill and flue fill respectively) extends across the study area except where replaced by Facies D1; the topographic rise in the westernmost wells and the subsequent appearance of Facies E2 (purple fill; Manitoulin Formation); how Facies E2 appears to prograde over Facies E3 and Facies E1 in well 64-P at the western end of the cross-section.

East



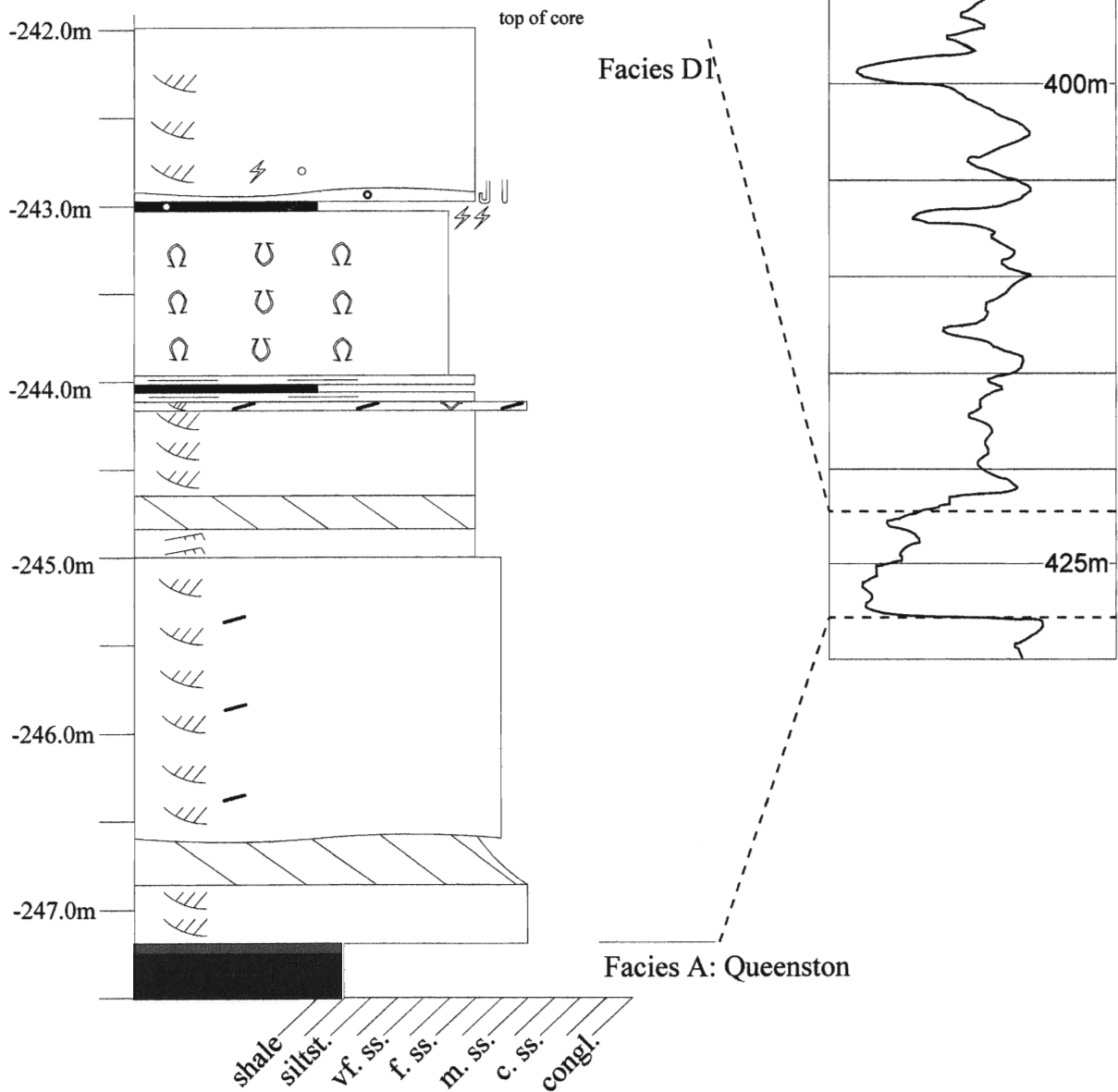


Figure 40. Core of the Whirlpool Sandstone from well 68-Q-2a. Notice the abundant cross-bedding. Also notice how Facies D1 fines upwards in the section.

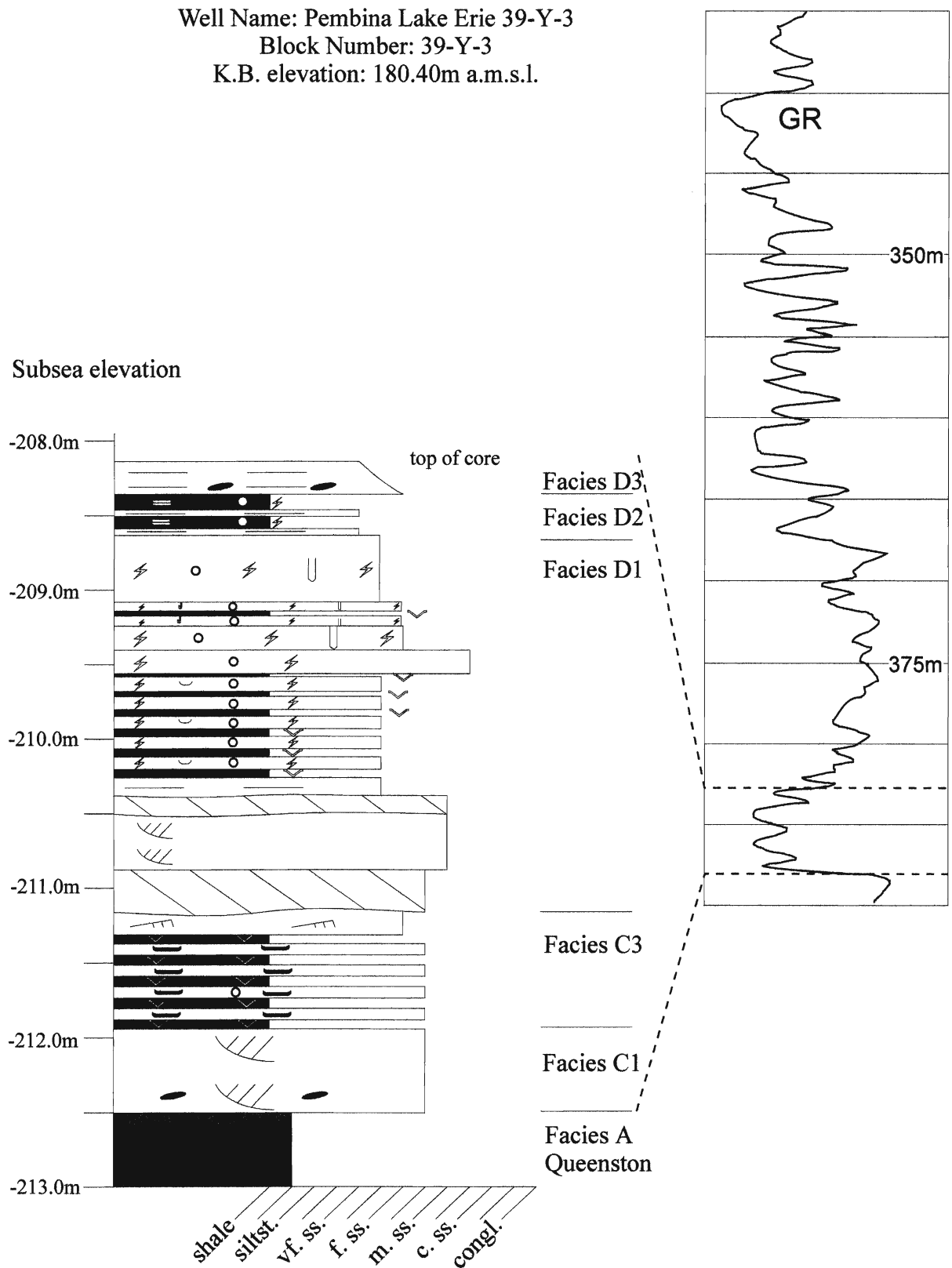


Figure 41. Core of the Whirlpool Sandstone from well 39-Y-3. Notice that Facies D1 appears to incise Facies C3. Also notice that in Facies D1 the vertical succession goes from cross-bedding into bioturbation, Facies D1 being capped by a thin Facies D2, then Facies D3.



Well Name: Pembina #3 LE 39-W  
 Block Number: 39-W  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation

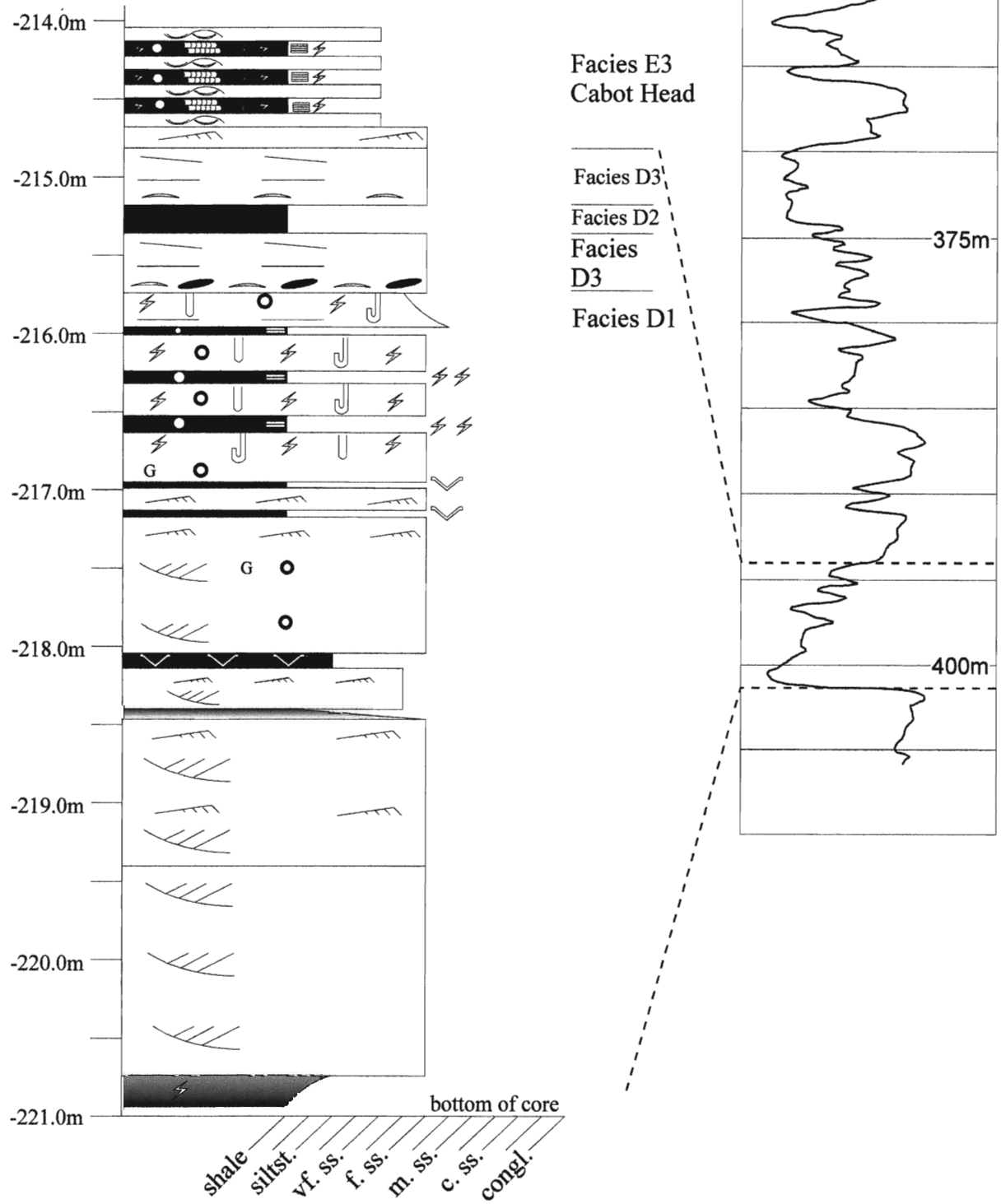


Figure 42. Core of the Whirlpool Sandstone from well 39-W. Notice the gradual vertical change of Facies D1 from cross-bedding into bioturbation, into Facies D3



## **Element E Geometry**

Element E was originally defined by its sheetlike nature in the study area. The study area cross-section (figure 39) suggests that Facies E1 is a sheet sandstone up to 2m thick that caps the Whirlpool Sandstone west of well 40-W. Figure 39 also suggests that Facies E1 passes laterally into Facies E2 towards the west. The carbonates of Facies E2 appear to have been deposited on a structural high that only appears in the westernmost portions of the study area. This structural high is probably the Algonquin Arch, which is normally indicated in outcrop by the presence of the carbonates of the Manitoulin Formation (Liberty and Bolton 1956).

The two westernmost wells of figure 39 display the western pinchout of the Whirlpool Sandstone. Facies C3 stretches far west of Facies E1, beyond where the bulk of Whirlpool Sandstone has pinched out. Another feature is that Facies E1 and Facies E2 both overlie Facies C3. A final feature is that the base of the Cataract Group rises towards the west where the bulk of the Whirlpool Sandstone has pinched out.

## **Geometry Summary**

The cross-sections show four main features in the Whirlpool Sandstone. The first is that the southeast-northwest trending thicks are composed largely of Facies B1 and B2, they sit structurally lower than surrounding material, and incise the Queenston Shale (Facies A).

The second feature is that northeast-southwest trending thicks are composed largely of Facies C1 and C2 and are generally restricted to the easternmost portion of the study area. Facies C1 and C2 sit structurally lower than the deposits in the surrounding wells and appear to incise the Queenston Shale (Facies A). The northeast-southwest trending thicks appear to contain a vertical sequence where Facies C1 is overlain by Facies C2. The northeast-southwest trending thicks are bordered by cores containing largely Facies C3.

The third feature is an apparent north-south trending topographic high between Facies E1 to the west and the northeast-southwest trending thick to the east. This topographic high consists of positive relief from a thick Facies D3 that caps the Whirlpool Sandstone. The topographic high controlled deposition of Facies E1, limiting its deposition to west of the feature. The northeast-southwest trending lobate bodies of Element D are composed of Facies D1 and appear to incise Facies C1, C2, and C3 and some portions of the Queenston Shale (Facies A). These lobate bodies are only found at or west of the topographic high described above.

The fourth is that Facies E1 overlies Facies C3 or Facies D2. Facies C3 appears as a thin sheet that extends far west, even underlying Facies E2 (Manitoulin Formation) where the major portions of the Whirlpool Sandstone have pinched out.

Also of importance is that further west, where the majority of the Whirlpool appears to pinch out, the base of the Cataract Group appears to rise structurally. This rise appears associated with the appearance of Facies E2 (Manitoulin Formation) and the pinchout of the Whirlpool Sandstone and probably represents the Algonquin Arch.

The facies descriptions and their geometries are summarized in Table 2.

**Table 2: Summary of facies descriptions and geometries.**

<b>Facies</b>	<b>Brief Description</b>	<b>Brief Geometry</b>
A	red, silty, massive shale; top normally weathered green; ichnology: no traces; Queenston Formation.	base of entire sequence; sheetlike throughout the study area.
B1	largely fine grained, cross-bedded sandstone; shale clast conglomerate; horizontally laminated sandstone; ichnology: no traces.	southeast-northwest trending thicks.
B2	shale and ripple cross-laminated sandstone; palynology: terrestrial; ichnology: no traces.	southeast-northwest trending thicks.
C1	largely medium grained, cross-bedded sandstone; shale clast conglomerate; massive or horizontally laminated sandstone; normally well cemented with very low porosity; ichnology: no traces.	concentrated in southwest-northeast trending thicks -- sits in structural lows; forms base of Element C.
C2	largely fine grained, cross-bedded sandstone; horizontally laminated sandstone; convolute bedded sandstone; tidal bundles; ichnology: rare, small <i>Paleophycus</i>	southwest-northeast trending thick -- sits in structural lows; caps "thick" sequence.
C3	coarsely interlayered bedding in sandstone or sandstone and shale; lenticular, wavy, and flaser bedded sandstones and/or shales; ripple cross-laminated sandstones; dessication cracks; palynology: nearshore, possibly brackish, possibly estuarine; ichnology: rare and small <i>Paleophycus</i> and <i>Planolites</i>	between southwest-northeast trending thicks east of Facies D3 barrier: sits on structural high; west of Facies D3 barrier: forms thin sheet over Elements A and B and Facies C1.
D1	fine to medium grained, high porosity, cross-bedded sandstone locally with graded foresets; horizontally laminated sandstone; convolute bedded sandstone; overall fining upwards sequence; cross-bedding commonly grades into bioturbated sandstone and shale; ichnology: rarely to strongly bioturbated sandstone and shale with small ichnofossil forms.	lobate bodies trending southwest-northeast; dissect Facies D3 barrier and found west of Facies D3 barrier; incise Facies A, C1, C2, and C3; capped by Facies D3 in full sequence.
D2	interbedded sandstone and shale with syneresis cracks; bioturbated sandstone; cross-bedded sandstone and silty sandstone (fossiliferous); ichnology: rarely to strongly bioturbated with small simple forms, some monospecific suites; horizontally laminated to planar tabular cross-bedded, convolute sandstone (fossiliferous).	mud at end of southwest-northeast trending thicks or sandstone laterally beyond the southwest-northeast trending thicks; forms very thin sheet above Facies C3 west of Facies D3 barrier.
D3	fine to medium grained, horizontal to low angle cross-laminated high density sandstone; ichnology: none except at top of unit.	roughly north-south trending, topographically elevated "barrier" between southwest-northeast trending thicks and Facies E1.
E1	fine grained, cross-bedded sandstone with shell fragment content, ichnology: rare, well formed <i>Paleophycus</i> ; Completely bioturbated fine to very fine grained sandstone locally with shell fragments, original sandstone bedding appears to be HCS; ichnology: high diversity, high density suites, robust forms.	sheet-like, only found west of Facies D3 barrier; erosively overlies Facies C3 and D2.

E2	limestone and interbedded limestone and shale; abundant fossil fragments; Manitoulin Formation.	forms on and on the side of a topographic high to the west of study area.
E3	massive black shale; bioturbated black shale, ichnology -- deep marine trace fossils <i>Zoophycos</i> , <i>Chondrites</i> ; interbedded sandstone and shale w/ HCS, ichnology -- high diversity, high density suites in shales, escape traces; Cabot Head Formation.	sheet like body capping the sequence throughout the study area.

Table 2 continued.

## **DISCUSSION**

### ***Environments of Deposition***

#### **Element A -- Queenston Shale**

##### **Facies A**

A detailed determination of the environment of deposition for the Queenston Shale is beyond the scope of this study, however, a short one is presented. Due to the lack of sedimentary structures in the Queenston Shale in subsurface, determination of the environment is difficult. Also due to the lack of trace fossils, it can be assumed that the environment was inhospitable to organisms. It underwent a period of erosion after deposition, as suggested by its eroded top.

##### **Interpretation of Element A**

From outcrop studies, Brogly (1984) concluded that the Queenston Shale represented prograding mudflats. Cracks in the top of the Queenston Shale below the Whirlpool Sandstone have been reported to be dessication cracks (Rutka 1986, as only one of many authors). In subsurface, these dessication cracks on top of the Queenston Shale are infilled with white sandstone and can be quite extensive (up to 92 cm vertical length). The green Queenston top exists even under deeply scoured sections of the Whirlpool Sandstone suggesting that it formed from diagenetic alteration by fluids migrating along the terminal Ordovician unconformity rather than subaerial exposure.

#### **Element B**

##### **Facies B1**

Facies B1 is consistently structurally lower than the surrounding facies and elements (figure 27), consisting of clean, largely trough cross-bedded and planar tabular cross-bedded

and horizontally laminated sandstones (e.g., figure 28). The lack of bioturbation in the sands suggests this took place in a harsh environment. Its association with the terrestrial shales of Facies B2 (appendix 1, Parkins 1997) suggests a terrestrial origin. Facies B1 is interpreted as deposits of a fluvial channel.

## **Facies B2**

This facies appears to be associated with the channels of Facies B1. The ripple cross-lamination and shales of this facies suggest a lower energy environment. There are no fossils or bioturbation present in the shales and no dessication cracks. The absence of known marine palynomorphs in the shales suggests that they were deposited in a terrestrial environment (appendix 1, Parkins 1997).

## **Interpretation of Element B**

Element B is interpreted as the deposits of fluvial channels. The lack of shale suggests that the fluvial system that formed the channelized deposits was probably not meandering or anastomosing (Walker and Cant 1984). This is also supported by the absence of caliche and dessication cracks in Facies B1 and B2. Element B is dominated by cross-bedded and horizontally laminated sands that have been interpreted in outcrop as sandy braided fluvial deposits (Rutka 1986) which may be comparable to those of the modern south Saskatchewan River (Cant 1978). The fluvial system is shown in red on the interpretative map (figure 44).

The trough cross-stratified sandstone probably formed near the base or along the sides of a channel. It may also have formed as part of channel aggradation to form a sandflat (Cant 1978). Planar tabular cross-bedded sandstone probably formed along the sides of a channel or as part of channel aggradation and accretion to form a sandflat (Cant 1978). The



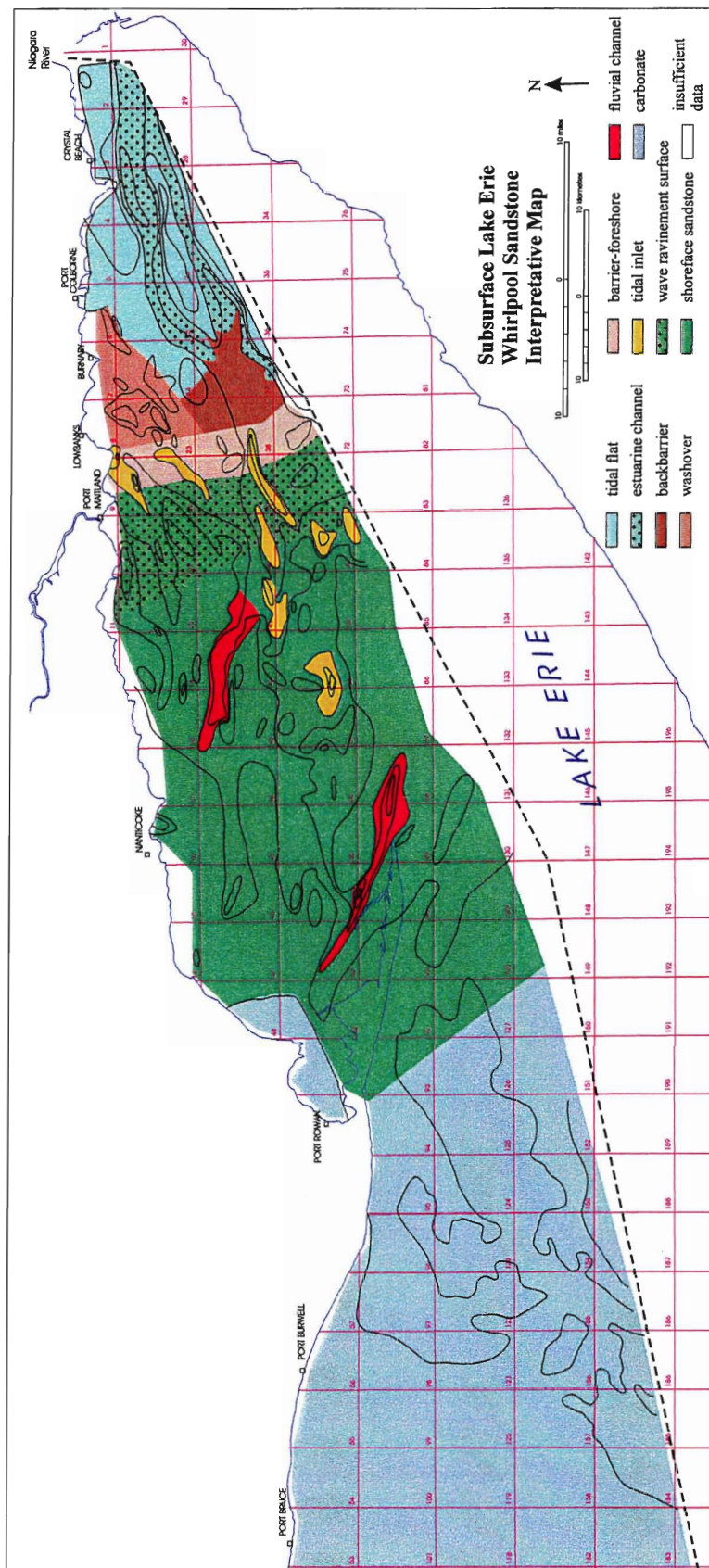


Figure 44. Interpretative map. Areas of facies concentrations. Based on the isopach map (figure 9) and the study area wide cross-section (figure 39).

horizontally laminated sandstone probably formed at the base of a channel, or possibly on top of a sandflat in fast moving shallow water. There is evidence for many scour surfaces and some shale clast conglomerates that should be expected in stacked fluvial channel sequences (Cant 1978). Shales and ripple cross-laminated sandstones probably formed during final stages of channel abandonment and as overbank deposits. They may also have formed as part of sand flat accretion (Cant 1978).

Rutka (1986) suggested that the lower portion of the Whirlpool Sandstone in outcrop consisted of braided fluvial deposits. This is consistent with the presence of braided fluvial shallow valleys in subsurface Lake Erie. Furthermore, these fluvial deposits in outcrop contain paleocurrent indicators of paleoflow towards the northwest (Rutka 1986). This paleocurrent direction is very similar to the orientation of the fluvial valleys in subsurface, therefore, flows in the fluvial channels in subsurface were probably in a northwesterly direction.

The fluvial deposits in subsurface are contained in shallow valleys, unlike those in outcrop, which are more sheetlike as widely exposed in the Niagara Gorge (Rutka 1986). The shallow valleys appear to be 2 km to 4 km in width (figure 44). In subsurface Lake Erie, relief on top of the Queenston Shale can exceed four metres in an area 2 km wide where incised by the fluvial Whirlpool Sandstone (figure 27). The greater amount of incision in subsurface may be due to a higher surface slope in subsurface Lake Erie than the surface slope in outcrop during deposition of the fluvial Whirlpool. Rutka (1986) suggested that a decrease in braided fluvial stream competence towards the northwest in outcrop was due to a decrease in slope in that direction. Middleton *et al.* (1987) roughly estimated a slope of 0.5 m/km slope for deposition of the braided fluvial deposits in outcrop.

Rutka (1986) suggested a source area to the southeast for the fluvial Whirlpool based on paleocurrent measurements. The relative proximity of the subsurface fluvial channels to the source area as compared to outcrop may explain the higher surface slope in subsurface. This suggests that shallow valleys in subsurface may contain feeder channels that fed the large sandy braided fluvial plain of the Whirlpool Sandstone in outcrop. However, the valleys in subsurface Lake Erie do not lead to any sandy braided fluvial sheet sandstone. Cheel and Middleton (1993) reported the presence of a widespread erosional surface on top of the fluvial Whirlpool in outcrop. Perhaps enough material was eroded in the area of subsurface Lake Erie to remove evidence of the sheet sandstone, and only the shallow fluvial valleys were preserved because of their structurally lower position.

There is no basis for accurate dating of the fluvial facies of the Whirlpool Sandstone. Palynology cannot be used because the palynomorphs present in the formation are not of a well-established age (appendix 1, Parkins 1997). There are erosional surfaces beneath and above the fluvial Whirlpool, contributing to the difficulty of determining the age. The fluvial Whirlpool has no known laterally equivalent formations. The initial Silurian transgression occurred in the earliest Silurian (Copper 1982). The age of the fluvial channels could range from latest Ordovician to earliest Silurian, and its deposition could very well have spanned the Ordovician-Silurian boundary.

Copper and Fay (1989) reported that uppermost Ordovician sediments of Gamachian or Hirnantian Age are missing from the Queenston Shale equivalent Kagawong Formation in the Michigan Basin, having been removed by erosion. It is most likely that deposition of the fluvial Whirlpool occurred sometime during and/or after this period.

## **Element C**

### **Facies C1**

This facies appears to be thickest where associated with structural lows trending northeast-southwest on top of the Queenston Shale. The presence of abundant cross-bedded, mostly medium grained sands suggests a relatively high energy environment. There is no shale in this facies. The geometry of the deposits of Facies C1 suggests that it was deposited in a channelized environment. The absolute lack of bioturbation further suggests a terrestrial environment or a very stressed environment.

### **Facies C2**

This facies also appears to be normally limited to structural lows that trend northeast-southwest. The presence of abundant cross-bedded sands suggests a relatively higher energy environment. There is very little shale in this facies. There are rare, simple forms of trace fossils present. It is interpreted that this facies was deposited in a channelized environment that was biotically stressed.

### **Facies C3**

This facies appears structurally elevated in areas adjacent to the main channels of Facies C1 and C2. There are tidal features present such as wavy and flaser bedding. Bioturbation is rare with only simple forms. There is more shale than in Facies C1 and C2, as well as many desiccation structures, and less commonly syneresis cracks. Palynological analysis of the facies suggests that it was deposited in a nearshore, possibly brackish, estuarine setting (appendix 1, Parkins 1997). Facies C3 appears to have been deposited in an interchannel setting, suggested by its close association with the channelized Facies C2.

## Interpretation of Element C

Element C is interpreted as an estuarine complex. The estuarine channels are composed of Facies C1 and C2 and form thick, approximately east-northeast to west-southwest trending sands (figure 34), that fill linear troughs incised into underlying facies (figure 31). Facies belonging to Element C are interpreted as estuarine channel deposits that differ distinctly from the fluvial channels of Element B. The estuarine channels trend almost orthogonal to the fluvial channels. Facies C1 and Facies C2 are associated with sun cracked and partial marine to nearshore marine deposits of Facies C3 where Facies B1 is associated with Facies B2 shales that are strictly terrestrial. Where Facies C3 is associated with Element B it overlies the fluvial deposits, whereas in the estuarine complex, Facies C3 is interbedded with Facies C1 and C2. The erosional base of the estuarine unit appears to bevel the paleosurface associated with the northwest-southeast trending fluvial shallow valleys of Element B (figure 45).

Facies C1 typically forms the lowermost unit of Element C and includes the coarsest grained sandstones. The large scale cross-stratification and geometry of Facies C1 suggests that it was deposited in channels. The absence of bioturbation and its position on the underlying, incised surface may indicate that Facies C1 represents the fluvial phase of estuary development with the rivers occupying northeast-southwest trending shallow valleys that appear to be up to 4 km wide. The underlying erosional surface dips towards the west (figure 34), beveling the regional southwest dip of fluvial shallow valleys of Element B (figure 45). This dip indicates that the valleys dipped towards the west-southwest and that the rivers flowed in a west-southwestward direction. Facies C2 includes thick-thin alternating sand and shale packages (figure 15a) that are interpreted to represent diurnal tidal bundles (Nio and Yang 1991). Facies C2 is also finer grained than Facies C1, suggesting a decrease in the

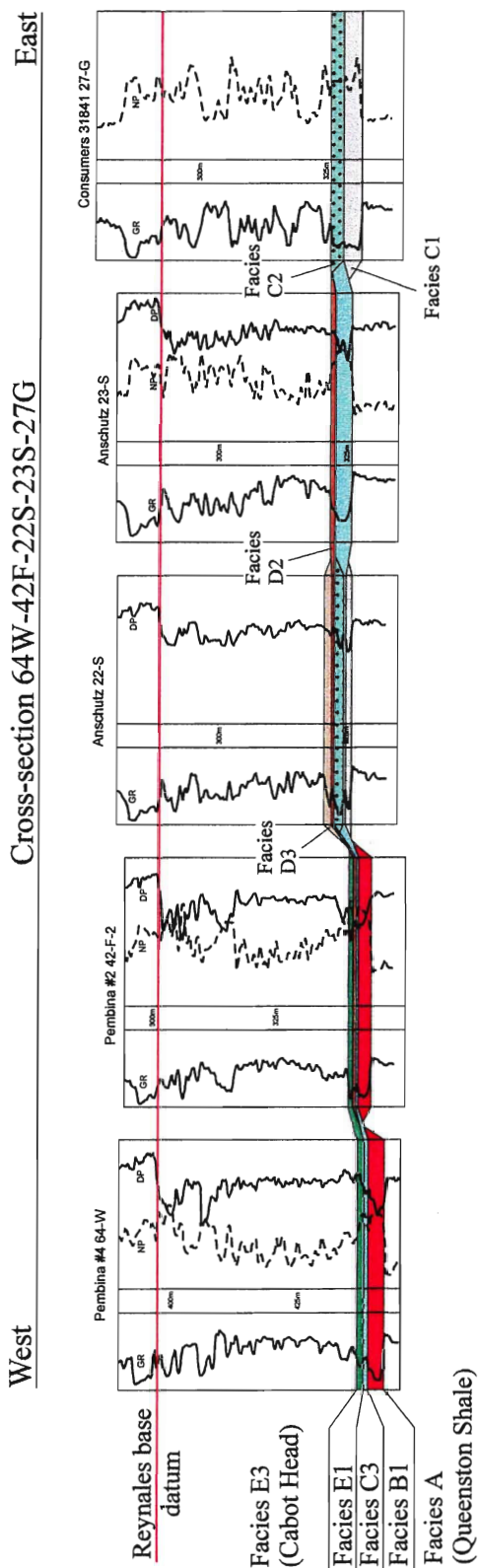


Figure 45. Cross-section displaying Element C bevelment of Element B related surface slope. Element B does not appear east of well 42-F where the surface slope has changed markedly. East of this bevelment, Element C dominates with Facies C1 and C2.

energy available in the depositional environment. Overall the sequence of channel fill reflects a transition from non-marine to marine conditions over time, reflecting a rise in sea level.

While Facies C1 and C2 are largely limited to the regions of incision into the underlying deposits, Facies C3 does occur interbedded with C1 and C2. Facies C3 is dominated by coarsely interlayered sandstone and shale and locally displays current ripple cross-lamination and flaser and wavy bedding. In addition, symmetrical wave ripples are present. Facies C3 is interpreted as the deposit of tidal flats that were associated with the channels in which Facies C1 and C2 were deposited. Coarsely interlayered bedding has been reported on modern North Sea tidal flats (Reineck and Singh 1980). The flaser and wavy bedding reflect the influence of tidal currents on the flats (Reineck and Singh 1980) and the presence of syneresis cracks indicates that the waters varied from fresh or brackish to saline (Reineck and Singh 1980). Sun cracks and curled shale flakes reflect the periodic drying of the tidal flat. The rare bioturbation of very simple forms (*Planolites* and *Paleophycus*) suggests an environment very harsh to organisms (Pemberton and Wightman 1996). There was at least some marine influence in this facies with the presence of scolecodonts and acritarchs (appendix 1, Parkins 1997). Facies C3 has been interpreted to represent tidal flat deposits.

The estuarine rivers are denoted on the interpretative map (figure 44) with a speckled blue-green fill and the tidal flats by a simple blue-green fill.

## **Element D**

### **Facies D1**

This unit normally fines upward from cross-bedded sand at the base into bioturbated sandstone and shale near the top. The sequence is commonly capped by Facies D3. Cross-bedding displays tidal influences with structures such as graded foresets. The lobate forms

on the element map (figure 10) trend northeast-southwest, similar in orientation to the estuarine channels described above, and appear to incise the estuarine facies of Element C (figures 39 and 43). Facies D1 was deposited in lobate scours.

## **Facies D2**

This facies varies widely in texture and structure. It occurs beneath Facies D3 in some cores. There is no true structure to this facies except of its positioning between the estuarine facies (Element C) and the topographically elevated Facies D3.

## **Facies D3**

This unit is composed largely of horizontal to low angle laminated sandstone with abundant shell fragments. This facies forms a topographically elevated unit between eastern and western sediments and trends roughly north-south. Where it occurs the facies normally overlies Facies D2 and is interpreted as foreshore deposits.

## **Interpretation of Element D**

Element D is interpreted as the deposits of a barrier island complex. The barrier itself appears to be made up of Facies D3, horizontal to low angle laminated, shell fragment rich, sandstone suggestive of a foreshore environment (Reineck and Singh 1980), which sits structurally higher than areas to the west (figure 35). The barrier appears to trend north-south (figure 38), approximately orthogonal to the interpreted estuarine valleys of Element C, that trend east and northeast to west and southwest. The barrier sandstone of Facies D3 is displayed on the interpretative map (figure 44) as a light brown colour.

Facies D2 most likely represents a backbarrier setting. The interbedded sandstone and shale of Facies D2 contains syneresis cracks (figure 20c), which indicate fluctuating salinity (Reineck and Singh 1980) and the low diversity assemblage of trace fossils suggests a harsh



environment, possibly a lagoon or backbarrier portion of an estuary (Pemberton and Wightman 1996). Small forms of trace fossils that are common in Facies D2, as well as a “nested” form of *Teichichnus* with a reduced number of spreiten, also suggests a harsh environment (Pemberton and Wightman 1996, and Reinson *et al.* 1988). The presence of mostly simple forms, such as *Chondrites* (figure 20b), *Planolites*, and *Paleophycus*, and less commonly *Thalassinoides* suggests a brackish water environment (Pemberton and Wightman 1996). A monospecific assemblage of *Teichichnus* in one shale (figure 19b) supports the interpretation of a brackish environment (Pemberton and Wightman 1996). Interbedded sandstone and shale units probably formed during influx of sediments from storm surges or during high estuarine channel discharge into the backbarrier.

Facies D2 is also characterized by sandstone with low diversity, high abundance trace fossil assemblage. This low diversity, high abundance trace fossil assemblage suggests bayfill where the estuarine channels meet the slow moving waters of a lagoon (Pemberton *et al.* 1996). The “nested” form of *Teichichnus* is present along with *Skolithos*, *Planolites*, and *Paleophycus* and much less commonly *Diplocraterion* (figure 20a), *Ophiomorpha*, *Helminthopsis*, *Arenicolites*, and *Gyrolithes*. Trace fossil forms are small, as in the interbedded sandstone and shale of Facies D2. The presence of syneresis cracks in the uncommon shales in this unit suggests fluctuating salinity (Reineck and Singh 1980). The presence of *Skolithos* and less commonly *Arenicolites* is suggestive of opportunistic trace fossil suites that could have formed soon after an influx of sediment (Pemberton *et al.* 1996).

The muddy lagoon portion of Facies D2 is displayed on the interpretative map (figure 44) as dark brown. No core actually penetrated this particular area of the Whirlpool Sandstone in subsurface and the presence of Facies D2 had to be inferred from the high shale content displayed in well logs from the general area behind the interpreted barrier (figure 39, well 37-

M) and the generally high shale content of Facies D2. Facies D2 commonly underlies foreshore deposits (Facies D3) which also suggests that this muddy area behind interpreted deposits in figure 39 contains Facies D2.

Cross-bedded and low angle cross-bedded and laminated sandstones and silty sandstones of Facies D2 was likely deposited under the influence of tides, as suggested by silty shale lenticular drapes over cross-beds. Low angle laminated silty sandstone with sandstone intraclasts can probably be attributed to lateral accretion of point bars (Brownsridge and Moslow 1991). This portion of Facies D2 is also associated with the tidal flats of Facies C3 and the estuarine channels of Facies C2. This unit probably formed in tidal creeks (Brownsridge and Moslow 1991) that drained from tidal flats or the barrier island into the backbarrier or into the estuarine channels.

The horizontally laminated to planar tabular cross-bedded sandstone of Facies D2 forms long, lobate, and interconnected sand bodies north of the estuary channels and is indicated on the interpretative map (figure 44) by a medium brown colour. Facies D2 is illustrated from this area in core from well 7-Y (figure 46). The sandstone's association with other Facies D2 units, the horizontal and low angle lamination and planar tabular cross-bedding, and convolute bedding with flame structures, suggests that this unit formed as part of a washover fan complex (Hobday and Jackson 1979; Schwartz 1982). Washover fans commonly occur in lobate and sheetlike forms (Reinson 1992). Because sets fine upwards it probably formed during washover by waning storm flows.

Facies D1 is probably the deposit of deeply scoured tidal inlets that dissect the barrier island. The inlets are denoted by yellow fill on the interpretative map (figure 44). Morphologically, these inlets are lobate in shape and trend northeast-southwest, perpendicular to the barrier island. The inlets also appear to incise pre-existing estuarine

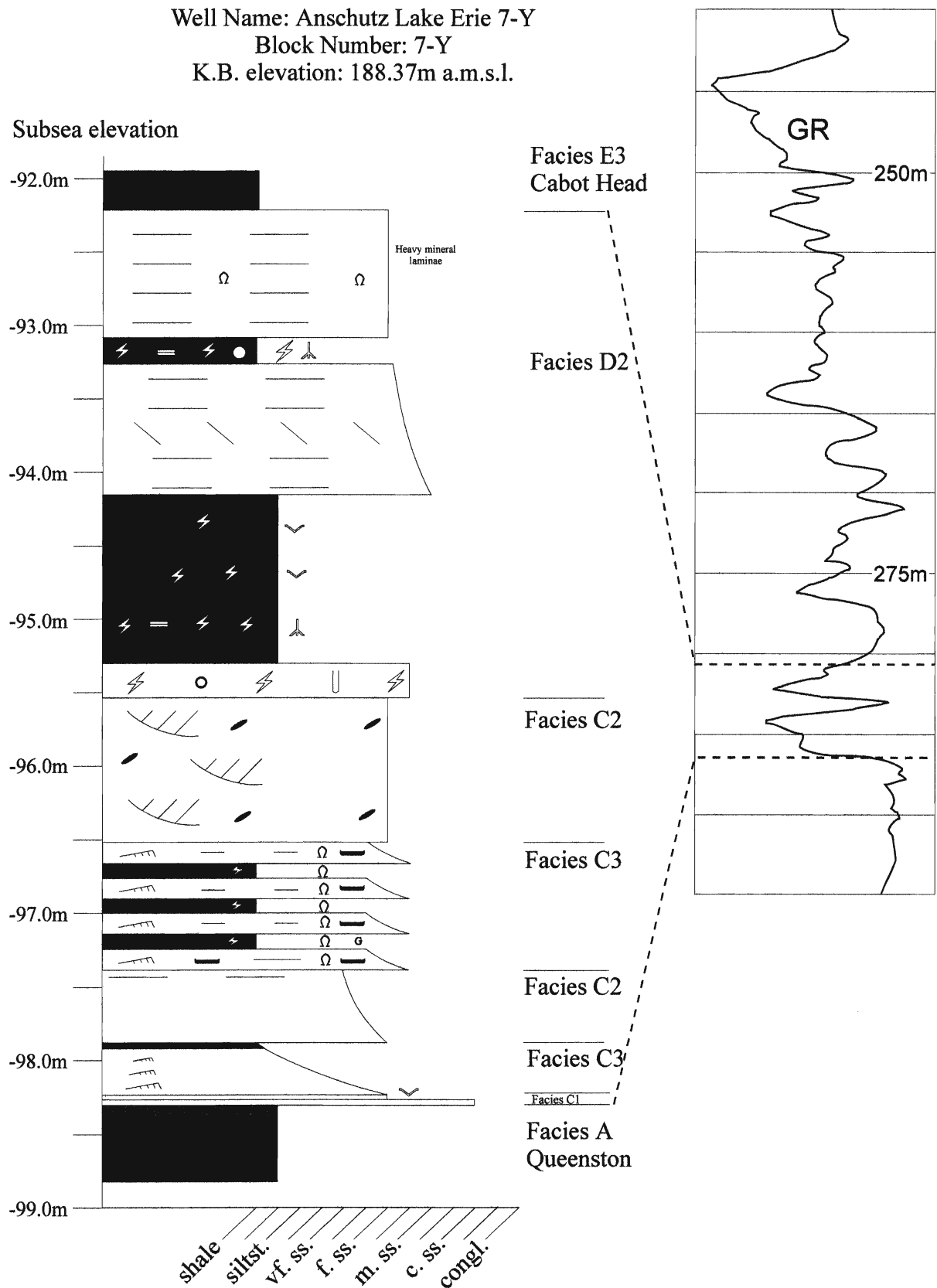


Figure 46. Core of Whirlpool Sandstone from well 7-Y. The sandstones capping the Whirlpool Formation in Facies D2 have been interpreted as washover deposits in a backbarrier setting.

deposits (Element C; figures 39 and 43). These inlets contain abundant cross-bedding, locally including graded forests (figure 17a) that have been reported in other tidal inlets (Harding 1988). The sands are commonly highly porous in well logs (figure 43). The presence of tidal inlets suggests that the tidal range was between 0 and 4 metres (Hayes 1975).

The inlet deposits have a characteristic fining upward pattern in gamma ray logs and in core (cores 68-Q, 39-Y and 39-W -- figures 40, 41, and 42 respectively). In the centre of the inlets the core still maintains its cross-bedded appearance throughout the section (e.g. core from well 68-Q; figure 40). Cross-bedded sandstone is laterally replaced by bioturbated sandstone and shale at the sides of these inlets (cores 39-Y, 39-W, and 39-T -- figures 40, 41, and 37 respectively), possibly reflecting inlet abandonment (Tye and Moslow 1996). The increasing intensity of bioturbation upward in the sequence suggests a mesotidal or macrotidal inlet rather than a microtidal inlet (Tye and Moslow 1996). Distinctly isolated inlet scours on the interpretative map (figure 44) suggests fairly stable inlets, and a mesotidal or macrotidal inlet rather than a microtidal inlet (Tye and Moslow 1996). The entire sequence is normally capped by a foreshore sandstone, which probably represents complete abandonment and reworking by foreshore processes.

## **Element E**

### **Facies E1**

Bioturbated sandstone with high diversity, high abundance trace fossil suites and robust trace fossil forms are probably the deposits of open marine environment. The higher sand content suggests a relatively nearshore location of deposition.

## **Facies E2**

Interbedded limestone and shale and fossiliferous limestone represents an environment far different than for most of the Whirlpool Sandstone in subsurface Lake Erie. Its position on top of a structural high suggests that Facies E2 was deposited as a carbonate bank or platform in shallow waters.

## **Facies E3**

Interbedded sandstone and shale was deposited in an environment that was periodically punctuated by higher energy events. Massive and bioturbated shale was probably deposited in a quiet water environment. High diversity trace fossil suites indicates an open marine environment.

## **Interpretation of Element E**

This element was deposited in a fully marine environment. West of the barrier island of Facies D3, Facies E1 is present and is denoted on the interpretative map (figure 44) by medium green. High diversity and high abundance trace fossil suites, along with fully robust ichnofossil forms, easily differentiates this facies from the backbarrier facies (Facies D2). The mix of burrowers, such as *Skolithos* and *Paleophycus*, and grazers, such as *Zoophycus* and *Planolites*, and the high sand content, suggests deposition in a mid- to lower-mid shoreface setting (Pemberton and Wightman 1996). The presence of *Zoophycus* in Facies E1 begins in the westernmost shoreface sandstone (e.g. core 64-W; figure 28) and does not appear in Facies E1 close to the interpreted barrier island complex (e.g. core 69-F; figure 36). This suggests that the energy of the environment decreased to the west (Pemberton and Wightman 1996).

The fully marine portion of the Whirlpool Sandstone in subsurface Lake Erie is similar to

that described in outcrop. They both represent the deposits of lower to middle shoreface settings. The only major difference is in the interpretations of the offshore direction. Cheel and Middleton (1993) suggested an offshore direction towards the northeast, based on offshore storm flow paleocurrent indicators. This study suggests an offshore direction towards the southwest as indicated by the relative position of estuarine channels, barrier island complex, and shoreface sandstone facies. This will be discussed at length later.

The presence of backbarrier facies (Facies D2) capping cores west of the barrier island occurs in wells 21-X and 71-I (figures 47 and 48 respectively) where the top of the Whirlpool Sandstone sits structurally lower than the tops to the east (figure 49). A similar situation was described by Reinson (1992, figure 50a). This area is probably the remnants of a wave ravinement surface and was undergoing erosion by wave action and not shoreface deposition near the end of Whirlpool Sandstone deposition. Subsurface Lake Erie Whirlpool Sandstone shoreface deposits directly overlie tidal flat and backbarrier deposits west of the wave ravinement surface (e.g. well 69-F; figure 36) supporting this interpretation. On the interpretative map (figure 44) the location of the wave ravinement surface before the final transgression over the Whirlpool Estuary is denoted by a speckled green fill.

The Manitoulin Limestone (Facies E2) probably formed as part of a carbonate bank as it drapes the structural high of the Algonquin Arch (Jones and Desrochers 1992). Glauconitic granules that are present in the limestone indicate a low rate of sedimentation (Reineck and Singh 1980) and abundant shell debris suggests a relatively high energy environment (Reineck and Singh 1980). The presence of shale interbedded with the carbonate beds probably represents periods of quiescence interrupted by higher energy events during which the carbonates were laid down. Considering that the shale content decreases towards the west and limestone content increases towards the west, the source of the higher energy carbonate

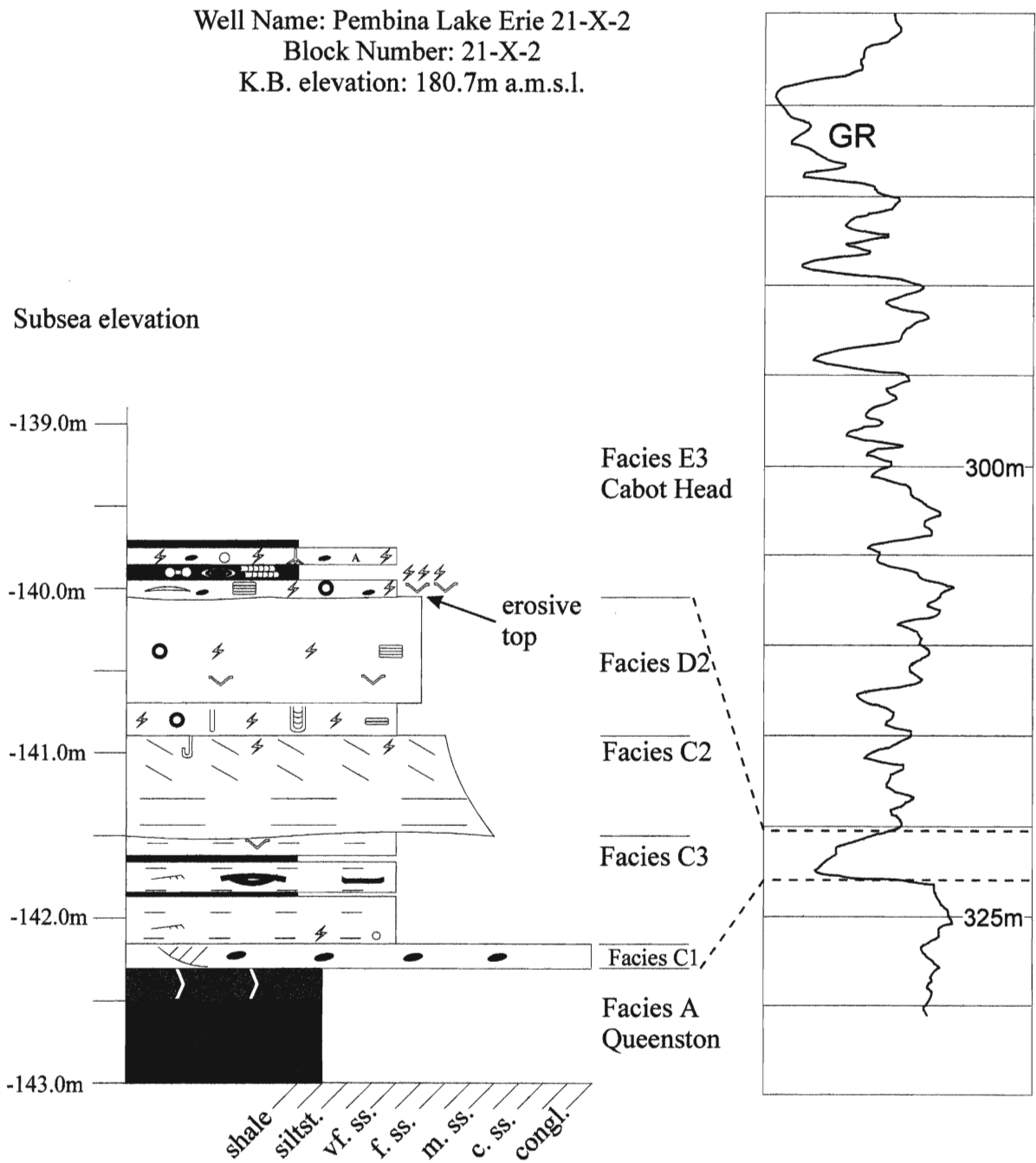


Figure 47. Core of Whirlpool Sandstone from well 21-X-2. The Whirlpool has an erosive top cutting into the backbarrier facies (Facies D2).

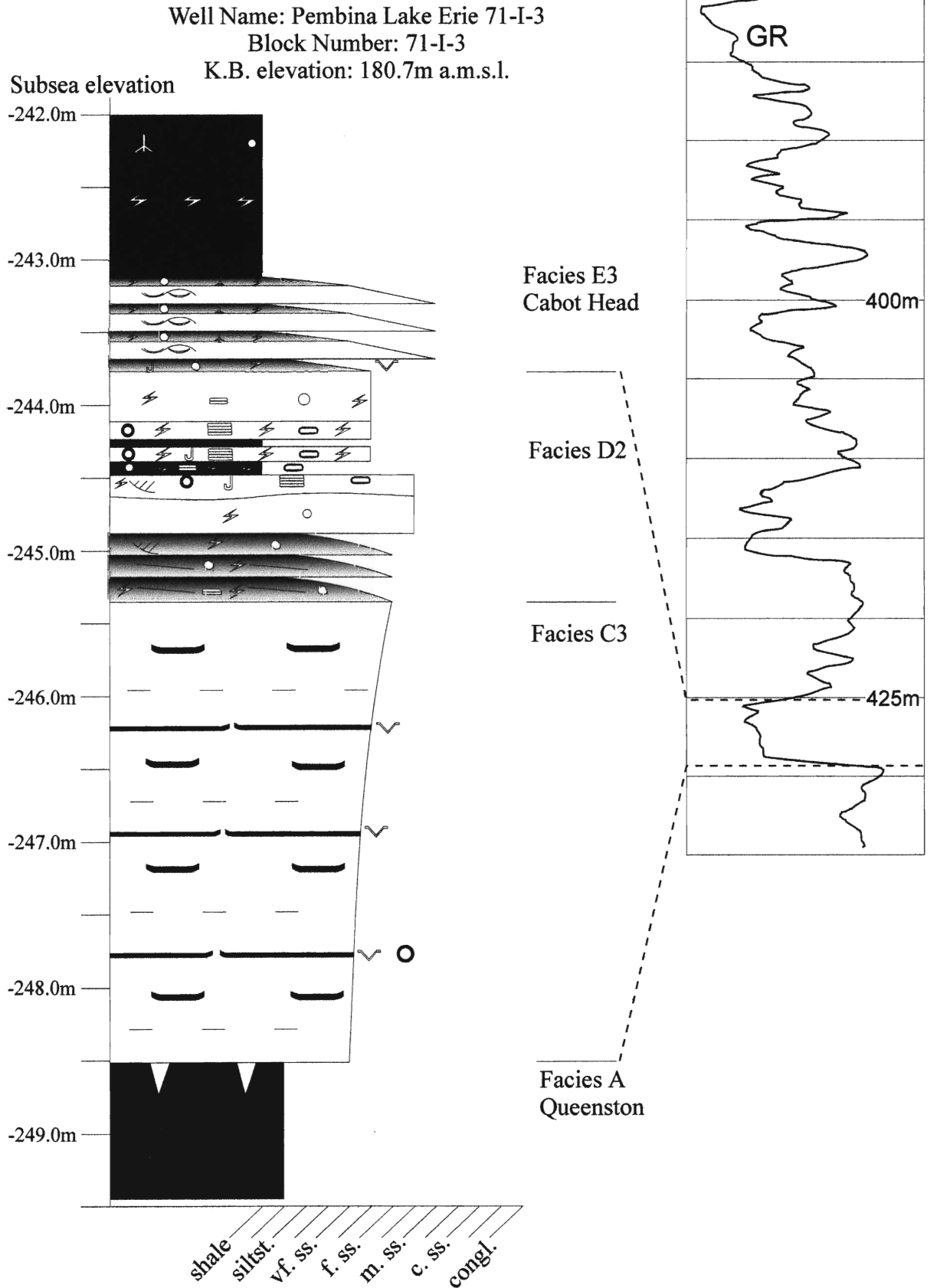


Figure 48. Core of Whirlpool Sandstone from well 71-I-3. Backbarrier facies (Facies D2) caps the Whirlpool Sandstone.



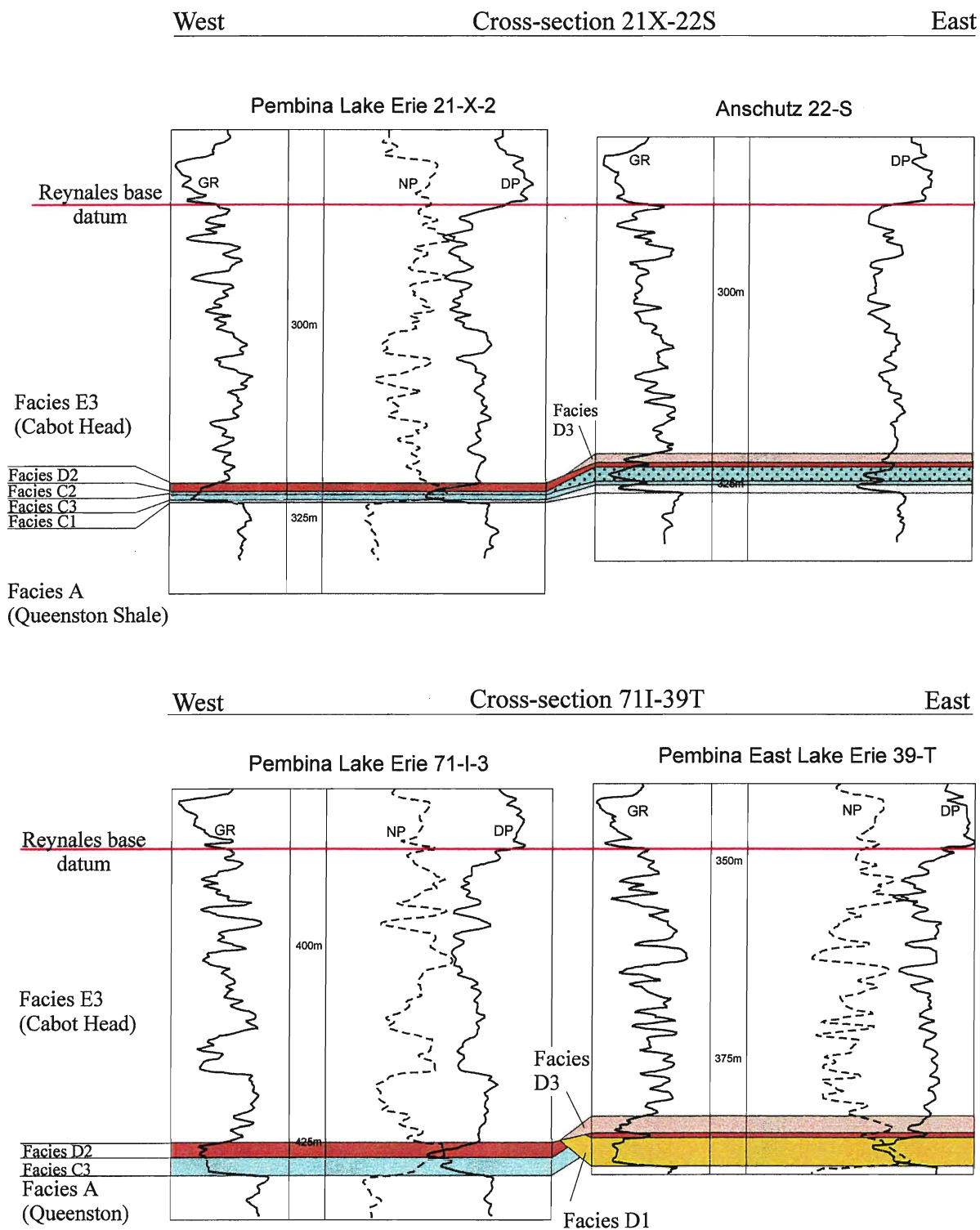


Figure 49. Cross-sections displaying how backbarrier facies (Facies D2) caps the Whirlpool Sandstone slightly seaward of the interpreted barrier island (Facies D3). Backbarrier facies west of the barrier island lie structurally lower than backbarrier facies to the east of the barrier island..

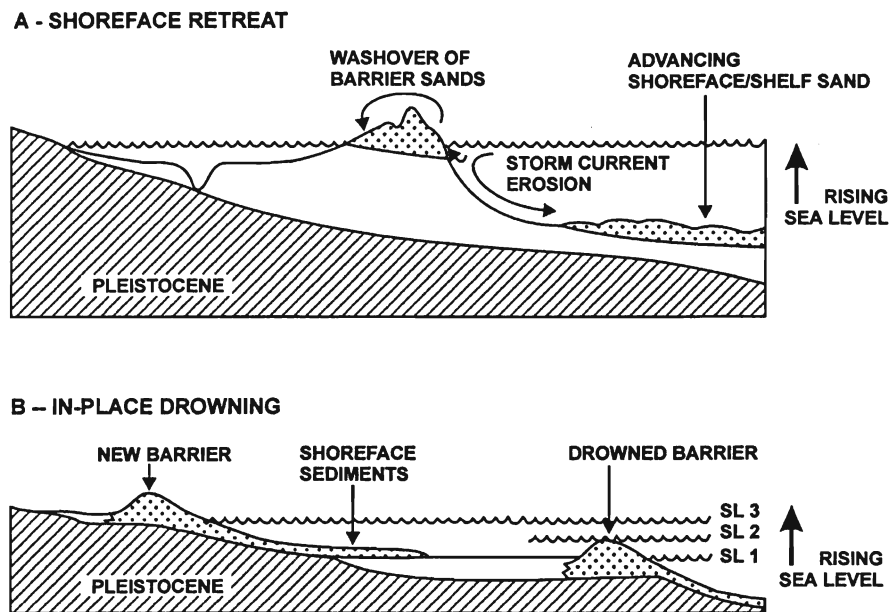


Figure 50. Forms of landward barrier migration. A) Erosional shoreface retreat, and B) in-place drowning. The area of "storm current erosion" in A) is also known as the "wave ravinement surface" (Allen and Posamentier 1993) or "transgressive disconformity" (Devine 1991). The Whirlpool barrier island displays erosional shoreface retreat with its lack of known drowned barriers, placement of barrier-foreshore facies over backbarrier facies, and shoreface sandstone facies erosional overlying backbarrier facies and tidal flat facies. From Reinson (1992).

beds is probably from the west, probably the topographic high on which the thickest portions of Facies E2 sits (figure 39). Anastas and Coniglio (1992) suggested a shallow water storm dominated, possibly tidally influenced, setting for Manitoulin Formation deposition on the Algonquin Arch. The area of deposition for the Manitoulin Formation is indicated by blue on the interpretative map (figure 44).

The Cabot Head Formation (Facies E3) was deposited in an unrestricted shallow marine setting. Hummocky cross-stratified sandstone interbedded with shale suggests that the environment was influenced by storms. The trace fossil assemblage and escape structures in the shales indicate a relatively quiet environment that was punctuated by events of higher energy that deposited the sandstone beds in a lowermost shoreface setting (Pemberton and Wightman 1996). The bioturbated shale contains abundant *Chondrites* and *Zoophycos*, suggesting deposition in an offshore setting (Pemberton and Wightman 1996). The massive black shale of the Cabot Head Formation is most likely an offshore deposit with little influence of storm currents. Bioturbation in this massive shale unit may not be visible because of a lack of sand to fill burrows.

### **The Whirlpool Estuary**

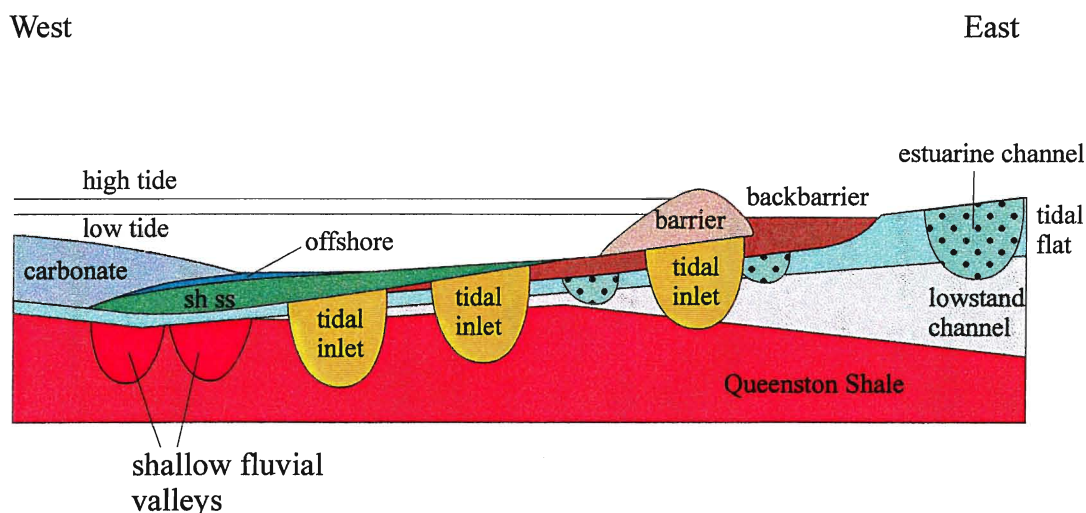
Table 3 summarizes the interpretations of the facies of the Whirlpool Sandstone. The environmental facies names will be used primarily in the remaining sections of this thesis. Figure 51 is an idealized west to east cross-section of all the Whirlpool facies in their relative positions and is based upon figure 39 and the interpretative map (figure 44).

The estuary and barrier island complex forms a sedimentologically complex mosaic, which is depicted on the interpretative map (figure 44). In the easternmost portion of the study area the Whirlpool Sandstone is exclusively estuarine channels (figure 44, speckled blue fill) and tidal flat deposits (figure 44, blue fill). The mouth of the estuary is filled with shaly

**Table 3: List of original facies codes and interpreted depositional environments.**

<u>Facies Name</u>	<u>Environmental Interpretation/Name</u>
Element A	mudflat
<i>Facies A</i>	<i>mudflat facies</i>
Element B	fluvial complex
<i>Facies B1</i>	<i>fluvial channel facies</i>
<i>Facies B2</i>	<i>fluvial overbank facies</i>
Element C	estuary complex
<i>Facies C1</i>	<i>lowstand channel facies</i>
<i>Facies C2</i>	<i>estuarine channel facies</i>
<i>Facies C3</i>	<i>tidal flat facies</i>
Element D	barrier island complex
<i>Facies D1</i>	<i>tidal inlet facies</i>
<i>Facies D2</i>	<i>backbarrier facies</i>
<i>Facies D3</i>	<i>barrier-foreshore facies</i>
Element E	open marine setting
<i>Facies E1</i>	<i>shoreface sandstone facies</i>
<i>Facies E2</i>	<i>carbonate facies</i>
<i>Facies E3</i>	<i>offshore facies</i>

Whirlpool Sandstone Schematic,  
Subsurface Lake Erie  
(not to scale)



### Depositional Environments

Queenston Shale -- mudflat facies (Facies A)

fluvial valley -- fluvial channel facies (Facies B1) and  
fluvial overbank facies (Facies B2)

lowstand channel -- lowstand channel facies (Facies C1)

estuarine channel -- estuarine channel facies (Facies C2)

tidal flat -- tidal flat facies (Facies C3)

tidal inlet -- tidal inlet facies (Facies D1)

backbarrier -- backbarrier facies (Facies D2)

barrier -- barrier-foreshore facies (Facies D3)

sh ss -- shoreface sandstone facies (Facies E1)

carbonate -- carbonate facies (Facies E2)

offshore -- offshore facies (Facies E3)

Figure 51. Schematic of the Whirlpool Sandstone from subsurface Lake Erie. Notice how the fluvial valleys are overlain by the tidal flat facies and how the tidal inlets incise the estuarine deposits. Also of note is the wave ravinement surface to the immediate west of the barrier which, during the act of transgressive barrier backstepping, removes the barrier-foreshore facies leaving only the lowermost backbarrier facies and tidal flat facies intact. This allows the tidal flat facies to form the transgressive marker far west of the barrier. Derived and generalized from figure 50 and the interpretative map (figure 55). Individual elements are not drawn to scale.

backbarrier sediments (figure 44, dark brown fill) as displayed in figure 39 at well 37-M. Where estuarine channels and mudflats are absent behind the backbarrier, sandy washover deposits dominate the backbarrier facies (figure 44, medium brown fill). Further west, south of Port Maitland, a barrier island complex (figure 44, light brown fill) extends from north to south across the entire study area. Deeply scoured tidal inlets (yellow fill) dissect the barrier and similar inlets are present west of the barrier. Open marine deposits of the shoreface sandstone facies are present west of the barrier island complex (figure 44, green fill). Stippled green on figure 44 indicates the zone where the barrier island and underlying deposits have undergone significant erosion by waves. Even further west, the shoreface facies of the Whirlpool Sandstone gives way to the marine carbonates of the Manitoulin Formation (figure 44, purple fill).

The estuarine Whirlpool is most likely the deposit of a mixed energy estuary since it shows many tide and wave influenced structures. Many modern wave-dominated and mixed-energy estuaries have tripartate distribution where sandy fluvial deposits are separated from sandy barrier island deposits by a low energy muddy funnel (figure 52; Roy *et al.* 1980; Nichols *et al.* 1991; Allen and Posamentier 1993; and Dalrymple and Zaitlin 1994). Clear tripartate distribution in the Whirlpool estuary is evident on the interpretative map (figure 44) suggesting a wave-dominated or mixed-energy setting (figure 52; Dalrymple *et al.* 1992).

The extensive tidal flat facies and the presence of several tidal inlets (figure 44) suggest tidal influence. Cores from wells 39-Y, 39-W, and 39-T (figures 41, 42, and 37 respectively) display abundant bioturbation as part of an inlet abandonment sequence and this is expected in mesotidal rather than microtidal settings (Tye and Moslow, 1996). The inlets appear to have a “drumstick” configuration on the interpretative map that suggests the action of strong tidal currents (Tye and Moslow, 1996). Evidence for tides includes the presence of graded

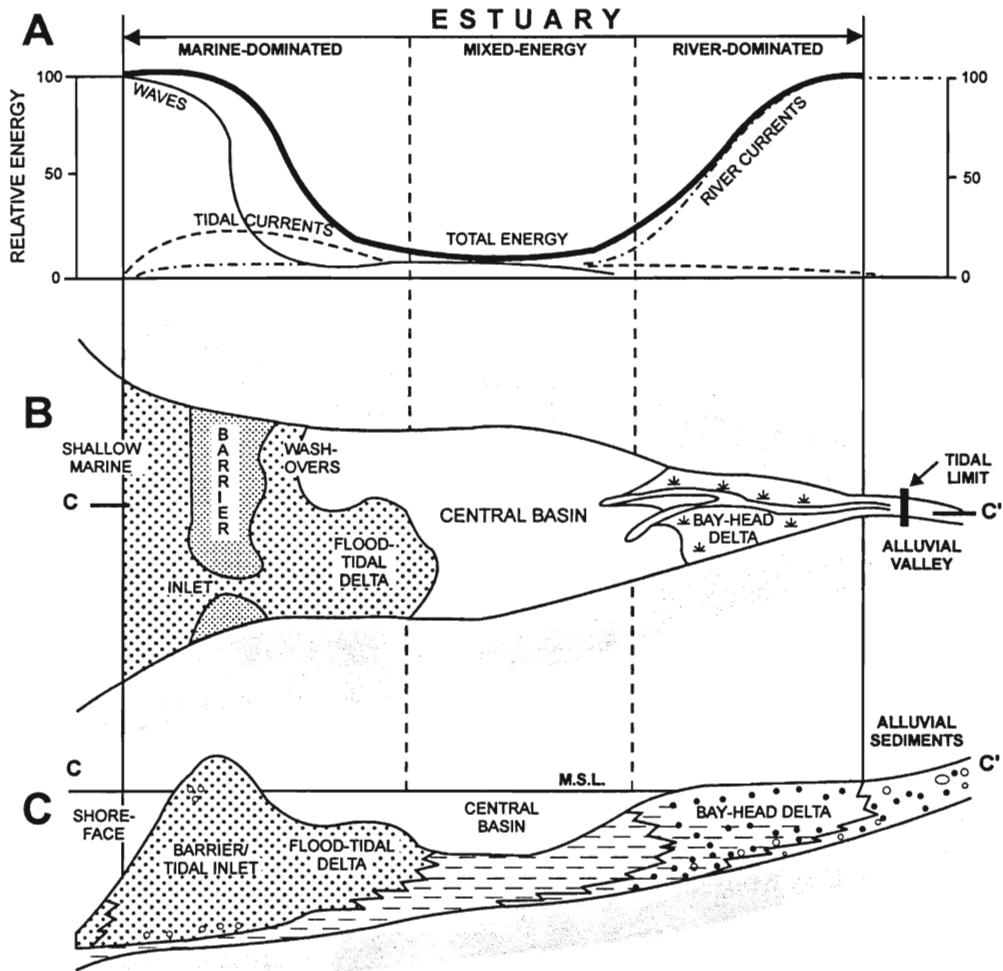


Figure 52. Wave dominated estuaries and distribution of A) energy, B) morphology, and C) sedimentary facies. The Whirlpool estuary strongly resembles this model, except that the barrier is not attached to the interfluvies, and there is no apparent large flood-tidal delta associated with the tidal inlets. From Dalrymple *et al.* (1992).

p foresets in the tidal inlet facies (figure 17a). Finally, far up the estuarine channels there appears to be tidal influence with the presence of diurnal tidal bundles on the foresets of laminar tabular cross-bedding (figure 15a).

The tidal range for the estuary can be roughly estimated. The presence of tidal inlet and barrier island deposits suggests a tidal range of less than 4 metres and the widespread presence of tidal flat deposits suggests a tidal range over 2 metres (Hayes 1975). The drumstick configuration and abandonment sequence of the inlets suggests a mesotidal range (Tye and Moslow 1996). Thus, the Whirlpool estuary is probably mesotidal, with a tidal range between 2 and 4 metres.

There are small bayhead deltas that appear to have prograded from the estuarine channels into the backbarrier area (figure 44), and these are expected in mixed-energy settings (Dalrymple *et al.* 1992). The well control from this area is not very good and the true extent of the bayhead deltas cannot be known without further exploration.

Tidal sand bars are also expected to form in a mixed-energy estuary by tidal modification of a prograding bayhead delta (Allen and Posamentier 1993). These have not been observed in the Whirlpool estuary. As mentioned above, the well control for the area of the bayhead delta is low and the presence or absence of tidal sand bars cannot be confirmed and will be assumed to be absent.

The lack of observed flood-tidal deltas can be explained by the tidal influence. Wave dominated inlets have large flood-tidal deltas where tide dominated inlets may have no flood-tidal deltas (Tye and Moslow 1996). The strong tidal influence in the Whirlpool estuary may have inhibited the formation of prominent flood-tidal deltas.

The Whirlpool estuary does not appear to be a river-dominated estuary. Cooper (1994) suggested that in a river-dominated estuary, the riverine processes extend to the mouth of the



estuary, removing the tripartate zoning seen in a wave-dominated estuary or mixed-energy setting. According to the interpretative map (figure 44) there is a clear tripartate zonation in the Whirlpool estuary.

The overall morphology of the Whirlpool estuary suggests the presence of a broad, shallow valley versus a narrow, deep valley as discussed in Ricketts (1991). In the Whirlpool estuary, the facies are laterally extensive and include a very large lagoon containing washover deposits and bordering tidal flats (figure 44). There is a barrier island with a distinctive shoreface and tidal inlets. The basal surface of the estuary is of low topography, only a few metres in depth (cross-section 5X-26S; figure 31), also suggesting a broad, shallow valley (Ricketts 1991).

The paleoslope in the estuarine channels was probably towards the west and southwest, as indicated by the relative positions of the shoreface, barrier, and the estuarine valleys, and the slope of the surface beneath the estuary complex (figure 34). The shoreface sandstone facies to the west of the barrier island completes the non-marine to marine transition from east to west.

The estuarine channel trends suggest that the source of sediment for the estuarine Whirlpool was most likely towards the east and northeast. Because the orientation of the estuarine valleys suggests a provenance towards the northeast, a problem arises; much of the older potential source material is removed towards the northeast due to the erosion associated with the Niagara Escarpment in western New York State. The source rocks for the estuarine deposits are possibly the Juniata Formation, and/or possibly the Oswego Sandstone (Rutka 1986).

The estuarine Whirlpool Sandstone appears to sit stratigraphically higher than the fluvial Whirlpool Sandstone. Both units are lithologically similar and erosion of the braided fluvial

deposits may have provided considerable detritus for the estuarine complex. Brusse *et al.* (1987) reported east-west trending, brackish channels nested into the top of the fluvial Whirlpool in outcrop near Lockport, New York State. Brett *et al.* (1991) cited palynological results that substantiated the brackish water interpretation. These brackish channels were probably filled with sediment scavenged from their incision into the fluvial Whirlpool. There have been no reports of an estuarine system reported in outcrop, other than possibly the shallow, brackish channels. There have also been no reports of barrier island deposits in outcrop. In subsurface it appears that this brackish unit makes up the major portion of the Whirlpool Sandstone, replacing most of the fluvial Whirlpool.

## ***Estuarine Sequence Stratigraphy***

The Whirlpool Sandstone displays a change from completely terrestrial sedimentation into completely marine sedimentation, suggesting a marine transgression over the course of its deposition. One would expect that the shallow fluvial valleys of the Whirlpool Sandstone would represent a lowstand systems tract that was followed by marine transgression and estuarine valley fill as the marine environment invaded the fluvial environment during a transgressive systems tract (Allen and Posamentier 1993). This is clearly not the case, as the fluvial shallow valleys run nearly perpendicular to the estuarine rivers (figure 44). Even then, the northwest flowing fluvial valleys exist only under the marine portion of the Whirlpool Sandstone and none are found under the main estuarine portions (figure 44). In outcrop there is an erosional surface between the fluvial and marine portions of the Whirlpool Sandstone (Rutka 1986, and Cheel and Middleton 1993).

The northwest-southeast trending fluvial deposits appear to be genetically unrelated to the deposits of the estuary complex. A significant physiographic change must have taken place between deposition of the fluvial deposits and deposition of the estuarine-marine deposits to alter flow patterns from towards the northwest during fluvial deposition to towards the southeast during estuarine deposition. This most likely occurred as a result of change from a northwestern dipping slope to southwestern dipping slope as inferred from channel trends and paleoflow. The cause of this tilting will be discussed later in detail.

There appear to be two major erosional surfaces related to different sets of channelized facies in the subsurface Whirlpool Sandstone. The first occurred prior to the deposition of the fluvial Whirlpool. In subsurface, the shallow fluvial valleys cut into and eroded the Queenston Shale (e.g. cross-section 92N-64P; figure 27) forming the first sequence boundary and a subsequent lowstand systems tract that contains deposits of a northwest flowing fluvial

system. A second sequence boundary formed at the base of the estuarine unit, the lowstand channel facies (Facies C1) also representing a lowstand systems tract.

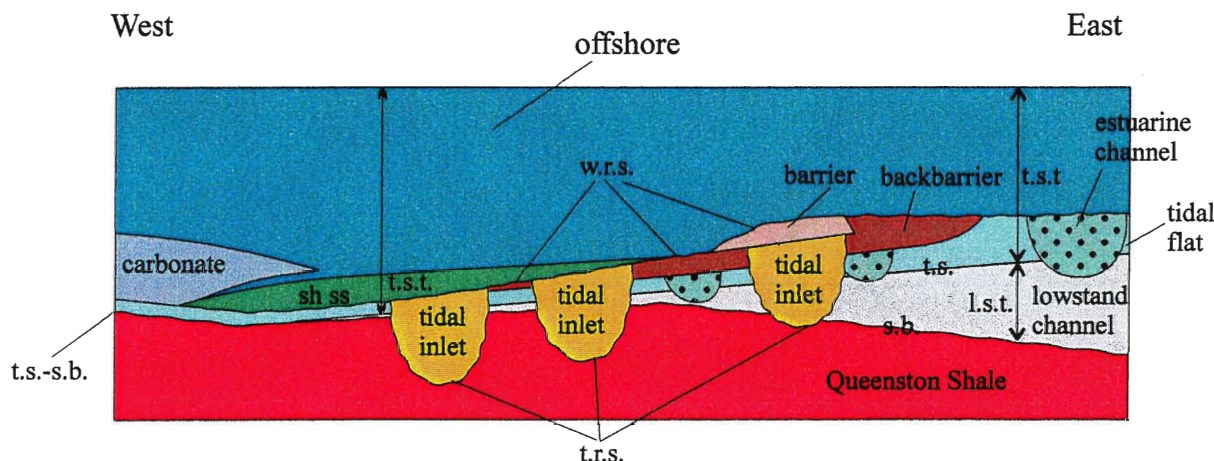
The sequence stratigraphy of the estuary is illustrated in figure 53, which is based on figure 51.

### **Lowstand Systems Tract**

The sequence boundary of the estuarine Whirlpool is placed at the base of the channelized lowstand deposits (figure 53) as discussed above. The estuarine Whirlpool completely replaces the fluvial Whirlpool at the eastern end of Lake Erie. This suggests that the older fluvial deposits, if they were present in the vicinity, were removed by erosion in the eastern part of Lake Erie. In cross-section 64W-27G (figure 45) the fluvial portions of the Whirlpool Sandstone appear to only exist west of well 22-S. East of well 22-S, the top of the Queenston Shale appears to have been beveled; west of well 22-S, the top of the Queenston dips towards the southwest whereas east of well 22-S the surface dips towards the northeast. The surface appears to be a major angular unconformity that separates the fluvial Whirlpool and Queenston Shale from the overlying estuarine Whirlpool. Estuarine channels scour the area east of the barrier island (cross-section 5X-26S, figure 31). There appears to have been some scouring by the estuarine channels west of the barrier island, though not as extensive as east of the barrier.

The sequence boundary of the estuarine sequence is displayed in figure 11a, 11b, and 14, where the lowstand channel facies (Facies C1) erosively overlies the Queenston Shale (Facies A). The lowstand channel facies (Facies C1) is overlain by tidal flat (Facies C3) and estuarine channel facies (Facies C2) (figure 53). These cross-bedded sands are present east and west of the barrier, though the lowstand systems tract of the estuary is much thinner towards the west.

Estuarine Whirlpool Sandstone  
Sequence Stratigraphy, Subsurface Lake Erie  
(not to scale)



#### Stratigraphic Surfaces

- s.b. -- sequence boundary
- t.s. -- transgressive surface
- t.r.s. -- tidal ravinement surface
- w.r.s. -- wave ravinement surface

#### Systems Tracts

- l.s.t. -- lowstand systems tract
- t.s.t. -- transgressive systems tract

#### Depositional Environments

- lowstand channel -- lowstand channel facies (Facies C1)
- estuarine channel -- estuarine channel facies (Facies C2)
- tidal flat -- tidal flat facies (Facies C3)

- tidal inlet -- tidal inlet facies (Facies D1)
- backbarrier -- backbarrier facies (Facies D2)
- barrier -- barrier-foreshore facies (Facies D3)

- sh ss -- shoreface sandstone facies (Facies E1)
- carbonate -- carbonate facies (Facies E2)
- offshore -- offshore facies (Facies E3)

Figure 53. Sequence stratigraphy of the estuarine-marine portion of the Whirlpool Sandstone and all the relevant stratigraphic surfaces. Notice how the tidal ravinement surface incises down and removes the sequence boundary and the transgressive surface. Also of note is the wave ravinement surface to the immediate west of the barrier which, during the act of transgressive barrier backstepping, removes the barrier-foreshore facies leaving only the lowermost backbarrier facies and tidal flat facies intact. This allows the tidal flat facies to form the transgressive marker far west of the barrier. The wave ravinement surface also forms an erosive base to the offshore facies where overlying the estuary and barrier island. This formed when rapid transgression dragged the wave ravinement over the barrier island and estuarine complex at the end of Whirlpool deposition..

The duration of time for deposition of the lowstand systems tract was probably not long considering that there is not much lowstand channel facies west of the barrier. Additional evidence for a short duration lowstand systems tract is the lack of major topography on the erosion surface. Broad, shallow valley estuaries, like the Whirlpool estuary, are created by relatively young drainage systems (Ricketts 1991).

Where the lowstand channel facies has not scoured into the underlying deposits, the sequence boundary has amalgamated with the transgressive surface (figure 53).

### **Transgressive Systems Tract**

Figure 39 shows a nearly continuous estuarine unit that runs from west of Long Point to easternmost Lake Erie. This estuarine unit underlies fully marine sediments of the shoreface sandstone facies and carbonate facies (Facies E1 and E2 respectively) and overlies either the subaerially eroded Queenston Shale (Facies A), fluvial channel facies (Facies B1), or lowstand channel facies (Facies C1), suggesting that a well developed tidally influenced transgressive surface exists throughout most of subsurface (figure 53). This transgressive surface is locally absent where it is incised by tidal inlets (Facies D1).

The base of the tidal flat facies (figure 53) represents the transgressive surface in the non-channelized areas. In estuarine channels the transgressive surface is marked by the initiation of tidal influence or by marine influence as indicated by bioturbation. The transgressive surface has amalgamated with the sequence boundary in places where the tidal flat facies directly overlies the Queenston Shale or over the fluvial Whirlpool. In these areas the lowstand deposits never existed or were eroded during transgression. The transgressive surface in an estuary represents the first marine incursion into a terrestrial environment (Allen and Posamentier 1993). If the marine incursion happens in a lowstand channel, then the lowstand channel forms an estuarine channel.

As discussed earlier in this thesis, a barrier island formed at the mouth of the estuary. In cores where the barrier-foreshore facies is present it overlies backbarrier or tidal inlet facies. The barrier appears to have erosively “backstepped” over backbarrier and tidal flat deposits. In core, this is found where the barrier island facies overlies the backbarrier facies (e.g. core 72-O; figure 54). This occurs during shoreline retreat; the barrier sands retreat, eroding previously deposited material, probably leaving only the lowermost deposits intact (figure 50a; Reinson 1992). This “backstepping” of the barrier takes place in response to marine transgression (Reinson 1992).

Backstepping of the barrier island can explain the absence of backshore sediments that would otherwise be expected in a barrier island sequence. Barrier island backstepping is an erosive process and would remove much of the backshore deposits except for the topographically lowest, most likely lagoonal sediments (Reinson 1992). Sediments deposited as inlet fill also sit structurally low and should be preserved. Because the backshore eolian and washover sands on a barrier island occupy relatively high topographic positions relative to the foreshore, then they would be prone to removal during barrier island backstepping.

The marine transgression that initiated the estuarine Whirlpool Sandstone was probably slow. A rapid transgression would have allowed preservation of the barrier sand on the shoreface (Reinson 1992). There are no observed barrier islands abandoned on the Whirlpool Sandstone shoreface. The method of transgression observed in the estuarine-marine Whirlpool was erosive rather than by in-place drowning of the barriers.

Well 68-Q contains the remnants of a tidal scour (figures 39 and 40), far west of the barrier island complex, that was transgressively abandoned on the shoreface. Further west of 68-Q, no tidal scour deposits have been identified. Based upon this, it is unlikely that the

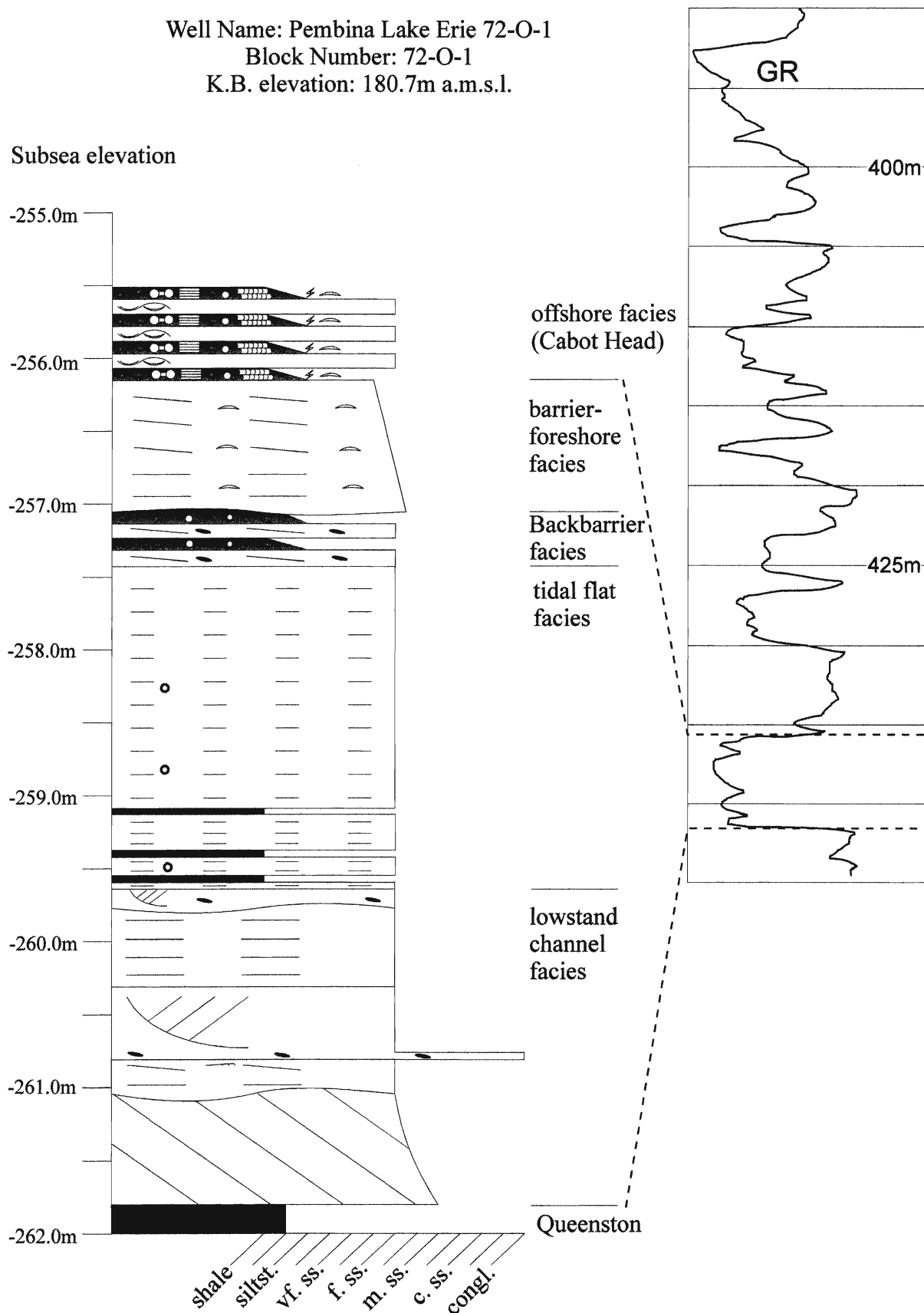


Figure 54. Core of Whirlpool Sandstone from well 72-O-1. Barrier-foreshore facies (Facies D3) caps the Whirlpool Sandstone and overlies backbarrier facies (Facies D2).



barrier island complex existed further west than the tidal inlet at 68-Q. The transgression and abandonment of tidal inlets on the shoreface is not unprecedented, having been reported by Hine and Snyder (1985) occurring off the east coast of North Carolina, recording transgressions during the Quaternary.

### **Highstand Systems Tract**

Most highstand systems tracts in mixed energy, wave- and tide-influenced estuarine environments are marked by prograding bayhead deltas and tidal sand bars, the latter forming by tidal modification of a bayhead delta (Allen and Posamentier 1993). A prograding bayhead delta and tidal sand bars eventually infill the estuary with fluvial and tidal sediments. In core, this would be reflected by fluvial sediments overlying backbarrier lagoon and bayfill facies in areas behind the barrier (Dalrymple *et al.* 1992). At the head of the Whirlpool estuary channels, on the interpretative map (figure 44), there appear to be estuarine channel facies entering the backbarrier. These are most likely representative of prograding bayhead deltas, though, their extent into the backbarrier was limited. There are no observed tidal sand bars in the estuary bay, however, the lack of well control in the area may be responsible for this. No maximum flooding surface is indicated on figure 53 because of the lack of prominent prograding bayhead deltas, which would indicate a highstand systems tract. To complicate matters further, the maximum flooding surface, which would mark the beginning of progradation of a bayhead delta, is normally difficult to detect in an estuary (Allen and Posamentier 1993) and would therefore be difficult to detect in core for this study.

Inlets abandoned on the shoreface by transgression only exist directly southwest of the main estuarine channels (figure 44). No transgressed inlets appear west of the northernmost inlet immediately south of Port Maitland. Stabilized sea levels could have allowed this inlet to form south of Port Maitland, away from the main estuary channels, possibly indicating a

stillstand systems tract. At the interpreted barrier island, the tidal inlet sequence in core always ends with a foreshore sandstone (figure 43), which is consistent with stabilized sea levels and is not consistent with further sea level rise. This suggests sediment starvation (Honig and Boyd 1992) or widespread dispersal of estuarine channel sediments into the backbarrier for the bayhead delta's absence, rather than a non-existent or short duration highstand systems tract.

### **Wave Ravinement Surface and Shoreface Deposits**

A wave ravinement surface in the estuarine-marine Whirlpool is located beneath the shoreface sandstone facies, cutting into backbarrier facies or into tidal flat facies (figure 53). In the study area, the backbarrier facies is commonly overlain by the shoreface sandstone facies west of the preserved barrier island deposits, which suggests backstepping in response to marine transgression. In this area the barrier has been totally eroded by marine processes during shoreline retreat, leaving only remnant backbarrier sediments and transgressively abandoned inlets which are then covered by shoreface deposits (figure 50a). The shoreface sandstone includes detritus from the eroding barrier (Devine 1991). The erosional surface created by this upper shoreface erosion is known as the “wave ravinement surface” (Allen and Posamentier 1993). This is illustrated in figure 20b where the shoreface sandstone facies (Facies E1) sharply overlies the backbarrier facies (Facies D2). This is also illustrated well in figure 55a where shoreface sandstone facies (Facies E1) overlies an obvious erosional surface cutting into tidal flat facies (Facies C3).

Immediately west of the barrier island (figure 53), the “transgressive disconformity” of Devine (1991) forms where the backstepping barrier exposes underlying backbarrier sediments to erosion on the upper shoreface (figure 50a). This is also known as the wave

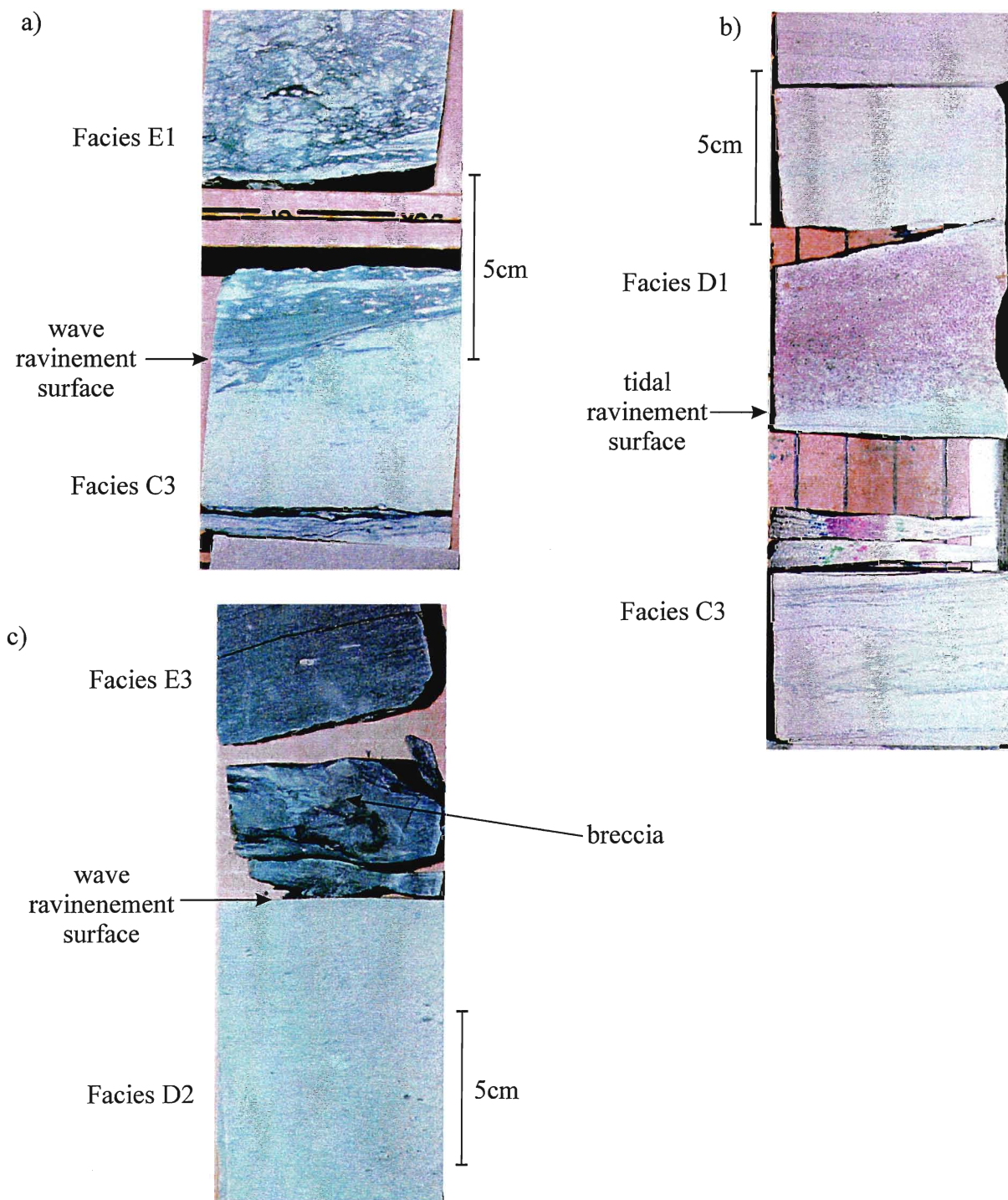


Figure 55. Stratigraphic surfaces. a) Wave ravinement surface of Allen and Posamentier (1993) with shoreface sandstone facies (Facies E1) erosively overlying tidal flat facies (Facies C3). From well Pembina Lake Erie 67-P-2, wave ravinement surface at -233.50m; b) Tidal ravinement surface of Allen and Posamentier (1993) where tidal inlet facies (Facies D1) scours into tidal flat facies (Facies C3). From well Pembina Lake Erie 39-Y-3, tidal ravinement surface at -211.17m; c) Wave ravinement surface with offshore facies (Facies E3) overlying backbarrier facies (Facies D2). In this instance, the erosional surface is marked by a breccia. From well Pembina East Lake Erie 26-M-1a, wave ravinement surface at -144.45m.

ravinement surface as noted in other estuaries (Allen and Posamentier 1993). The backbarrier sediments capping the Whirlpool Sandstone in cores from wells 21-X-2 and 71-I-3 (figures 47 and 48) are an erosional remnant of estuary deposits that were exposed by wave ravinement during the marine transgression.

### **Tidal Ravinement Surface and Tidal Inlet Deposits**

The presence of tidal inlets causes complications in the sequence stratigraphy of the Whirlpool estuary by adding another stratigraphic surface, the tidal ravinement surface. This is where the inlet has incised into previously existing material (Allen and Posamentier 1993; figure 53). In well 39-Y an exceptional tidal ravinement surface is preserved cutting into the tidal flat facies beneath the inlet (figure 55b). Tidal ravinement surfaces may incise deeply, even eroding the transgressive surface and the sequence boundary (Allen and Posamentier 1993). Cross-section 39Y-72G (figure 43) best displays this tidal ravinement surface and how it removed the sequence boundary and transgressive surface that are present in the neighbouring wells. Core from well 39-Y (figure 41) displays a sequence boundary (base of lowstand channel facies, Facies C1), transgressive surface (base of tidal flat facies, Facies C3), and tidal ravinement surface (base of tidal inlet facies, Facies D1). This core is located on the edge of an inlet and this is probably why the lower stratigraphic surfaces were not removed with the cutting of the tidal ravinement surface. Core from well 39-W (figure 42) is closer to the middle of the inlet and contains nothing but tidal inlet facies (Facies D1), the lower surface of the tidal inlet facies being the tidal ravinement surface.

### **Wave Ravinement Surface and Offshore Deposits**

The final phase of marine transgression, that abandoned the Whirlpool estuary in an offshore setting, appears to have been erosive (figure 53). A final relatively rapid

transgression removed any backshore sands that were elevated above the plane of the transgressive surface as the wave ravinement surface passed over the barrier island (Reinson 1992). As a result, where the Cabot Head Formation overlies the Whirlpool estuary, the boundary displays evidence for erosion (figure 55c). The wave ravinement surface is well displayed in core from well 26-M-1a where a small scale breccia in offshore shale deposits overlies the eroded estuarine Whirlpool (figure 55c). The wave ravinement surface associated with the offshore facies is confined to areas above the barrier island complex or estuarine complex.

The wave ravinement surface associated with the base of the offshore deposits was created by the same wave ravinement that creates the wave ravinement surface under the shoreface sandstone facies, the only difference being the rate of transgression. Initially, slow transgression during Whirlpool estuarine deposition resulted in shoreface deposits erosively overlying estuarine deposits. At the end of Whirlpool deposition, sudden, rapid transgression moved the wave ravinement surface over the barrier island and up the estuary, allowing offshore deposits to erosively overlie estuarine deposits. No shoreface deposits are apparently preserved on the abandoned estuary during this rapid transgression. A relatively fast transgression over a low gradient coast would move the shoreline rapidly landward, possibly preventing accumulation of any shoreface deposits over the erosional surface, and abandoning a mostly preserved estuary in an offshore setting. The lack of deep incision at the base of the Whirlpool estuary suggests a low gradient coast.

### **Sequence Stratigraphy Discussion**

According to Brett *et al.* (1990) the fluvial Whirlpool is a lowstand systems tract that forms the base of the Medina and Cataract groups. It is most likely that the lowstand channel facies of the estuarine Whirlpool is also part of a lowstand systems tract, and both fluvial

channel facies and lowstand channel facies appear to represent to separate incision events. The presence of a set of fluvial valleys trending northwest-southeast (fluvial channel facies), and another set of fluvial sediments related to the estuary trending northeast-southwest (lowstand channel facies), suggests that incision took place at two different times. Therefore, the two facies represent two different systems tracts.

The transgressive surface throughout the estuarine Whirlpool in subsurface Lake Erie marks the beginning of the Cataract transgression. The marine Whirlpool, which overlies the fluvial Whirlpool in outcrop, is thought to be a transgressive systems tract (Brett *et al.* 1990). The transgressive systems tract of the Whirlpool Sandstone in subsurface Lake Erie is marked by an initial estuarine unit and by a subsequent shoreface sandstone deposited over a wave ravinement surface. The marine Whirlpool in outcrop overlies an erosional surface (Cheel and Middleton 1993) but lacks the estuarine deposits that are present in subsurface Lake Erie, thus the marine facies in outcrop forms the same systems tract as the shoreface sandstone facies in subsurface Lake Erie. This suggests that the erosional surface in outcrop between fluvial and marine facies (figure 5) is also a wave ravinement surface.

The lower part of the Manitoulin Limestone is considered here to be equivalent to the marine Whirlpool. In the western portion of the study area the Manitoulin overlies the same tidal flat facies as the shoreface Whirlpool Sandstone does in the eastern portion of the study area (figure 53). The tidal flat facies in the western portion of the study area is calcareous (core 51-A, figure 56), suggesting that the two are related. In addition, near the western pinchout of the marine Whirlpool the sandstone becomes increasingly calcareous (e.g. core from well 92-N; figure 57).

In well 64-P (figure 39) the Whirlpool Sandstone is overlain by offshore facies which in turn is overlain by Manitoulin Limestone. The offshore facies (Facies E3) in nearby wells

Well Name: Cons. Amoco Lake Erie 13076

Block Number: 51-A

K.B. elevation: 179.22m a.m.s.l.

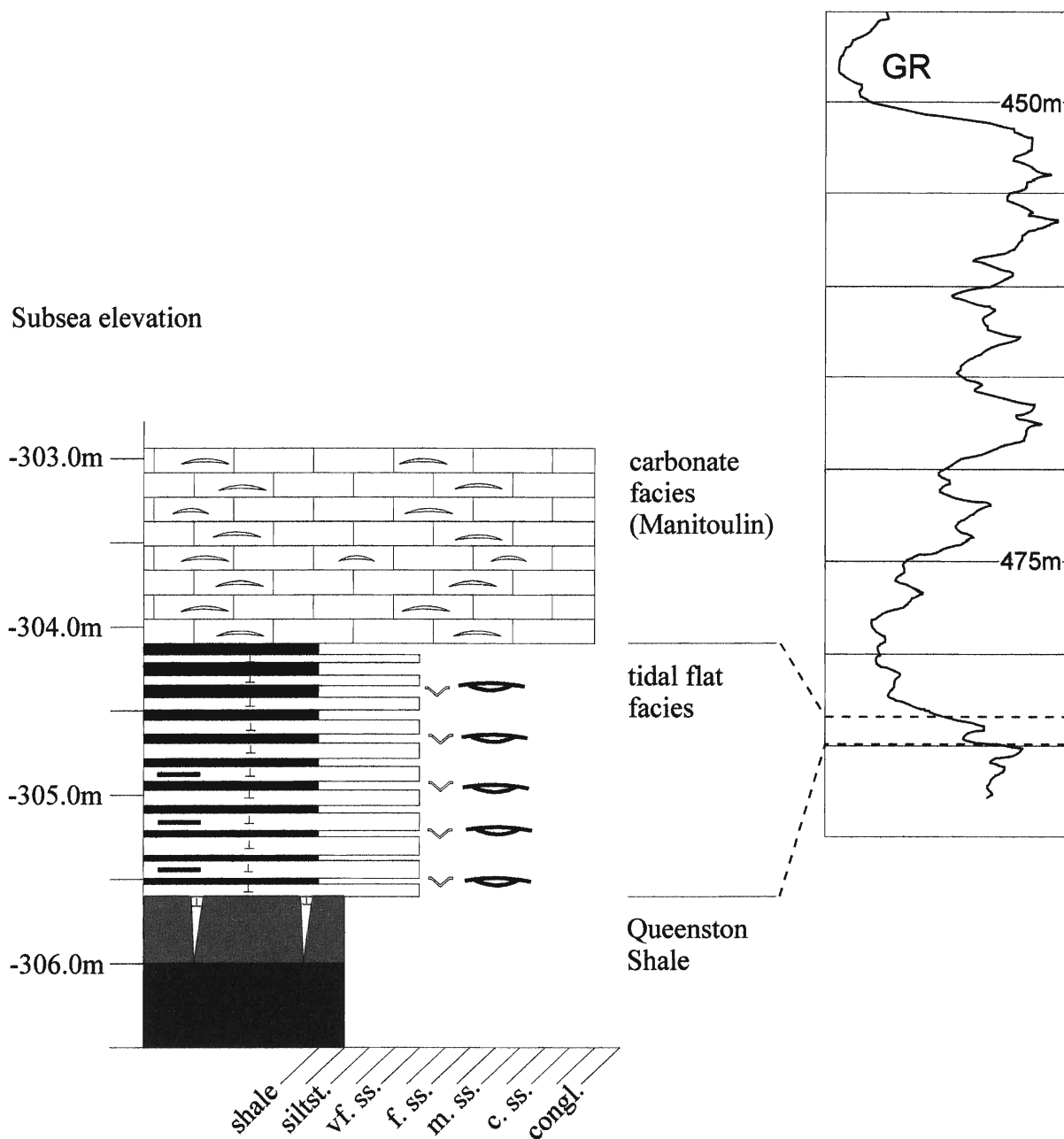


Figure 56. Core of the Manitoulin Limestone in well 51-A. Carbonate facies (Facies E2) overlies calcareous tidal flat facies (Facies C3) far west of the Whirlpool Sandstone pinchout.

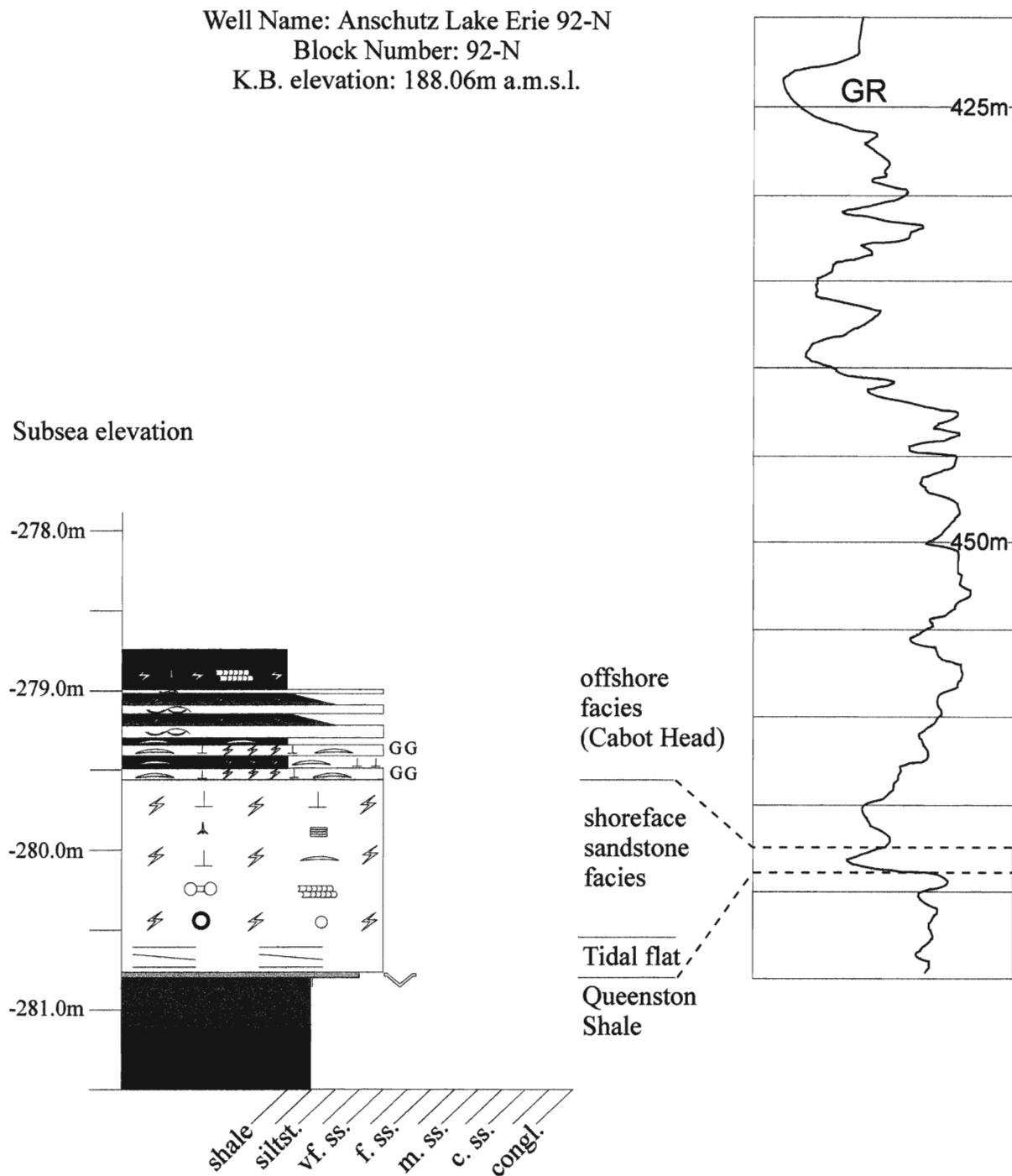


Figure 57. Core of the Whirlpool Sandstone from well 92-N. Notice the calcareous nature of the shoreface sandstone facies (Facies E1) and the glauconitic content of the offshore facies (Facies E3), which is similar to the mineralogy of the Manitoulin Formation (Facies E2).



contains glauconite (core from well 92-N; figure 57) and is shell rich, very similar to the lithology of the Manitoulin Limestone. The shell rich part of the offshore facies is also present further north in well 64-P (figure 29) where the Manitoulin Limestone appears to have prograded over the Whirlpool Sandstone. The vertical sequence is from deeper facies of the offshore facies into relatively shallower facies of the Manitoulin Limestone at this western area.

Upper portions of Manitoulin Limestone and Cabot Head are part of a transgressive systems tract. This is clear in the well logs at the west end of figure 39 where the Cabot Head Formation clearly forms an overall fining upward sequence as sea levels rose over the Algonquin Arch.

## ***Controls on Early Silurian Appalachian Basin Deposition***

A discussion of controls on Whirlpool Sandstone deposition is necessary in order to determine the role of eustasy and tectonics in the early Silurian Appalachian Basin.

### **Fluvial Whirlpool**

Rutka (1986) suggested that a southeast migrating peripheral bulge caused uplift and erosion of previously existing basin sediments in the earliest Silurian in the Appalachian Basin. Later, those sediments were dispersed by a braided fluvial system flowing off of a northwest migrating peripheral bulge. The Whirlpool Sandstone was thought to have pinched out towards the south on the northwest flank of the bulge (Rutka 1986, and Duke 1991; figure 4). However, more recently Dorsch and Driese (1995) documented an unconformity at the base of the “upper” Tuscarora Formation (figure 3) in the central Appalachians (central Virginia). They stated that this angular unconformity truncates the Whirlpool Sandstone farther north, eroding any physical link between it and its detrital source to the south. The apparent “pinchout” of the fluvial Whirlpool may be due to this rather than to any depositional limits imposed by a peripheral bulge. There may not have been any limiting factor to the fluvial Whirlpool’s extent prior to the formation of the unconformity.

An alternate hypothesis for fluvial Whirlpool deposition presented by Dorsch and Driese (1995) involved eustatic sea level fall at the end of the Ordovician caused by transfer of water from world seaways into the continental ice sheets of the Hercynian glaciation in Saharan Africa. The drop in sea level caused subaerial exposure and erosion of sediments, fluvial systems distributing these sediments to the north and northwest as the braided fluvial system of the lower Whirlpool Sandstone. However, a eustatic drop in sea level would have caused large amounts of erosion on the Algonquin Arch and evidence for this is lacking (Middleton

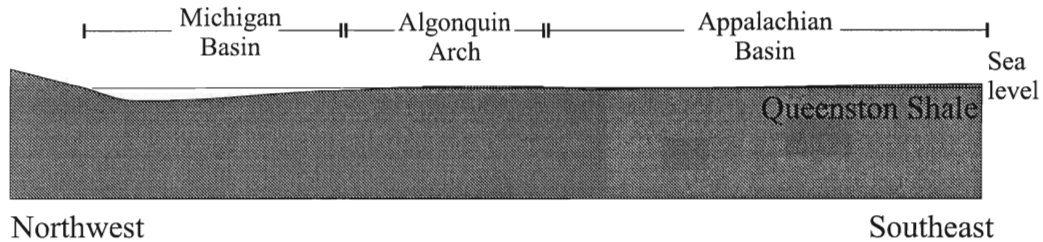
1987).

If fluvial Whirlpool deposition does not have its roots in eustatic sea level fall, it must have been caused by tectonic events. In the late Ordovician, the Queenston Shale had filled the Appalachian and Michigan basins (figure 58a, Middleton 1987). Quinlan and Beaumont (1984) suggested that during the Late Ordovician, the crustal loading associated with the foreland Appalachian Basin was located to the southeast of the northernmost portion of the Appalachian basin. Cessation of this loading would have allowed upward lithospheric flexure as the thrust sheets were erosionally offloaded. The unloading model of Beaumont *et al.* (1988) allows erosion of proximal sediments while preserving distal sediments (figure 59b) through the creation of an “anti-peripheral bulge”. The area of the “anti-peripheral bulge” would be a site of deposition rather than erosion.

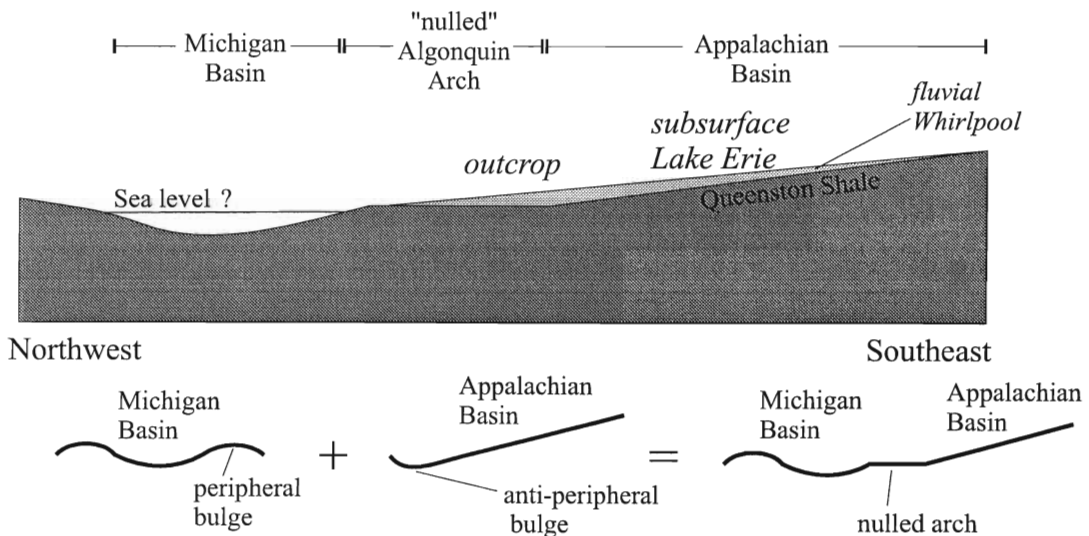
The upward lithospheric flexure would expose sediments deposited in the Appalachian Basin to erosion. The detritus would have been shed, by rivers flowing west through north, away from the site of previous crustal loading. The mature, multi-cyclic texture of the fluvial Whirlpool is explained by this erosion of pre-existing basin sediments (Rutka 1986).

Upward flexure of the lithosphere would have eliminated the Algonquin Arch as a prominent feature at the end of the Ordovician. The interaction between the Appalachian “anti-peripheral” bulge and the intracratonic Michigan Basin peripheral bulge would have “nulled” the Algonquin Arch, removing the topographic high that separates the Appalachian and Michigan Basins (figure 58b). In this scenario, the Algonquin Arch would be a relatively flat area, whereas in the Appalachian Basin, the surface slope would be relatively higher. On the Algonquin Arch there is considerable fluvial Whirlpool extending towards the north, almost as far north as Georgian Bay (Rutka 1986), suggesting that the Algonquin Arch was

a. Latest Ordovician: Michigan and Appalachian Basins are filled with the coastal mudflats of the Queenston Shale.



b. Flexural uplift: An anti-peripheral bulge forms in place of the Appalachian Basin peripheral bulge, nulling the Algonquin Arch; deposition of fluvial Whirlpool; higher slope in the Appalachian Basin promotes deeper incision, while on the "nulled" Arch, there is less incision.



c. Tilting-Reloading: Loading to the south causes tilting (not illustrated), creating a new surface slope towards the west or southwest; activation of the Appalachian Basin peripheral bulge and resultant Algonquin Arch uplift or arching; Deposition of lowstand channel facies of the Whirlpool Sandstone; marine transgression?

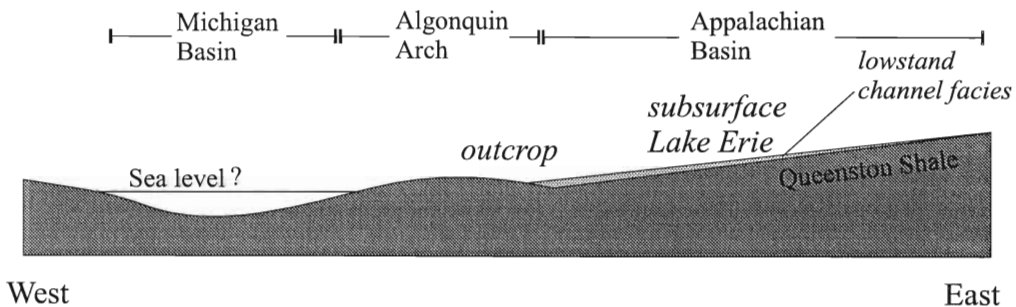
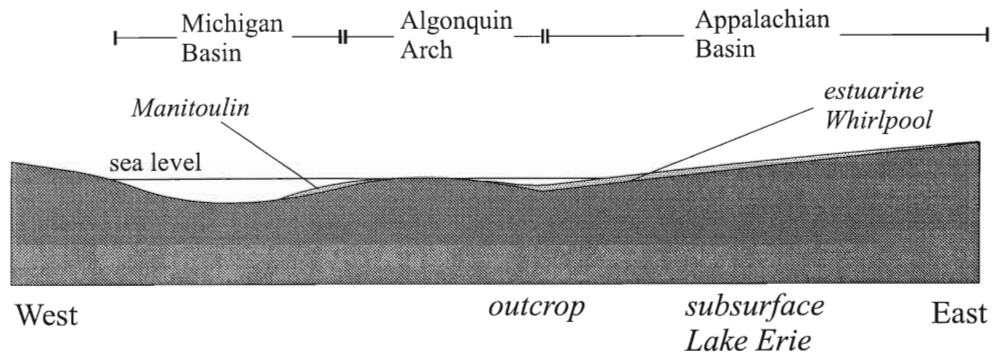
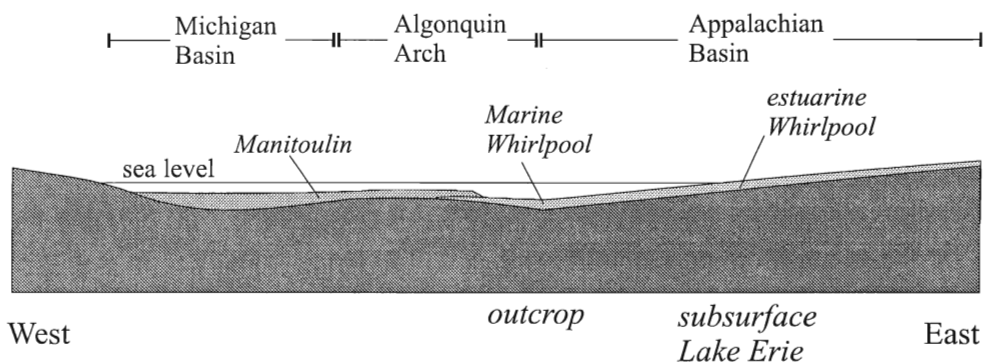


Figure 58. Modeling of the Michigan Basin, Algonquin Arch, and Appalachian Basin spanning the time of deposition for Whirlpool Sandstone.

d. Loading and subsidence of basin: The Appalachian Basin peripheral bulge is in an "uplift" stage (Quinlan and Beaumont 1984) but the basin itself is undergoing overall subsidence; deposition of the estuarine Whirlpool with transgression; deposition of marine Whirlpool; early stage Manitoulin Formation.



e. Algonquin Arch uplift: Tectonic loading leads to a subsiding Appalachian Basin, causing a transgressive systems tract in the estuarine Whirlpool Sandstone; a rising Algonquin Arch that keeps up to the pace of transgression allows progradation of the Manitoulin Formation over the Whirlpool Sandstone.



f. Rapid transgression: Further tectonic loading causes basin subsidence and rapid transgression, abandoning the Whirlpool estuary in an offshore setting; peripheral bulge flexure causes intermittent subaerial erosion in the Manitoulin Formation; Cabot Head Formation deposition over the Whirlpool Sandstone.

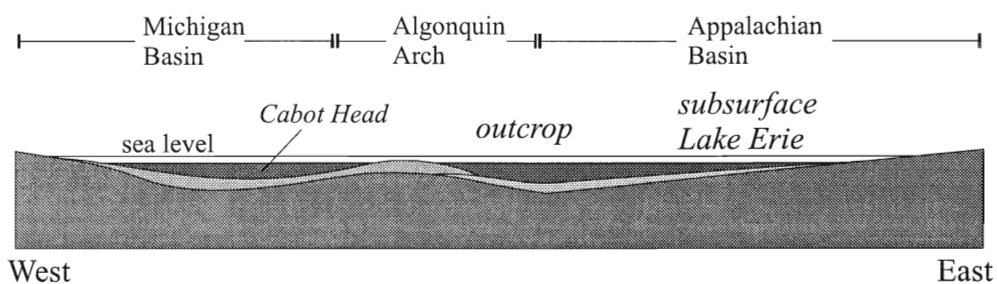


Figure 58 continued. Modeling of the Michigan Basin, Algonquin Arch, and Appalachian Basin spanning the time of deposition for Whirlpool Sandstone.

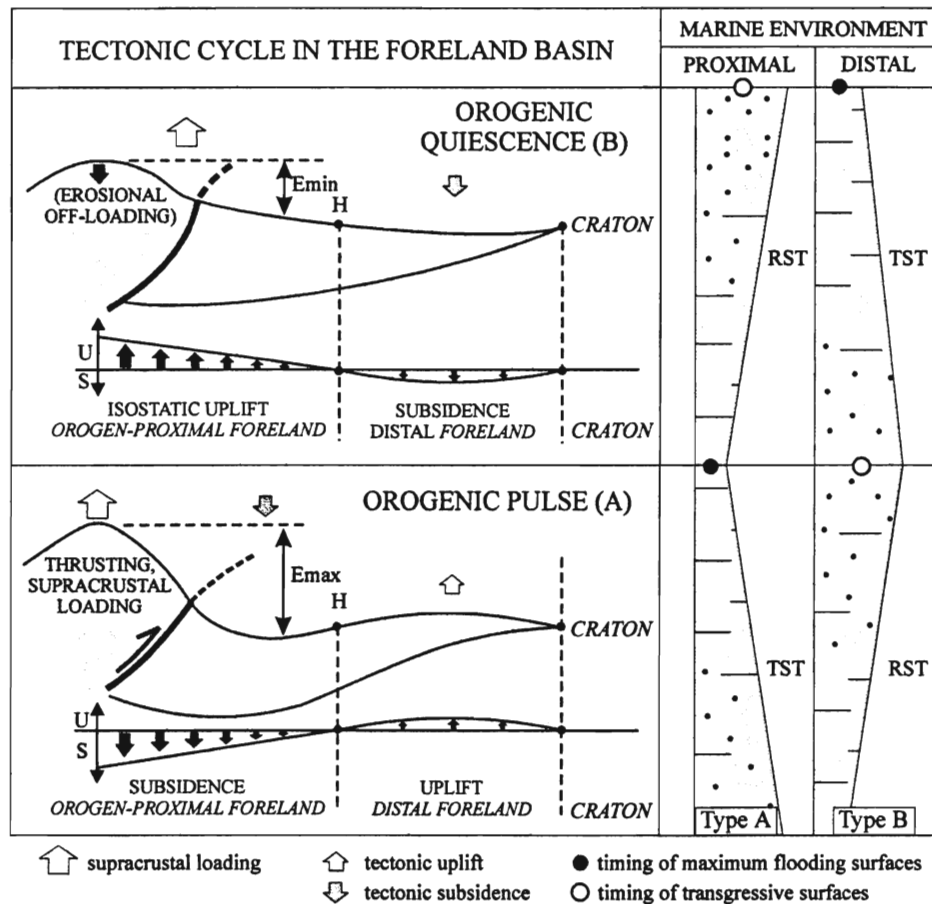


Figure 59. Lithospheric flexure and transgressive-regressive sequences. During an orogenic pulse (A), crustal loading causes transgression in the orogen-proximal portion of the foreland basin and regression in the distal portion of the foreland basin (estuarine Whirlpool deposition). During orogenic quiescence (B) erosional offloading causes regression in the orogen-proximal portion of the foreland basin and transgression in the distal portion of the foreland basin (fluvial Whirlpool deposition). Modified from Catuneanu *et al.* (1997).

not a structural barrier preventing the influx of fluvial sediments from the southeast.

The differing slopes should have had an effect on forms of fluvial deposition. The increased surface slope in the orogen-proximal portion of the basin should have led to greater channeling and valley carving. Based on outcrop, Rutka (1986) noted an increase in fluvial stream competence towards the southeast that suggested greater surface slope. Unlike the braidplain deposits in outcrop (Rutka 1986), the fluvial Whirlpool in subsurface Lake Erie is confined to shallow valleys, suggesting a higher surface slope in the south, closer to the site of erosional offloading. Rutka (1986) also noted that to the northwest, towards and on the Algonquin Arch, the fluvial competence was relatively less and that the fluvial deposits are extensive tabular sands rather than linear channelized sand bodies. This suggests a lower surface slope, possibly due to a “nulled” Algonquin Arch. The break in slope from the uplifted Appalachian Basin onto the “nulled” Algonquin Arch (figure 58b) may have caused the Whirlpool fluvial deposits to change from a more channelized environment into a less confined sandy braidplain setting.

The origin of intracratonic basins, such as the Michigan Basin, is enigmatic, though the role of overthrust loading in a neighbouring foreland basin strongly influences the depositional patterns in an intracratonic basin (Quinlan and Beaumont 1984). Sedimentation patterns would be disrupted on the Algonquin Arch and in the Michigan Basin, and such disruption at the end of the Ordovician is widely reported (Middleton 1987). Laferriere *et al.* (1986) noted karsting at the Ordovician-Silurian boundary in the Michigan Basin in Indiana.

In conclusion, there was a pause in crustal loading during the Taconic orogeny at the end of the Ordovician. Without replacement of loaded material, erosional offloading would have allowed upward lithospheric flexure and exposed Ordovician sediments in the Appalachian Basin to erosion. The shallow valleys of the fluvial Whirlpool in subsurface Lake Erie were

cut into the newly created orogen-proximal slope, whereas the sheet sandstones (Rutka 1986) were deposited on a “nulled” Algonquin Arch.

### **Estuarine-Marine Whirlpool**

There is an obvious difference between the orientation of the fluvial Whirlpool Sandstone shallow valleys and the overlying estuarine complex. They are oriented normal to one another. It is likely that a change in paleoslope took place due to some form of tilting in response to tectonic activity (Cheel and Middleton 1993).

The relative position of the estuarine channels, barrier-foreshore, and shoreface sediments in the Whirlpool Sandstone in subsurface Lake Erie suggests that the offshore direction was towards the west or southwest (figure 44). Cheel and Middleton (1993) concluded that the offshore direction was towards the east or northeast, based on an outcrop study that demonstrates that scours on the erosional surface between the fluvial and marine Whirlpool had a northeasterly to easterly paleocurrent direction. According to their interpretation, the northwesterly dipping slope during the deposition of the fluvial Whirlpool Sandstone was rotated to form a north-northeast trending slope in response to crustal loading towards the east in the northern Appalachians. The presence of brackish channels nested into the top of the fluvial Whirlpool in outcrop near Lockport, New York State (Brett *et al.* 1991) suggests that the marine and brackish Whirlpool in outcrop is similar in age to the estuarine Whirlpool in subsurface.

In subsurface Lake Erie the fluvial Whirlpool Sandstone surficial tilt appears to have changed from a northwest orientation to a west or southwest orientation prior to estuarine deposition. During the late Ordovician most of the tectonic loading was towards the southeast (Beaumont *et al* 1988). A cessation in thrusting probably led to a relaxation phase and uplift that led to the deposition of the fluvial Whirlpool Sandstone. According to



Quinlan and Beaumont (1984), renewed thrusting in the Appalachians in the lower Silurian occurred towards the southeast and south. This additional loading towards the south would probably change the surficial tilt towards the southwest after deposition of the fluvial unit and prior to the deposition of the estuarine Whirlpool. Immediately after this tilting a new fluvial system formed, depositing the lowstand channel facies of the Whirlpool estuary (figure 58c)

During the deposition of the fluvial Whirlpool, the area of the “nulled” Algonquin Arch was not a prominent structural barrier. The marine Whirlpool described in Cheel and Middleton (1993) lies along the side of the Algonquin Arch and is overlain by the Manitoulin Formation. Figure 39 shows that Manitoulin deposition was strongly linked to the Algonquin Arch in subsurface Lake Erie, only appearing on or immediately west of the Arch. Something must have occurred to raise the Arch between fluvial and marine times.

Orogenic activity, as suggested by the tilting after deposition of the fluvial Whirlpool and prior to the deposition of the estuarine Whirlpool, may have reactivated the peripheral bulge (figure 59) from its “anti-peripheral bulge” state during fluvial Whirlpool deposition and re-established the Algonquin Arch as a prominent feature (figure 58c). The peripheral bulges from the Appalachian and Michigan basins began to interact again in an arching or uplift stage (Quinlan and Beaumont 1984). The importance of the Algonquin Arch at the beginning of the Silurian is clearly evident at the west end of the study area (figure 39). Additional crustal loading to the south would be far enough away from the Michigan Basin peripheral bulge such that the Michigan and Appalachian bulges would not yoke but remain separate topographic highs (Middleton 1987). This topographic rise would also occur north of the study area and has been reported in outcrop along the Niagara Escarpment (Liberty and Bolton 1956). Transgression along the Algonquin Arch in outcrop and subsurface would have progressed towards the west (figure 58d). Transgression in areas east of the influence of

the Algonquin Arch would progress towards the east, as in the Whirlpool estuary in subsurface Lake Erie (figure 58d). The marine Whirlpool in outcrop on the Algonquin Arch may have formed on the opposite side of a “seaway” than the estuarine Whirlpool.

No barrier island deposits have been documented in outcrop. In subsurface, there are tidal flat facies underlying the Manitoulin Formation on the Algonquin Arch (figure 56). Rutka (1986) reported the presence of wavy bedding in the marine facies of the Whirlpool in most sections along the Algonquin Arch. This wavy bedded material is probably similar to the tidal flat facies of this study. There appears to be a simple tidal flat setting along the Algonquin Arch during the initial transgression. The lack of a barrier island setting along the Algonquin Arch is likely, considering that the sediment supply for a possible barrier would be low due to a lack of possible source material on the Algonquin Arch. The shoreface Whirlpool Sandstone on the Algonquin Arch in outcrop may have received its detritus from wave ravinement of the fluvial Whirlpool during the initial transgression.

On the western side of the Algonquin Arch, the early Silurian began with deposition of the Manitoulin Formation. The contact between the Manitoulin and underlying Queenston Formation is reported to be sharp and the lowermost portion of the Manitoulin containing mud chips composed of Queenston Shale (Anastas and Coniglio 1992). In the area of the Bruce Peninsula, the Manitoulin Formation is thought to have been deposited in a shallow storm dominated, possibly tidally influenced, setting on a southwest sloping ramp (Anastas and Coniglio 1992). This southwest sloping ramp is the western side of the Algonquin Arch.

Figures 39 and 53 display the sequence stratigraphy of the estuarine and shoreface Whirlpool Sandstone along with the lower portions of the Manitoulin Formation. In figures 39 and 53 it appears that the lower portion of the Manitoulin Formation prograded over the Whirlpool Sandstone and offshore facies of the Cabot Head Formation. This could be

explained by flexural response of the lithosphere to crustal loading as described in Catuneanu *et al.* (1997; figure 59) who suggested that in the orogen-proximal area of the basin, subsidence occurs and creates a marine transgression and transgressive sequence. In the orogen-distal portion of the basin, uplift occurs with the rising of a peripheral bulge. This uplift in the distal portion of the basin creates a relative sea level fall and a regressive sequence. The Algonquin Arch became a prominent feature in the early Silurian and further uplift may have resulted in local sea level regression and in the progradation of the Manitoulin Limestone over the deeper water facies of the Whirlpool and Cabot Head formations (figure 58e).

A question arises as to whether tectonic activity is responsible for rapid transgression and deposition of the Cabot Head Formation over the Whirlpool Sandstone. Unconformity-bounded units in bioherms of upper portions of the Manitoulin Formation (Grawbarger 1978) and numerous hardgrounds throughout the Manitoulin Formation (Anastas and Coniglio 1992) suggest fluctuating sea levels. There is only slow transgression evident in the Whirlpool Sandstone, which is followed by rapid transgression and Cabot Head Formation deposition, with no evidence for other fluctuations in the Whirlpool Sandstone itself. There are several fifth-order, internal, transgressive sequences in the Cabot Head Formation immediately above the Whirlpool Sandstone (Brett *et al.* 1990). In the above paragraph, a regressive sequence on the Algonquin Arch during Whirlpool Sandstone deposition was linked to supracrustal loading and peripheral bulge flexure. The transgressive sequences of the Cabot Head Formation could very well compliment the erosional surfaces in the Manitoulin Formation on the Algonquin Arch (figure 59) using the same logic from the previous paragraph, instead this time, regression led to subaerial exposure and erosion. This suggests that tectonic activity strongly influenced sea levels on the Algonquin Arch, and that

it probably was also influential in sea level change after deposition of the Whirlpool Sandstone in the Appalachian Basin.

The estuarine Whirlpool is probably Early Llandoveryan in age, because it is equivalent to the lower portions of the Manitoulin Formation which has been reported as being Early Llandoveryan in age (Copper 1982, and Eley and Legault 1988). Based upon one brachiopod species, Copper (1982) dated the initial transgression as earliest Llandoveryan in age (Rhuddanian), suggesting that the transgression occurred extremely close to the Ordovician-Silurian boundary, but definitely above it. This date of initial transgression is based upon biostratigraphy and is more reliable than the dating for the initial transgression in Dorsch and Driese (1995) which used no biostratigraphy.

The tidal flat facies that widely overlies the initial transgressive surface of the Whirlpool in subsurface Lake Erie has interesting implications. This surface exists under the siliciclastic wedge in the main part of the basin and under the carbonate bank on the Algonquin Arch. The presence of a tidally influenced transgressive surface as the base of the Silurian succession raises an important implication about the nature of the epeiric seaway that existed at the initiation of Medina Group deposition. It suggests that there was a tidal influence in the epeiric seaway as sea level rose and estuarine sedimentation began.

Future research must examine the role of the Algonquin Arch and early Silurian sedimentation in the Appalachian Basin. In particular, how did tectonics affect the sedimentology of the Manitoulin Formation which was deposited on the Algonquin Arch? Also, did the Algonquin Arch remain raised throughout deposition of the Medina and Cataract groups and if it did eventually fall, when did it subside and what effects did this have on sedimentology in the Appalachian Basin?

### ***Significance to Natural Gas Exploration***

The results of the study are extremely valuable in exploration and exploitation of natural gas reserves in subsurface Lake Erie. The recognition of a large estuarine unit in subsurface may be particularly useful for future exploration.

Compared to outcrop, the northwest flowing fluvial system is not extensive in subsurface, most likely due to erosion prior to deposition of the estuarine unit. However, the fluvial valleys do exist and follow a predictable trend that can be recognized on the isopach map. These valleys filled with thick units of clean quartzose sand that are good exploration targets. Well 64-W of cross-section 64W-88G (figure 30) pierces one of these valleys and is a producer of natural gas. The only problem with these fluvial valleys is that there is not much exploration potential left. The valleys have been extensively exploited by oil and gas companies. The westernmost valley could still have exploration potential towards the southeast of well 88-G (figure 33).

The estuarine unit of the Whirlpool Sandstone provides intriguing possibilities for natural gas exploration. The wide range of sedimentary environments it encompasses is important. First to be considered are the estuarine valleys. These have already been widely exploited, but the south of Crystal Beach there is still considerable potential (figure 9). In this area the Whirlpool estuarine valley sands are thick and porous. The southern valley is considerably thinner but may also have potential for exploration and, because of the higher structural elevation, there should be little water or oil present.

Not widely reported for the estuarine Whirlpool is the presence of a bayhead delta or tidal sand ridges. These have not been recognized, but exploration in their likely location at the head of the estuarine valleys as they enter into the lagoon in block 37, is sparse and they may still be undiscovered. This could provide a whole new area for exploration.

The tidal flat facies has low potential for gas exploration. The relatively high shale content in this facies reduces the permeability of the sandstone. Tidal flats also contain thin, laterally discontinuous sandstone bodies.

Lagoonal sediments have a limited potential for exploration. Obviously, the shaly units are not potential targets. However, according to Reinson *et al.* (1988), sandy bay fill sediments can be significant producers of hydrocarbons. Even though the presence of the sandy bay fill of the backbarrier facies in the Whirlpool Sandstone appears to be spatially limited, it is a possible target.

Washover deposits may also have potential for production. They are mainly horizontally laminated and would be good conduits for hydrocarbons. Because washover fans exist in a lagoonal environment, such sands may contain significant amounts of shale reducing the reserve potential. Also, the washover sands tend to have low porosity, which is discouraging for exploration purposes.

A flood-tidal delta has not been recognized in the estuarine Whirlpool. Like the bayhead delta and tidal sand ridges, the areas where flood-tidal deltas may be present have not been well explored.

The greatest potential for exploration is most likely through the exploitation of transgressed or stillstand tidal inlets. The porous sand of an abandoned inlet is illustrated through well logs and core for well 68-Q-2A (figure 40). The sands in these tidal inlets appear clean and porous (figure 43) and normally contain hydrocarbons. On the isopach map (figure 9), in block 23, there is a lobate body, behind the barrier island. The morphology of this sand body suggests that it may be made up of the deposits of a flood-tidal delta. No core exists from this body so determination of its depositional environment is speculative. Immediately southwest of this body is a long lobate shape that may be the remains of a tidal

inlet. This possible inlet is largely unexploited and could be a good hydrocarbon producer.

The barrier island itself would normally be of great potential in the search for natural gas because of the foreshore unit's clean, well sorted sandstone and lateral extent make it a very predictable target. However, the foreshore unit has a very low porosity and production of natural gas has not been successful. The foreshore unit appears in core from wells 39-T, 39-W, 39-Y, and 72-O. The reason for this low porosity is unclear.

The shoreface sandstone facies of the Whirlpool Sandstone has no producing wells. Shoreface sand ridges have not been recognized in subsurface. Reworked estuarine deposits also do not appear to be producers. The Manitoulin Formation is not known as a producer of natural gas in subsurface Lake Erie, though in outcrop it is known to leak bitumen and is composed of bioherms and patch reefs (Anastas and Coniglio, 1992). The Cabot Head Formation has very few gas wells from subsurface Lake Erie due to its general very low porosity.

## CONCLUSIONS

The lower Silurian Whirlpool Sandstone is composed of two overall units: a fluvial unit and an estuarine to marine transitional unit. The lowermost unit is a sandy braided fluvial system flowing towards the northwest and is confined to shallow valleys. The channels are largely filled by cross-bedded, well sorted, quartzose sands, with little ripple cross-laminated or overbank deposits. Erosionally overlying this lower unit is an estuarine to shoreface complex. In the east, the unit consists of estuarine channels and tidal flat deposits. The channels consist largely of cross-bedded quartzose sands and change in vertical sequence from fluvial to brackish deposits. The tidal flat or overbank deposits consist largely of coarsely interlayered sandstones and shales with less common lenticular, wavy and flaser bedded sandstones and shales. To the west the tidal flats pass into backbarrier facies. This unit consists of shale to muddy sandstone displaying a restricted ichnofauna association. Associated with the backbarrier are extensive washover deposits containing horizontally laminated and convolute bedded sandstone. Separating the backbarrier facies from shoreface sandstone facies is a barrier island sandbody. The shell fragment rich sands are horizontal to low angle laminated, representing an ancient foreshore. The barrier is dissected by tidal inlets showing fining upward abandonment sequences. These inlets also appear to the west of the barrier, on the shoreface. On the west side of the barrier, the Whirlpool Sandstone is predominantly the deposit of a shoreface environment displaying a high diversity and high abundance of ichnofauna. The sandy marine deposits are replaced by marine carbonates westwards. The offshore direction is towards the west or southwest.

The estuary generally displays a change from terrestrial to marine influence in vertical sequence. The sequence boundary is overlain by the lowstand systems tract deposits of the lowstand channel facies. The transgressive surface is then overlain by transgressive systems



tract deposits of the tidal flat facies or estuarine channel facies. Slow, erosive transgression caused barrier island deposits to erosively backstep over backbarrier deposits. Further transgression caused the backbarrier deposits to be exposed to erosion on the shoreface. Subsequently, processes on the transgressing shoreface caused the shoreface sandstone facies to erosively overly the backbarrier and tidal flat deposits over a wave ravinement surface. Several tidal inlets are abandoned on the shoreface from east to west. The tidal inlets incise pre-existing estuarine material, in many instances removing the sequence boundary and the transgressive surface; the tidal inlet deposits overlie a tidal ravinement surface. A stillstand systems tract is suggested by tidal inlets outside of the transgressed shallow valley and by the inlet abandonment sequence at the preserved barrier ending with a foreshore sandstone. Sharply overlying the estuary are offshore sandstones and shales of the Cabot Head Formation that were deposited after a final transgression which dragged the wave ravinement surface on the upper shoreface over the barrier island and other landward deposits.

A hiatus in crustal loading during the Taconic orogeny in the latest Ordovician led to erosion and a relaxation phase causing isostatic rebound. The isostatic rebound caused a relative drop in sea level leading to the Cherokee Unconformity. This rebound also distributed the eroded material towards the west, northwest and north as the terrestrial deposits of the fluvial Whirlpool. The “anti-peripheral bulge” of the rebound interfered with the peripheral bulge of the Michigan Basin, causing minor uplift and nulling the Algonquin Arch and allowing the detritus of the fluvial Whirlpool to spread onto the nulled Algonquin Arch via a braided fluvial system.

The Taconic Orogeny resumed in the earliest Silurian with crustal loading to the south and southeast. This caused tilting of the surface slope in subsurface Lake Erie towards the southwest. Lowstand deposits were scoured into the new slope. The renewed crustal loading

reactivated the peripheral bulge of the Appalachian Basin allowing it to interact with the bulge of the Michigan Basin. This allowed rejuvenation of the Algonquin Arch as an important feature of the northern Appalachian Basin. The crustal loading depressed the Appalachian basin and allowed marine transgression to occur. The renewed Algonquin Arch allowed the early Silurian transgression to proceed up two slopes, one to the east and one to the west. The transgression towards the east entered the lowstand valleys and created the estuarine Whirlpool. Further crustal loading caused a final rapid marine transgression, abandoning the Whirlpool estuary under offshore sediments of the Cabot Head Formation. Later relative sea level drop created the Tuscarora unconformity and truncated the fluvial Whirlpool Sandstone from locations south of northeastern Pennsylvania, giving the Whirlpool the appearance of a pinchout.

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## **APPENDIX 1: Palynological Analysis**



**Palynological Analyses**  
**of Two Shale Samples**  
**From the Whirlpool Formation**  
**in Cores From Lake Erie**

by

**William G. Parkins**

## **Introduction**

Two samples of shale from the Whirlpool Formation obtained from cores drilled in the area of Lake Erie were submitted for palynological analysis. It is hoped that the results obtained from these analyses yield more data on the depositional environment of each sample.

## **Method**

Table I lists the samples submitted and the weight of each sample used. Each sample was crushed to coarse sand size fragments and placed in a 10 percent solution of HCl for 24 hours in order to remove as much of the carbonates as possible from the sample. The solution was decanted off and the remaining residue was washed three times in distilled water. The residue was then placed in a 25 percent solution of HF at room temperature for 14 days to remove the silicates from the sample. The resulting residue was centrifuged and washed three times in distilled water. The sample was then placed in a 5 micron sieve and the fine fraction which passed through the sieve was discarded. A small drop of the remaining residue was mounted on a glass slide in corn syrup. Three slides were made for each sample. Each slide was examined at 100 X and 200 X under a light transmitting microscope and any palynomorphs that were present were identified.

## **Results**

Both sample 64-W-4 and sample 64-P yielded a fairly abundant and diverse assemblage of palynomorphs. Preservation varied from poor to excellent in both samples although preservation was slightly better on average in sample 64-P. Table 2 lists the palynomorphs recovered from sample 64-W-4 while Table 3 lists those from sample 64-P.

## Discussion

Sample 64-W-4 produced a moderately diverse assemblage of spores and spore-like palynomorphs as well as a small number of other miscellaneous objects. No acritarchs or other definite marine microfossils were observed.

By far the most common palynomorph in this assemblage was Leiosphaeridia spp. (Table 2). Unfortunately, these microfossils are so simple morphologically that one cannot determine if any given form is an acritarch or a monad spore. This distinction is important since acritarchs occur in predominantly marine environments while spores would indicate a freshwater-terrestrial environment. Exactly the same problem was encountered by Strother and Traverse (1979) in the shales of the Llandoveryan Tuscarora Formation of eastern Pennsylvania and by Miller and Eames (1982) in the shales of the Medina Group at Lewiston, N.Y. in the Niagara Gorge.

The spore-like palynomorphs recovered from this sample present another problem. Most of them resemble monad, diad, and tetrad spores. However, these particular forms are known only from a limited number of sites, namely those of Strother and Traverse (1979) and Miller and Eames (1982). Thus they cannot be used for correlation except on a limited basis and are, at present, of little use in determining the age of the sample. Both Strother and Traverse (1979) and Miller and Eames (1982) believed that the spore-like palynomorphs were derived from “pre-vascular” terrestrial or semi-aquatic plants. However, both studies carefully pointed out that until these palynomorphs have been found in the sporangia or conceptacles of plant macrofossils preferably of Early or Middle Silurian age, that no definitive proof of their origin in terrestrial or freshwater environments exists and one can only state with caution that the environment was probably or possibly terrestrial or freshwater.

The assemblage includes the trilete spore Tetrahedraletes medinensis. Such trilete spores are known only from bryophytes and other primitive terrestrial plants. One should still be cautious, however, since these spores form only a small portion of the palynomorph assemblages. The absence of definitive marine microfossils, the dominance of spore-like palynomorphs and the presence of Tetrahedraletes in this assemblage would indicate that sample 64-W-4 was probably deposited in a freshwater-terrestrial environment.

Sample 64-P produced a diverse assemblage of spores and spore-like palynomorphs as well as a few acritarchs and three scolecodont jaws (Table 3). The observations and cautions concerning the spore-like palynomorphs discussed for sample 64-W-4 are equally relevant in this sample. The trilete spore Tetrahedraletes medinensis is again present but more common in this assemblage. In addition, well preserved acritarchs which are strictly marine palynomorphs are sparsely represented. Finally, scolecodonts were recovered from the sample. Scolecodonts are the jaws of errant polychaete worms, a group of mostly marine annelids (Barnes 1987).

The spore-like palynomorphs cannot be used to determine the age for 64-P for reasons stated in the discussion of 64-W-4. The taxonomy of scolecodonts jaws has been in a state of disarray for a long time and are therefore also useless for age determination. The acritarchs in 64-P are the same as those found by Miller and Eames (1982) in the Niagara Gorge. These acritarchs were either long ranging or known only from the Medina Group itself and were therefore no aid in determining the age of the rock.

Since acritarchs and scolecodonts denote a marine environment and the spore-like palynomorphs possible terrestrial-freshwater environments and since sample 64-P contained all three types of microfossils it would appear that this interval was deposited in a nearshore, possibly estuarine, possibly brackish water environment. The fact that most of the acritarchs

were acanthomorphs also supports a nearshore environment. One peculiar aspect of the assemblage, however, is the very low number of acritarchs compared to scolecodonts. In the vast majority of cases, one would expect the acritarchs to outnumber the scolecodonts by at least an order of magnitude. A possible explanation would involve a flood discharging into an estuary or a similar nearshore environment. The site of deposition would lie at or near the distal end of the flood where the current energy would be sufficient to re-suspend the clay and fine silt fraction of the bottom which would be transported seaward out of the deposition site. This would also remove most of the light, tiny acritarchs while leaving the heavier scolecodonts behind. Also the fangs and dentacles of the jaw elements would tend to snag the bottom making them even more difficult to remove. At the same time spore-like palynomorphs would settle out of the freshwater-terrestrial derived flood water.

### **Conclusions**

Sample 64-W-4 was probably deposited in a freshwater-terrestrial environment. Sample 64-P was probably deposited in a nearshore, possibly brackish water, possibly estuarine environment.

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**Table 1: samples submitted for palynological analyses**

<b><u>Sample No.</u></b>	<b><u>Weight Used (gm)</u></b>
64-W-4	5.1
64-P	4.8

**Table 2: Palynomorphs recovered from sample 64-W-4****Spores and Spore-like Palynomorphs**

Dyadospora murusattenuata Strother and Traverse 1979 (4 specimens)  
Dyadospora murusdensa Strother and Traverse 1979 (5 specimens)  
Nodospora burnhamensis Strother and Traverse 1979 (18 specimens)  
Nodospora oyleri Strother and Traverse 1979 (one specimen)  
Nodospora cf N. retimembrana Miller and Eames 1982 (one specimen)  
Nodospora cf N. rugosa Strother and Traverse 1979 (2 specimens)  
Rugosphaera ? cerebra Miller and Eames 1982 (5 specimens)  
Tetrahedraletes medinensis Strother and Traverse 1979 (5 specimens)  
Vermiculatisphaera cf V. obscura Miller and Eames 1982 (one specimen)

**Palynomorphs of Uncertain Affinity**

Leiosphaeridia sp. B Miller and Eames 1982 (3 specimens)  
Leiosphaeridia spp. (57 specimens)

**Miscellaneous**

large unidentified thick walled sphere (one specimen)  
 cyanobacteria-like sphere (2 specimens)  
 algae-like filament (one specimen)  
 thin, reticulate cuticle (one specimen)  
 cylindrical tube (2 specimens)  
 conical chitinous tube (one specimen)  
 clump of 3 cells (one specimen)  
 clump of 4 cells (one specimen)  
 clump of 5 cells (one specimen)  
 chain of 6 cells (one specimen)  
 elongate clump of 8 cells (one specimen)  
 unidentified (one specimen)



**Table 3: Palynomorphs recovered from sample 64-P****Acritarchs**

- Multiplicisphaeridium sp. C Miller and Eames 1982 (2 specimens)  
Multiplicisphaeridium sp. (one specimen)  
Retisphaeridium ? fragile Miller and Eames 1982 (one specimen)  
Veryhachium europaeum Stockmans and Williere 1960 (one specimen)

**Spores and Spore-like Palynomorphs**

- Dyadospora murusattenuata Strother and Traverse 1979 (5 specimens)  
Dyadospora murusdensa Strother and Traverse 1979 (9 specimens)  
Nodospora burnhamensis Strother and Traverse 1979 (25 specimens)  
Nodospora cf N. olyeri Strother and Traverse 1979 (one specimen)  
Nodospora retimembrana Miller and Eames 1982 (3 specimens)  
Rugosphaera ? cerebra Miller and Eames 1982 (10 specimens)  
Rugosphaera tuscarorensis Strother and Traverse 1979 (3 specimens)  
Tetrahedraletes medinensis Strother and Traverse 1979 (16 specimens and one tetrad)  
 undescribed trilete spore with reticulate ornamentation (one specimen)

**Palynomorphs of Uncertain Affinity**

- Leiosphaeridia sp. B. Miller and Eames 1982 (2 specimens)  
Leiosphaeridia spp. (72 specimens)

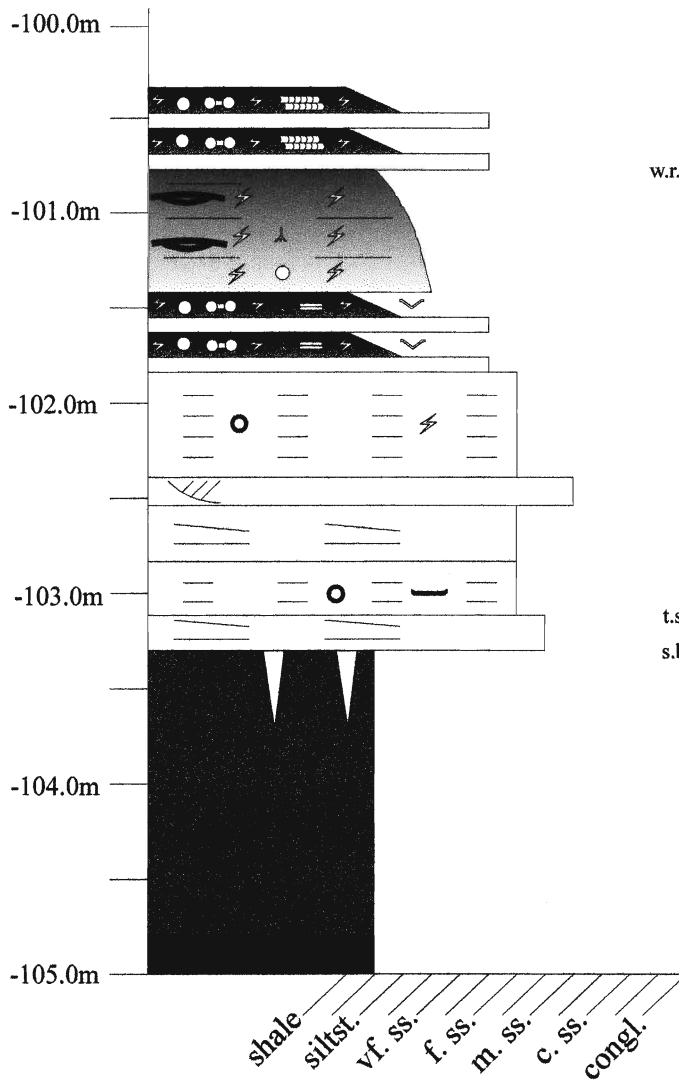
**Miscellaneous**

- scolecodont jaw (3 specimens)  
 cylinder with spiral ornament, Strother and Traverse 1979, pl. 3, No. 14 (2 specimens)  
 large chiton-like sheet (one specimen)  
 clump of 3 cells (2 specimens)  
 clump of 4 cells (one specimen)  
 clump of 7 cells (one specimen)

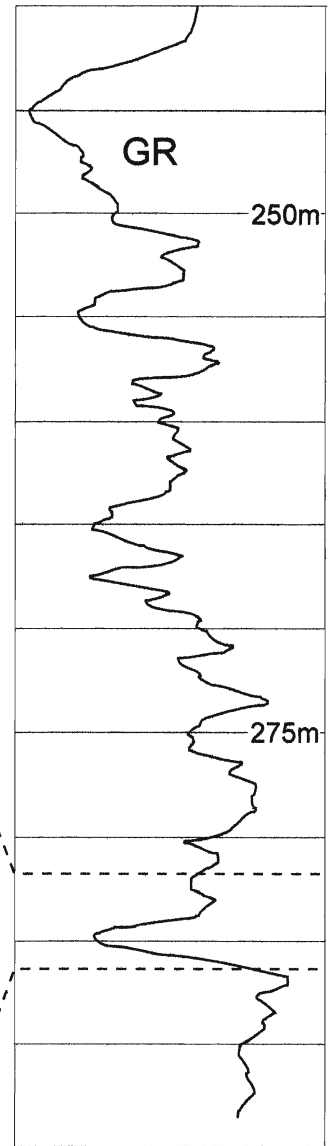
## **APPENDIX 2: Core Sections**

Well Name: Anschutz Lake Erie 5-X  
 Block Number: 5-X  
 K.B. elevation: 182.58m a.m.s.l.

Subsea elevation

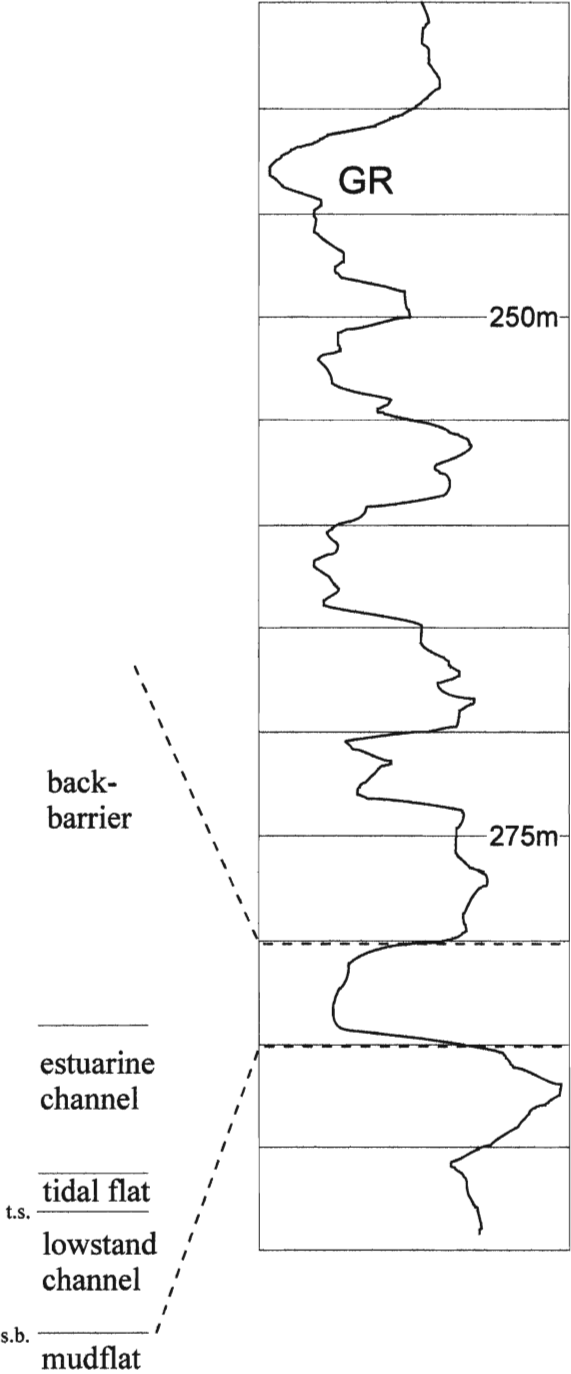
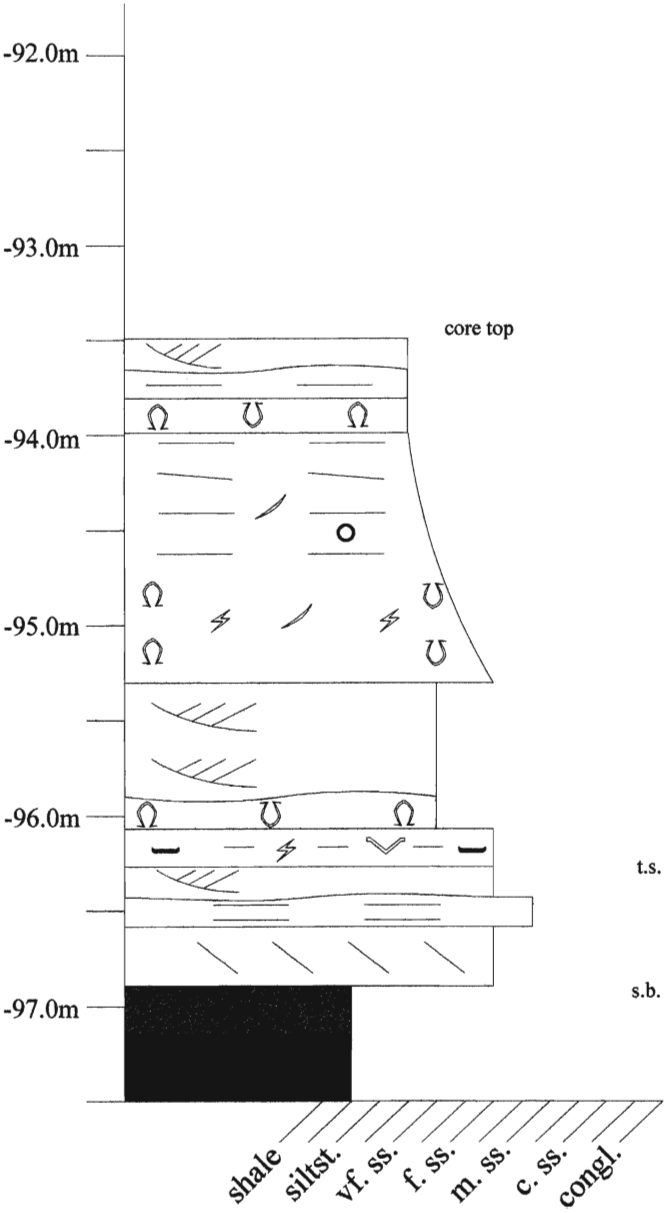


offshore  
 w.r.s. back-barrier  
 tidal flat  
 estuarine channel  
 tidal flat  
 t.s. lowstand  
 s.b. mudflat



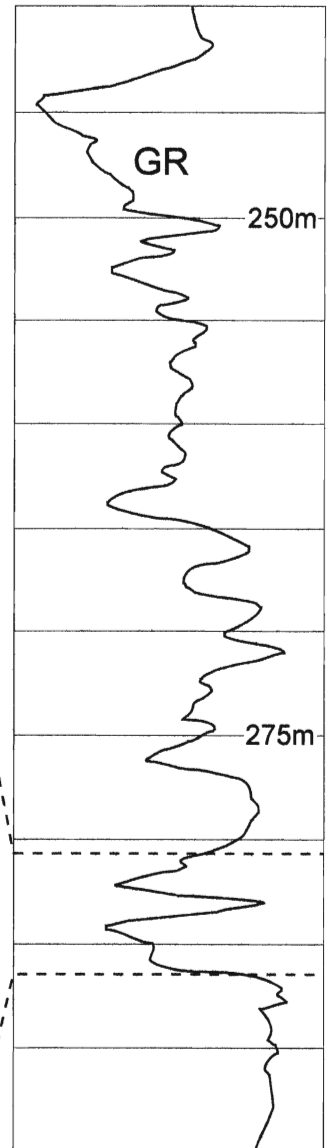
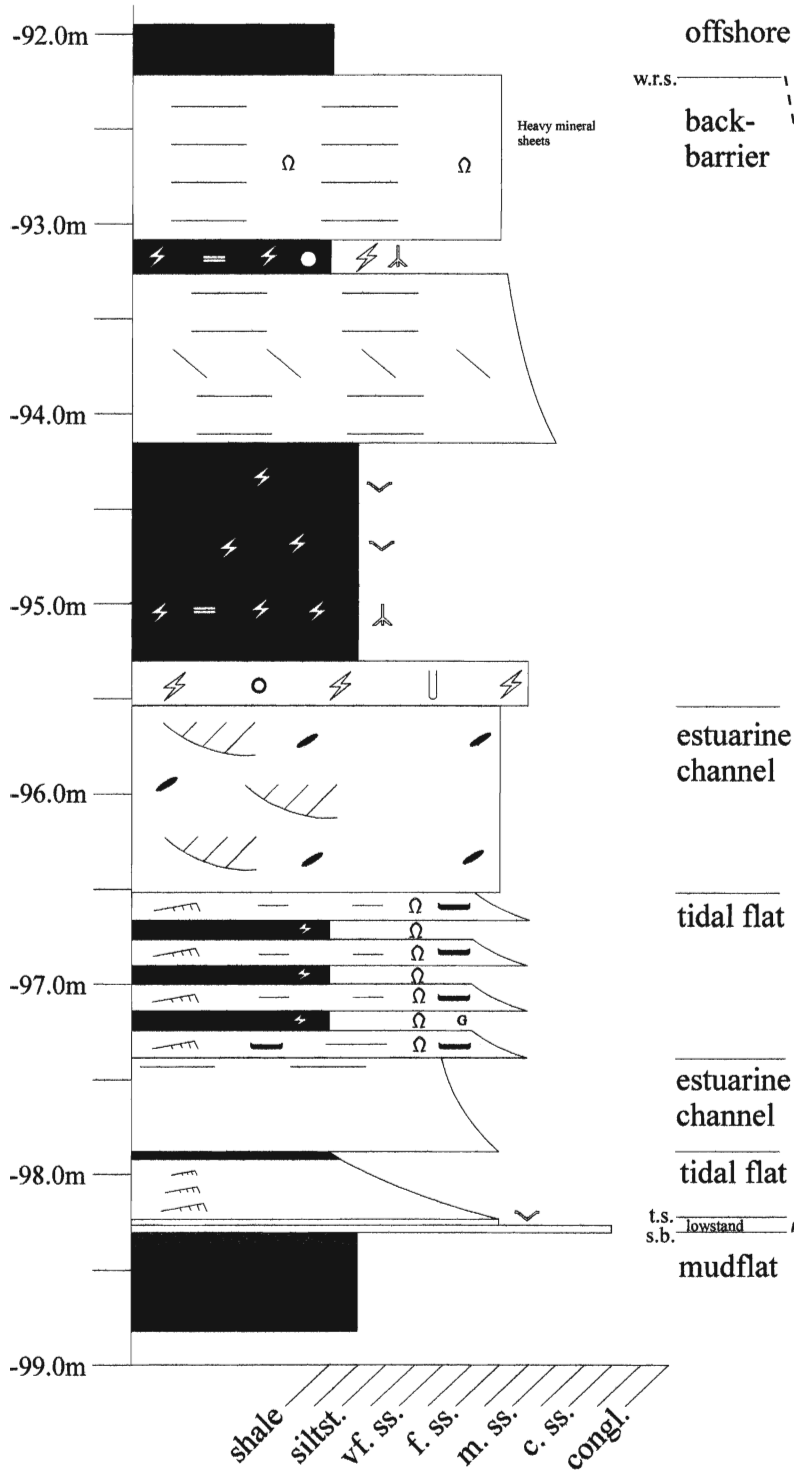
Well Name: Anschutz Lake Erie 6-R  
Block Number: 6-R  
K.B. elevation: 187.76m a.m.s.l.

Subsea elevation



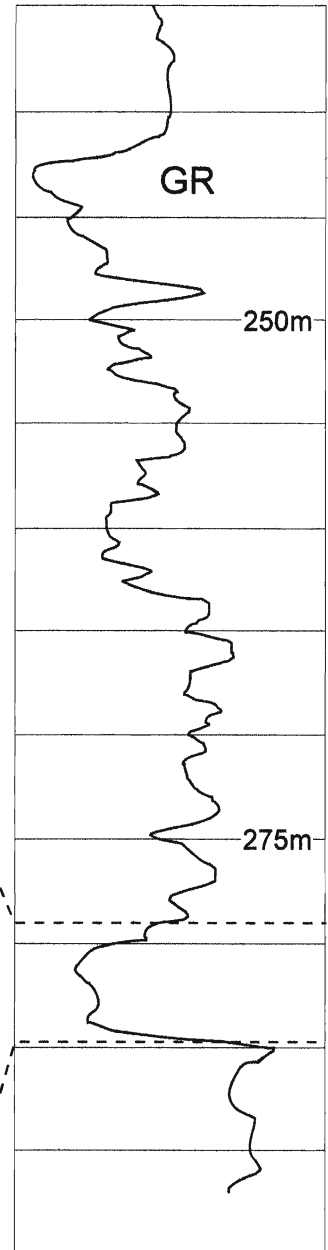
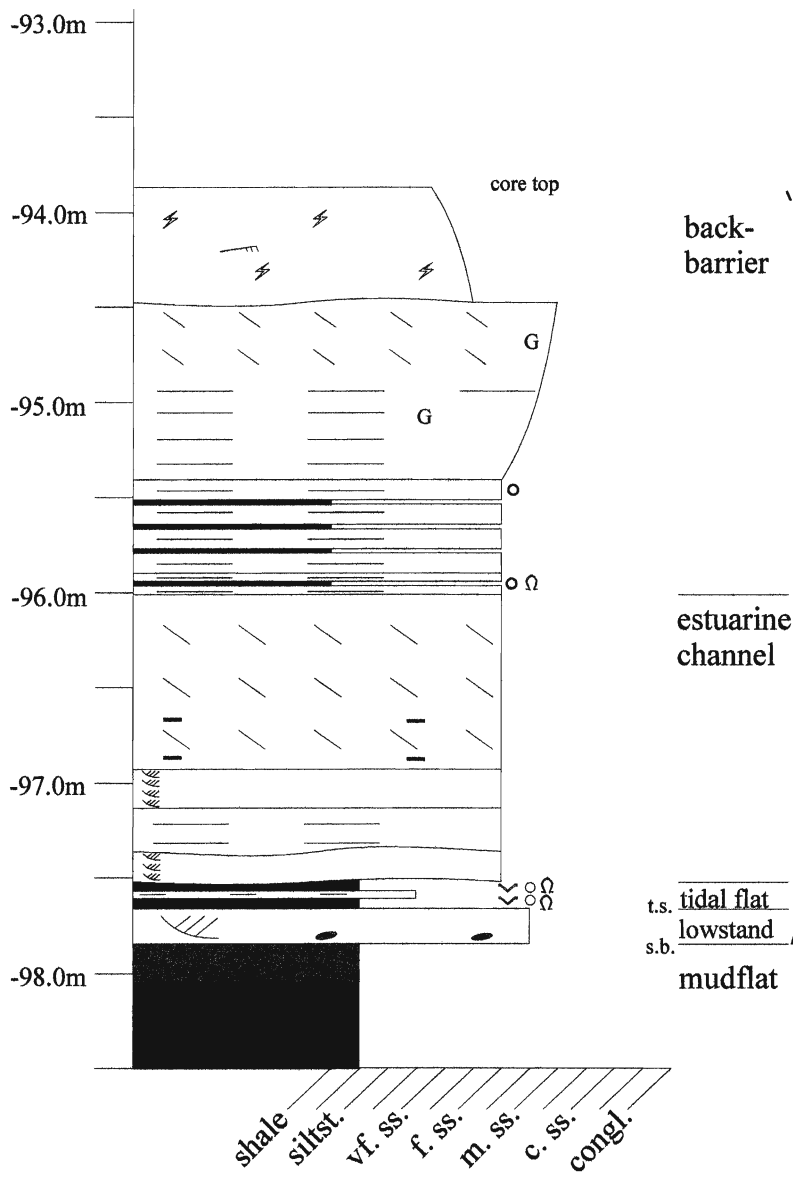
Well Name: Anschutz Lake Erie 7-Y  
Block Number: 7-Y  
K.B. elevation: 188.37m a.m.s.l.

Subsea elevation



Well Name: Anschutz Lake Erie 8-V  
 Block Number: 8-V  
 K.B. elevation: 187.15m a.m.s.l.

Subsea elevation

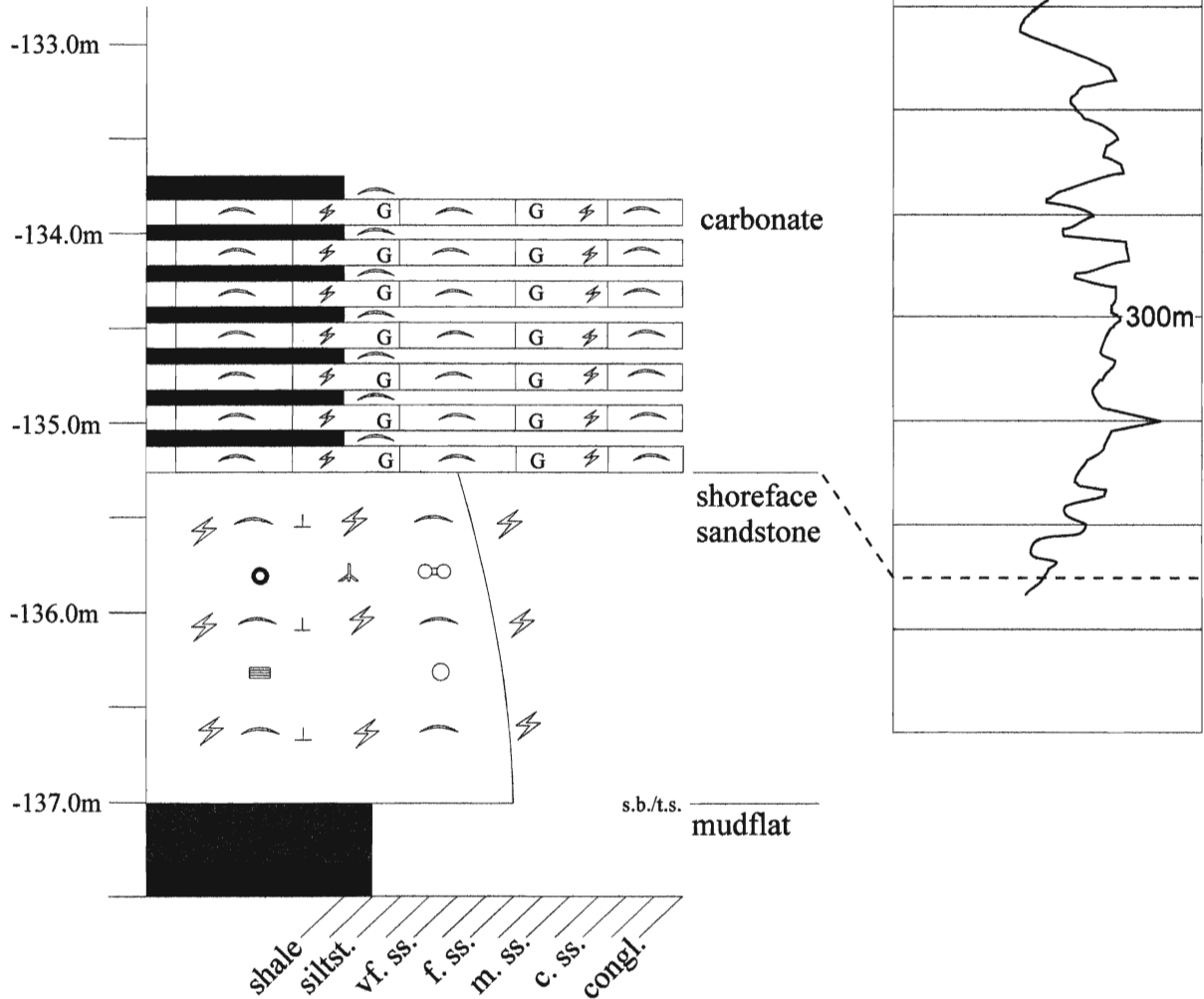


Well Name: Long Point Port Dover No. 3

Block Number: 14-S-3

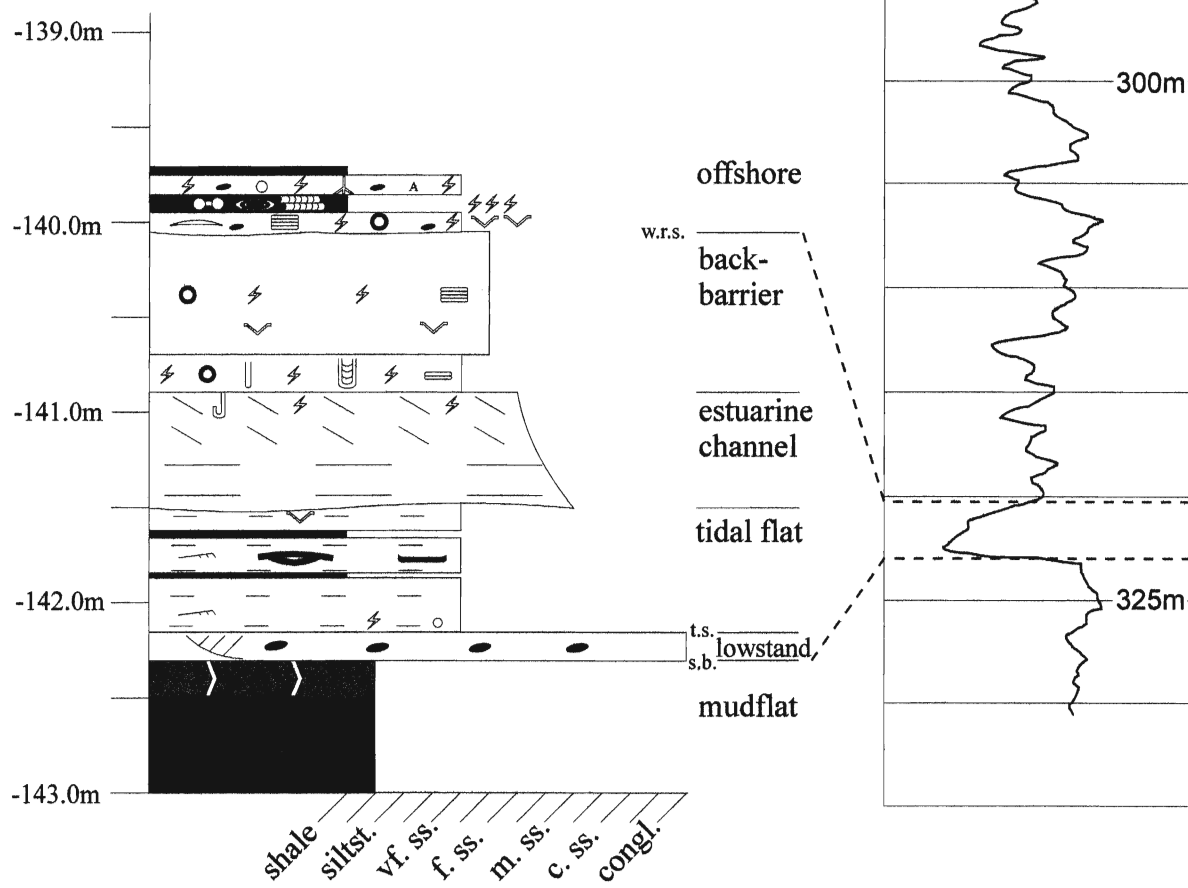
K.B. elevation: 177.39m a.m.s.l.

Subsea elevation



Well Name: Pembina Lake Erie 21-X-2  
 Block Number: 21-X-2  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



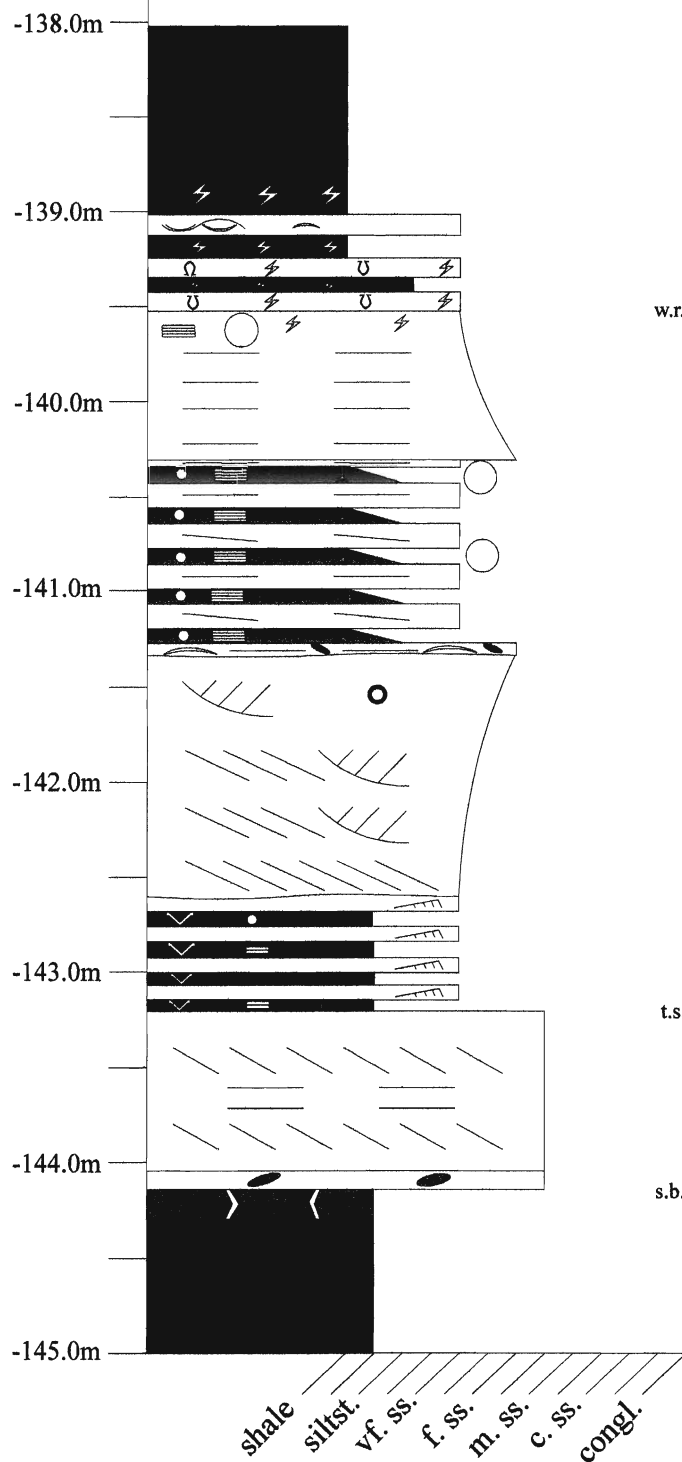


Well Name: Anschutz Lake Erie 22-S

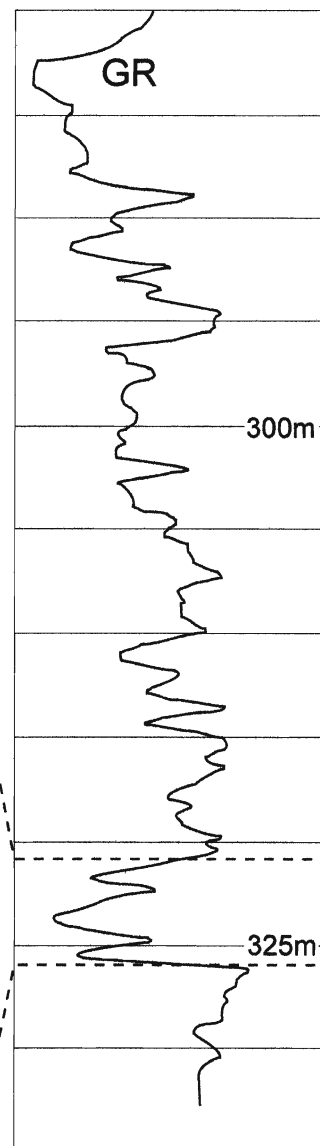
Block Number: 22-S

K.B. elevation: 182.0m a.m.s.l.

Subsea elevation

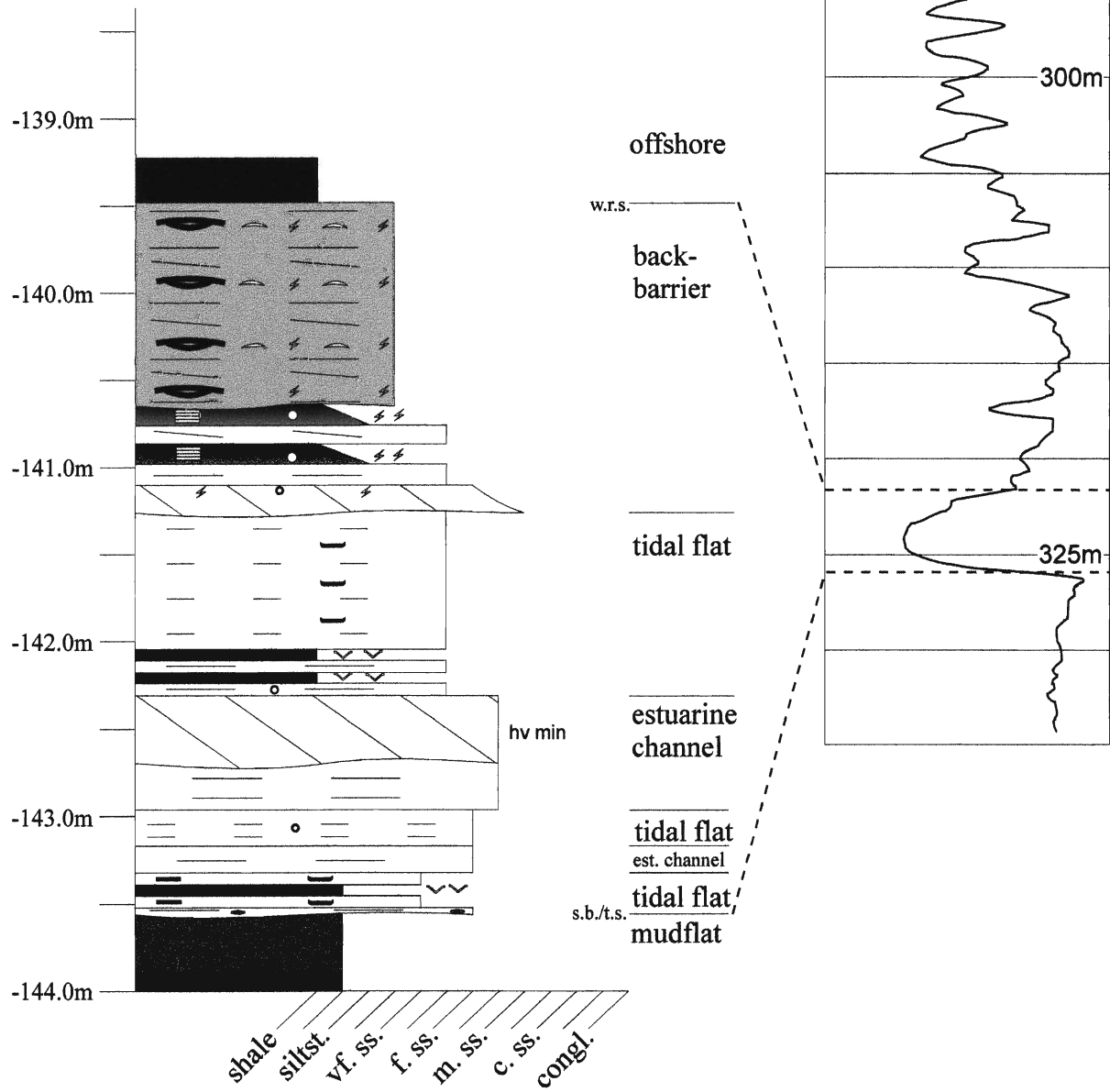


offshore  
w.r.s.  
barrier-foreshore  
back-barrier  
estuarine channel  
tidal flat  
t.s.  
lowstand channel  
s.b.  
mudflat



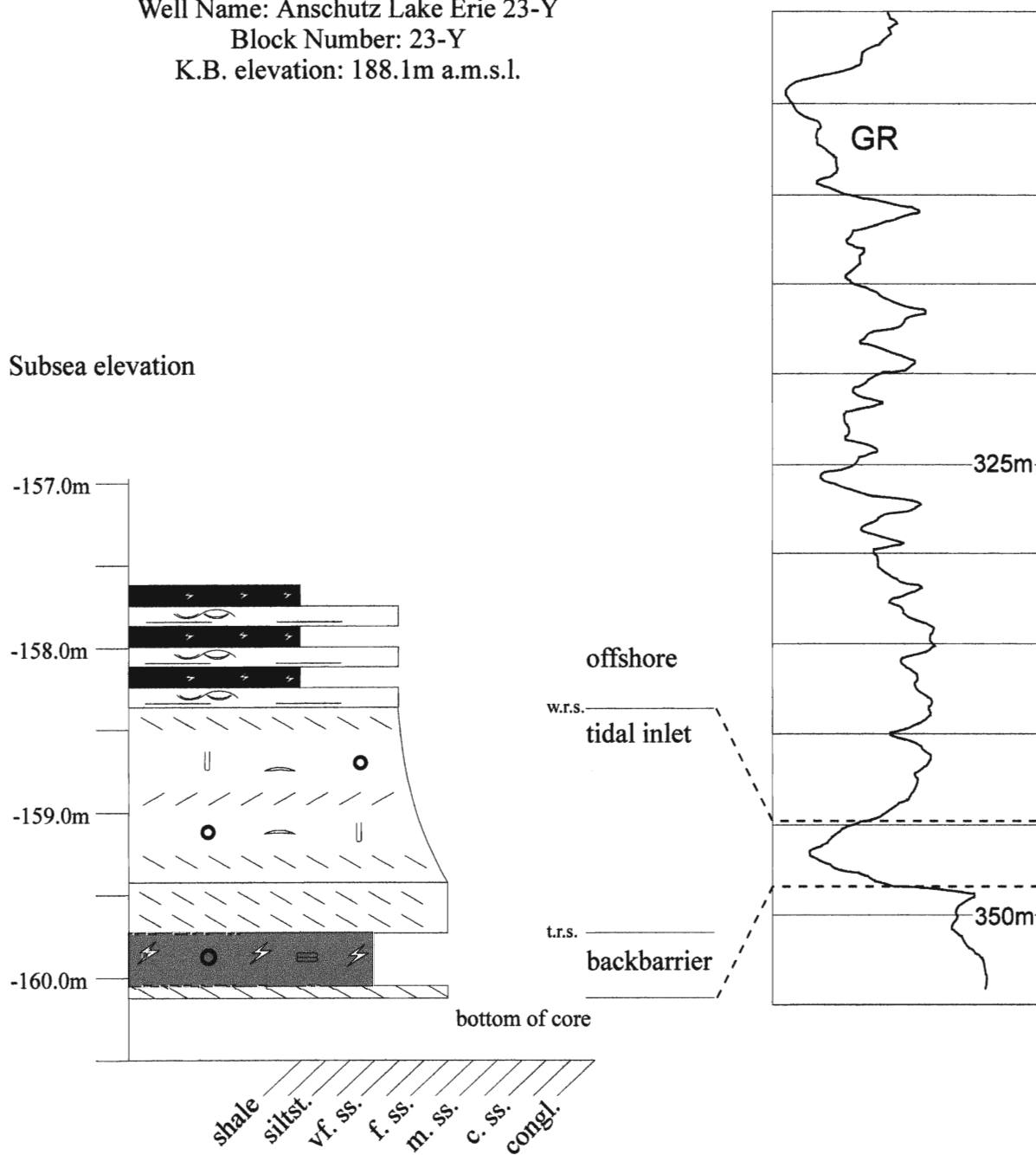
Well Name: Anschutz Lake Erie 23-S  
 Block Number: 23-S  
 K.B. elevation: 182.58m a.m.s.l.

Subsea elevation



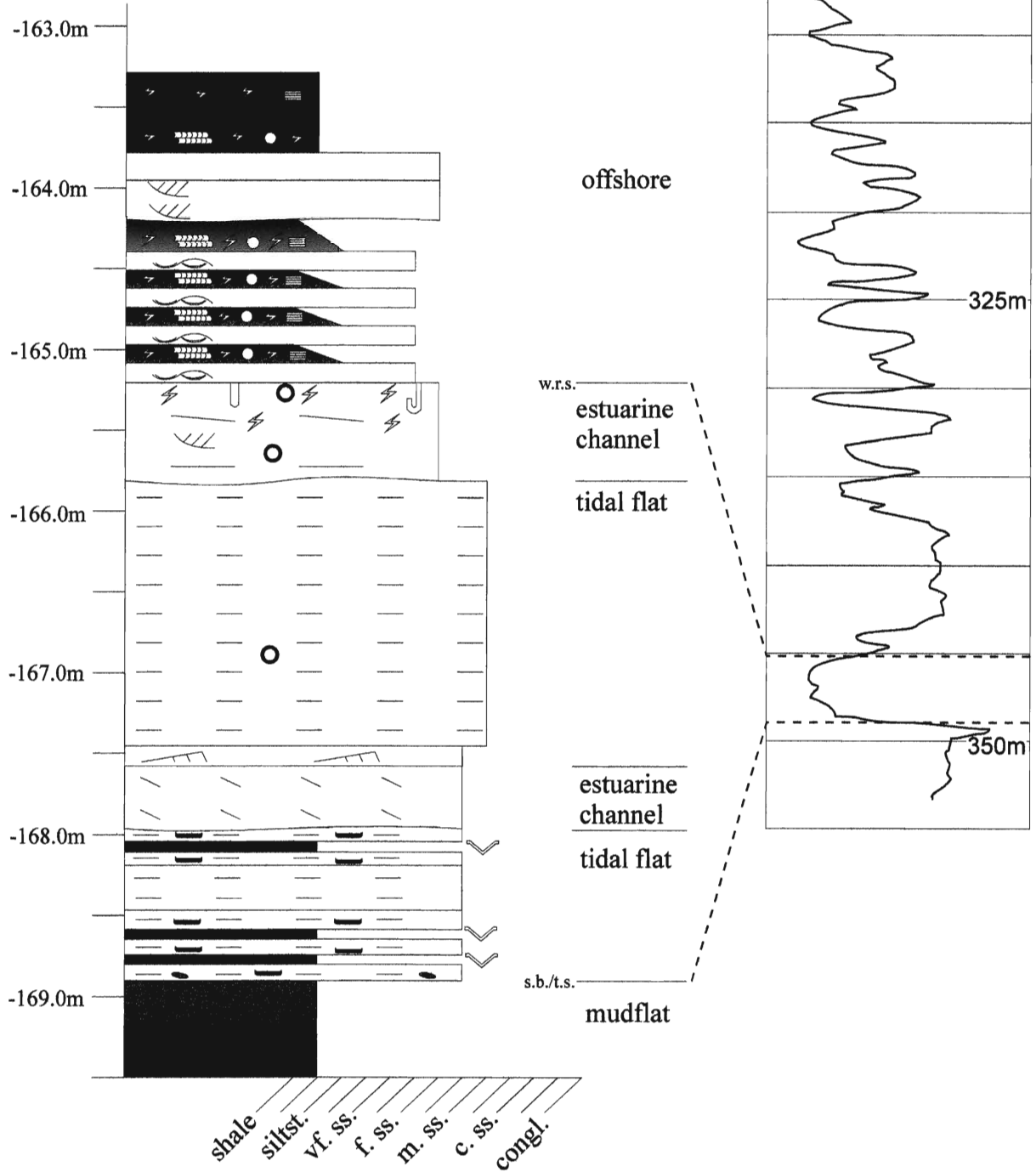
Well Name: Anschutz Lake Erie 23-Y  
 Block Number: 23-Y  
 K.B. elevation: 188.1m a.m.s.l.

Subsea elevation



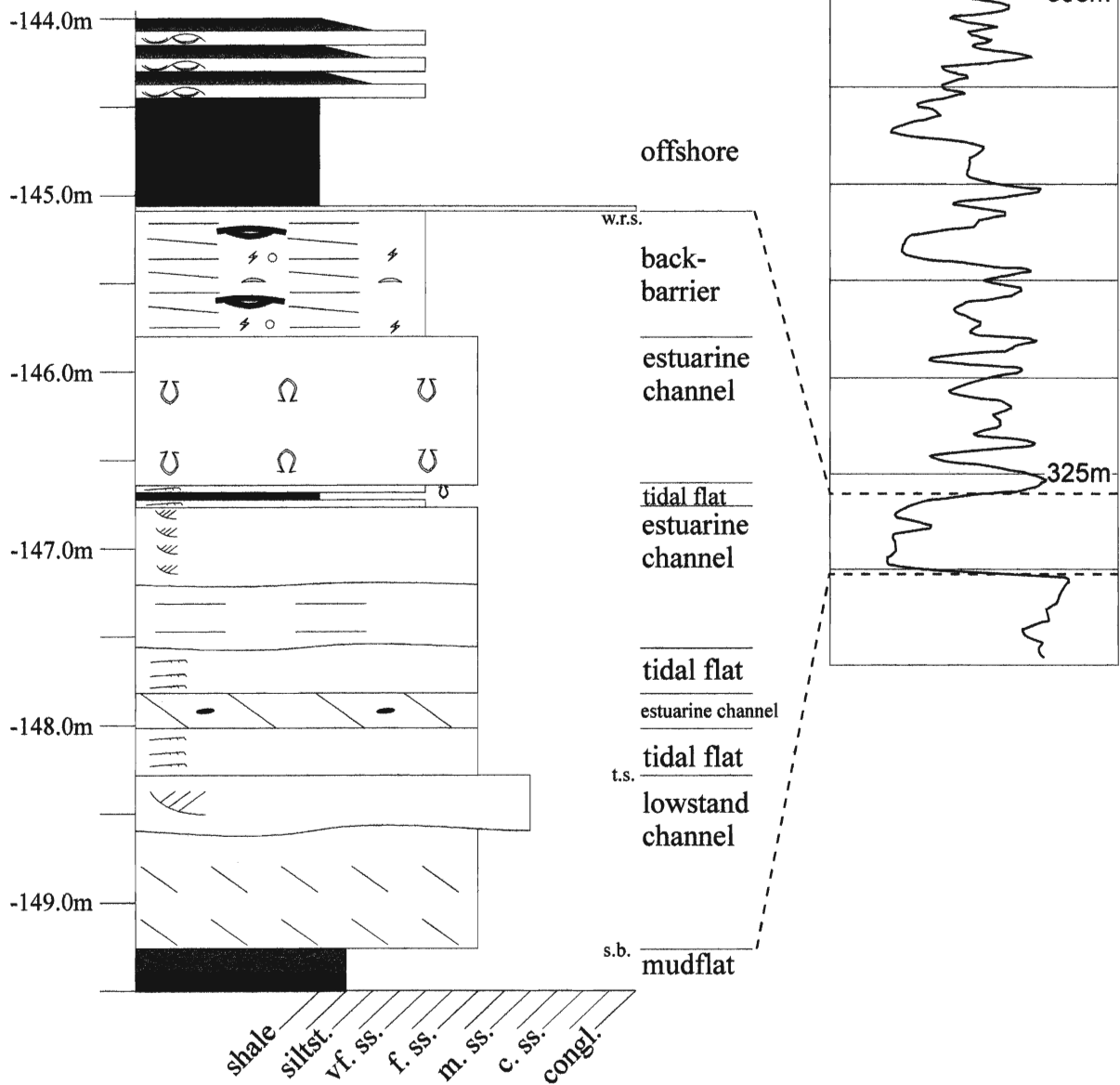
Well Name: Pembina Lake Erie 24-V-1  
 Block Number: 24-V-1  
 K.B. elevation: 180.40m a.m.s.l.

Subsea elevation



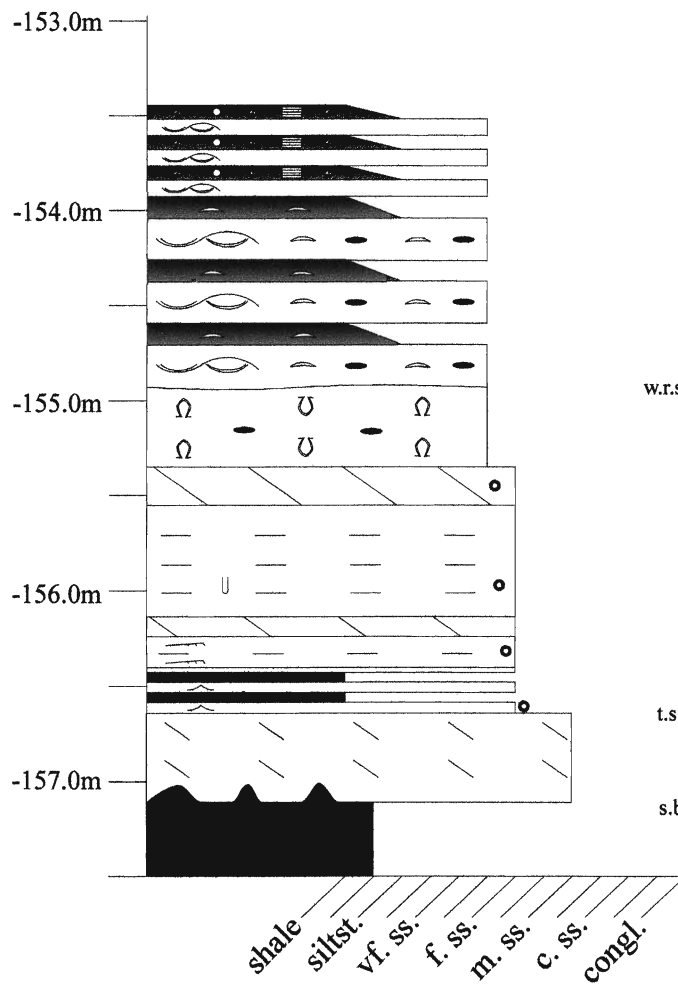
Well Name: Pembina East Lake Erie 26-M-1A  
 Block Number: 26-M-1A  
 K.B. elevation: 180.89m a.m.s.l.

Subsea elevation



Well Name: Pembina East Lake Erie 26-S-1B  
 Block Number: 26-S-1b  
 K.B. elevation: 180.89m

Subsea elevation



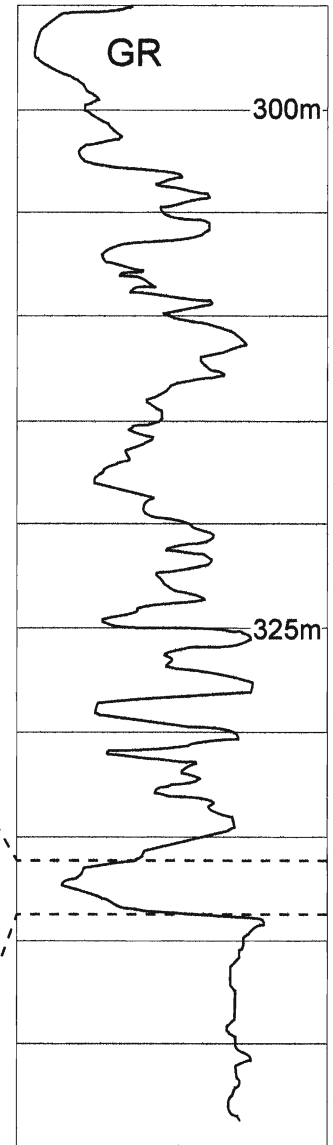
offshore

w.r.s. ———  
 estuarine  
 channel

—————  
 tidal flat

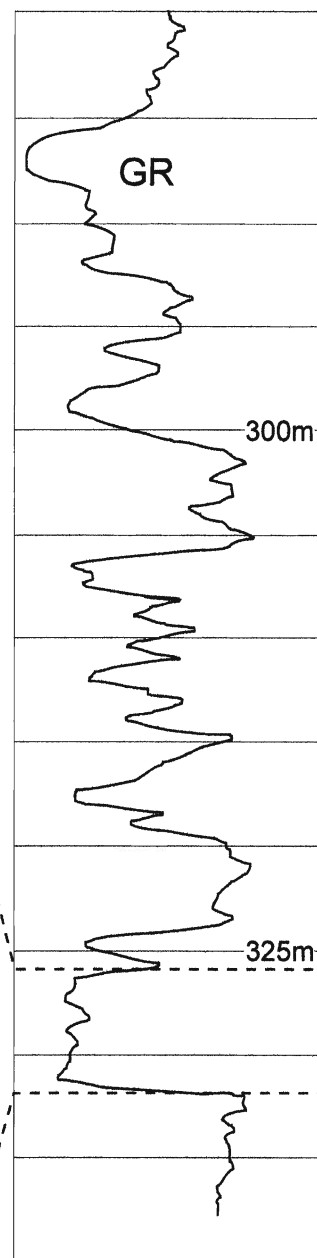
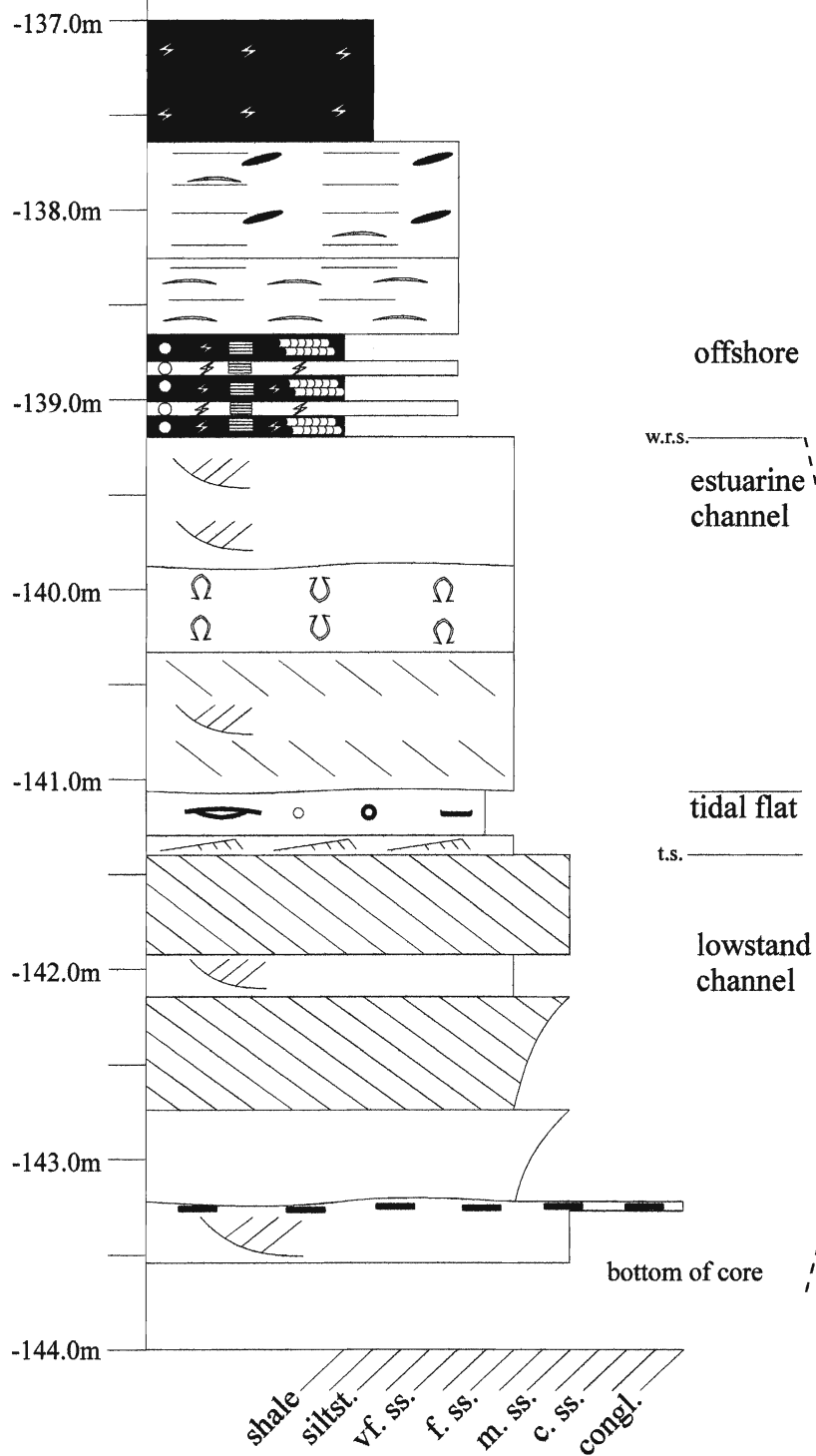
t.s. ———  
 lowstand  
 channel

s.b. ———  
 mudflat



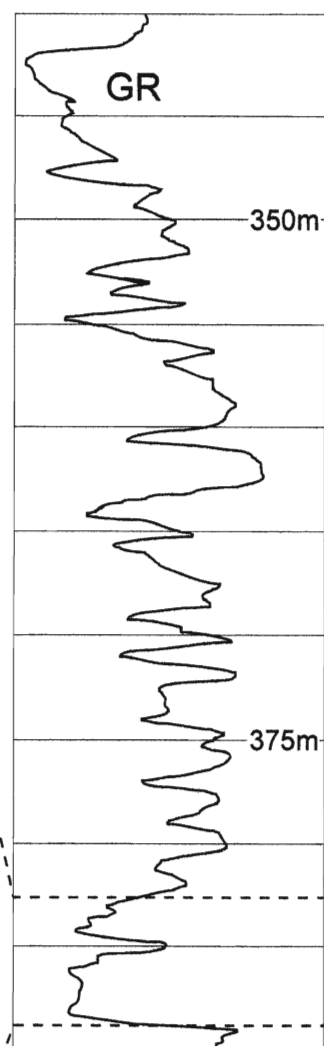
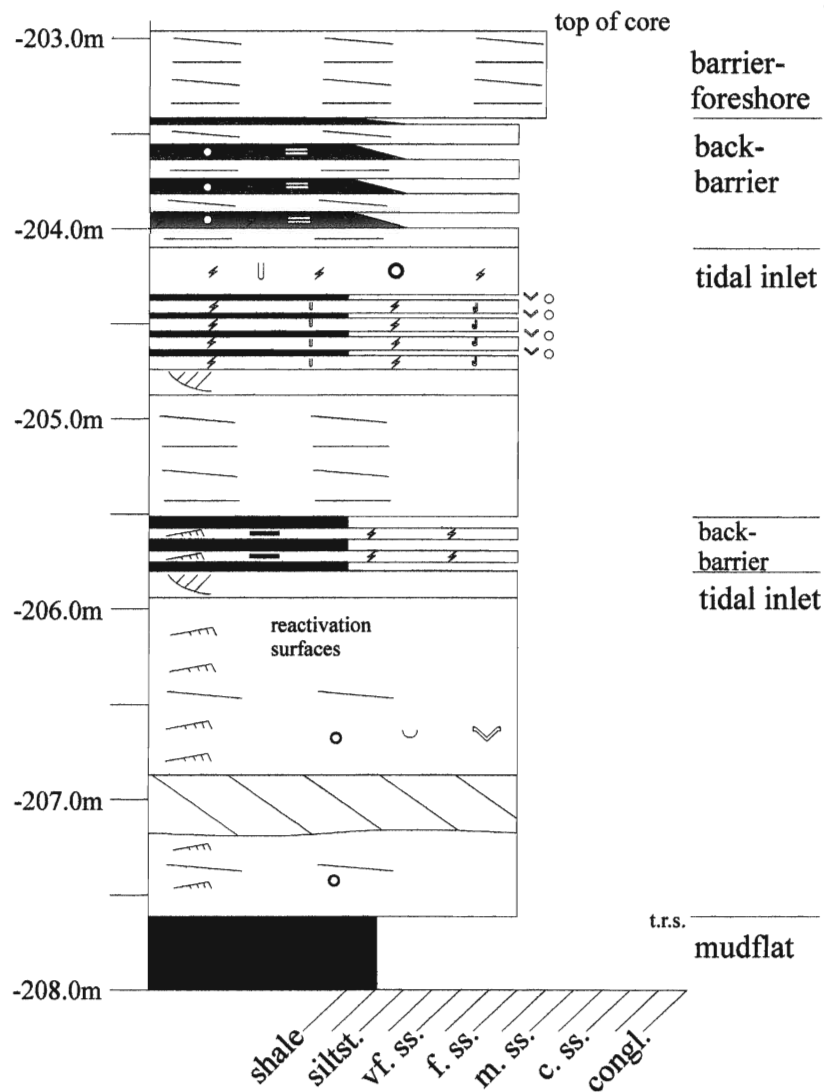
Well Name: Consumers 31841  
 Block Number: 27-G  
 K.B. elevation: 187.45m a.m.s.l.

Subsea elevation



Well Name: Pembina East Lake Erie 39-T-2  
 Block Number: 39-T-2  
 K.B. elevation: 180.9m a.m.s.l.

Subsea elevation



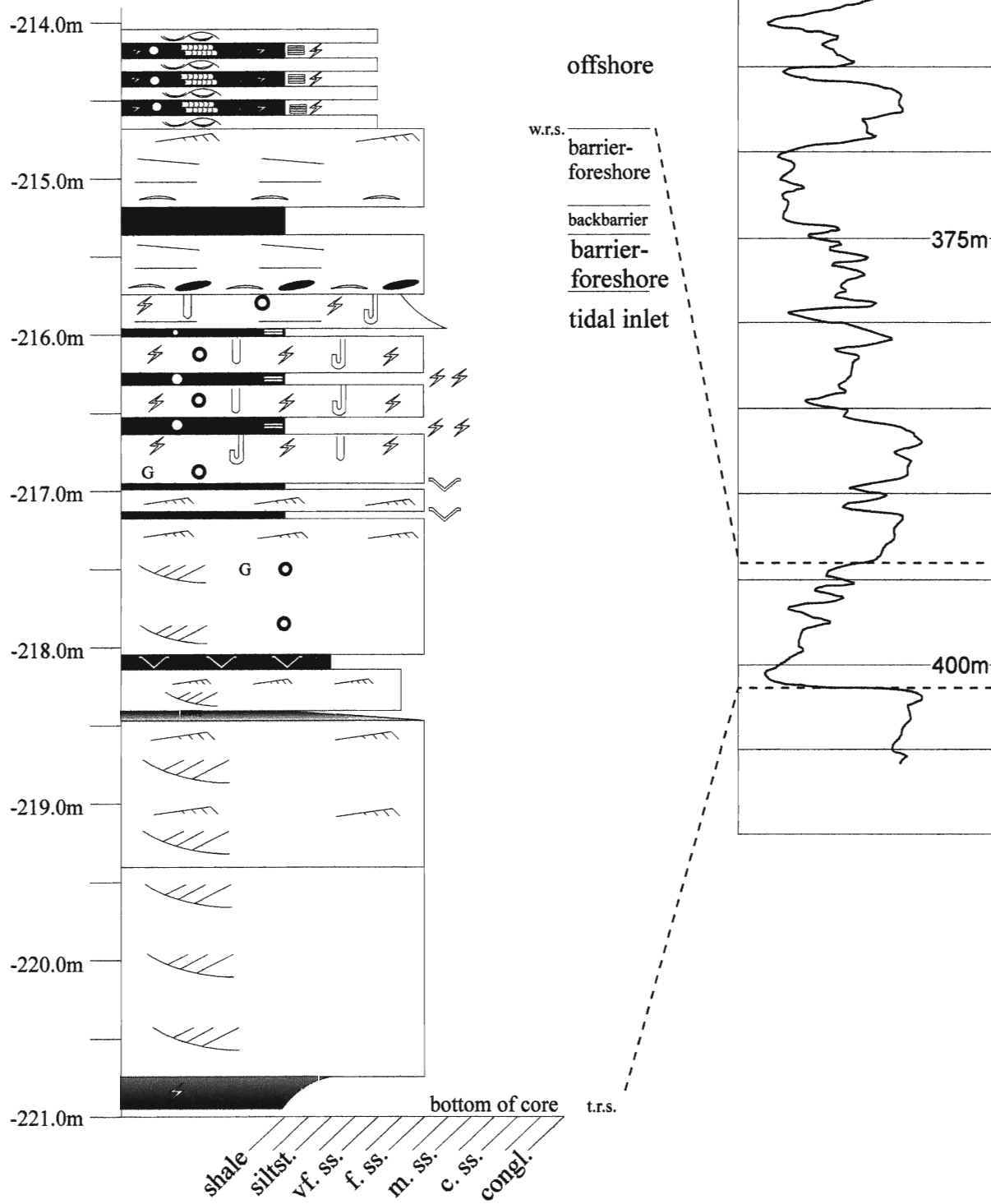


Well Name: Pembina #3 LE 39-W

Block Number: 39-W

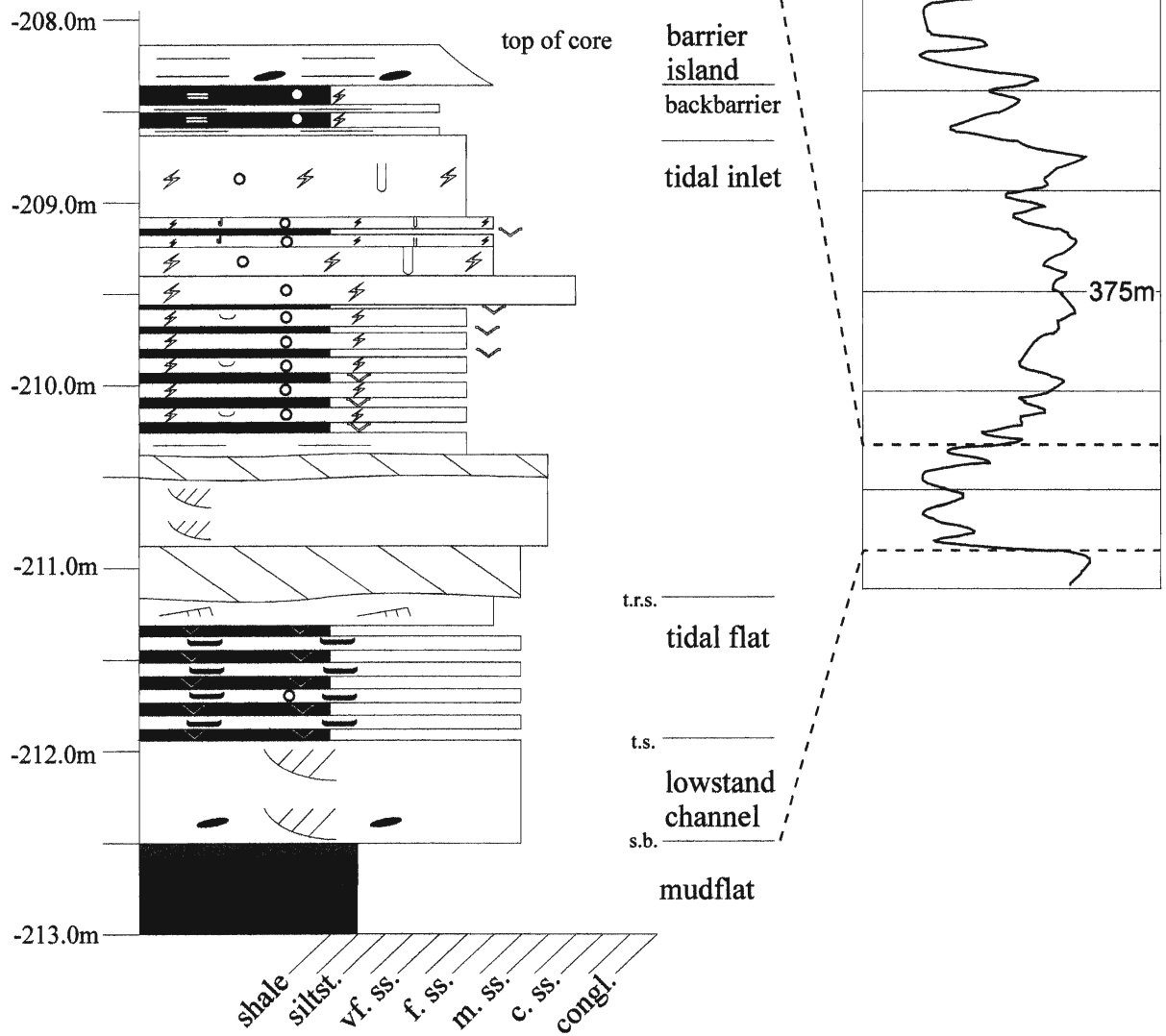
K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



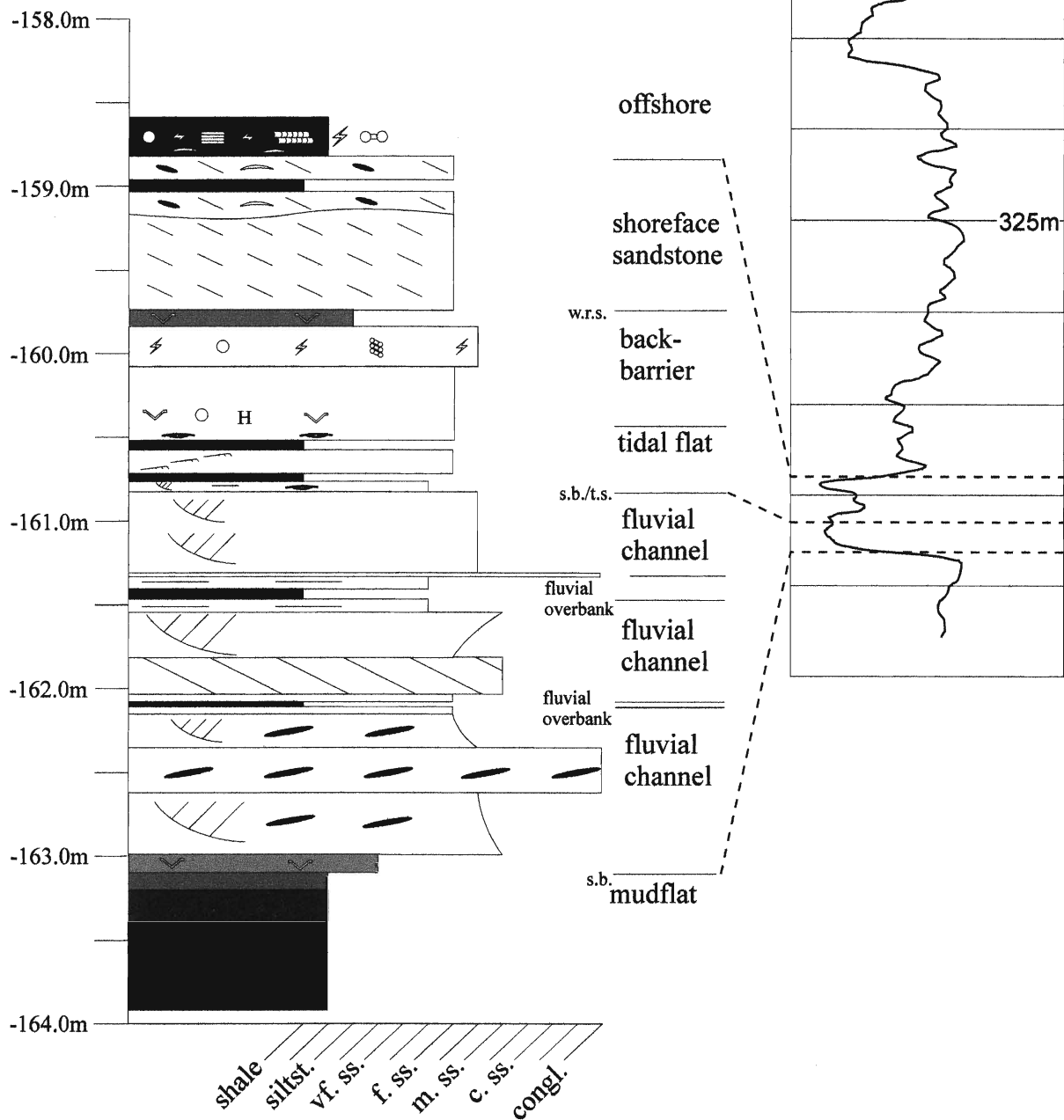
Well Name: Pembina Lake Erie 39-Y-3  
 Block Number: 39-Y-3  
 K.B. elevation: 180.40m a.m.s.l.

Subsea elevation

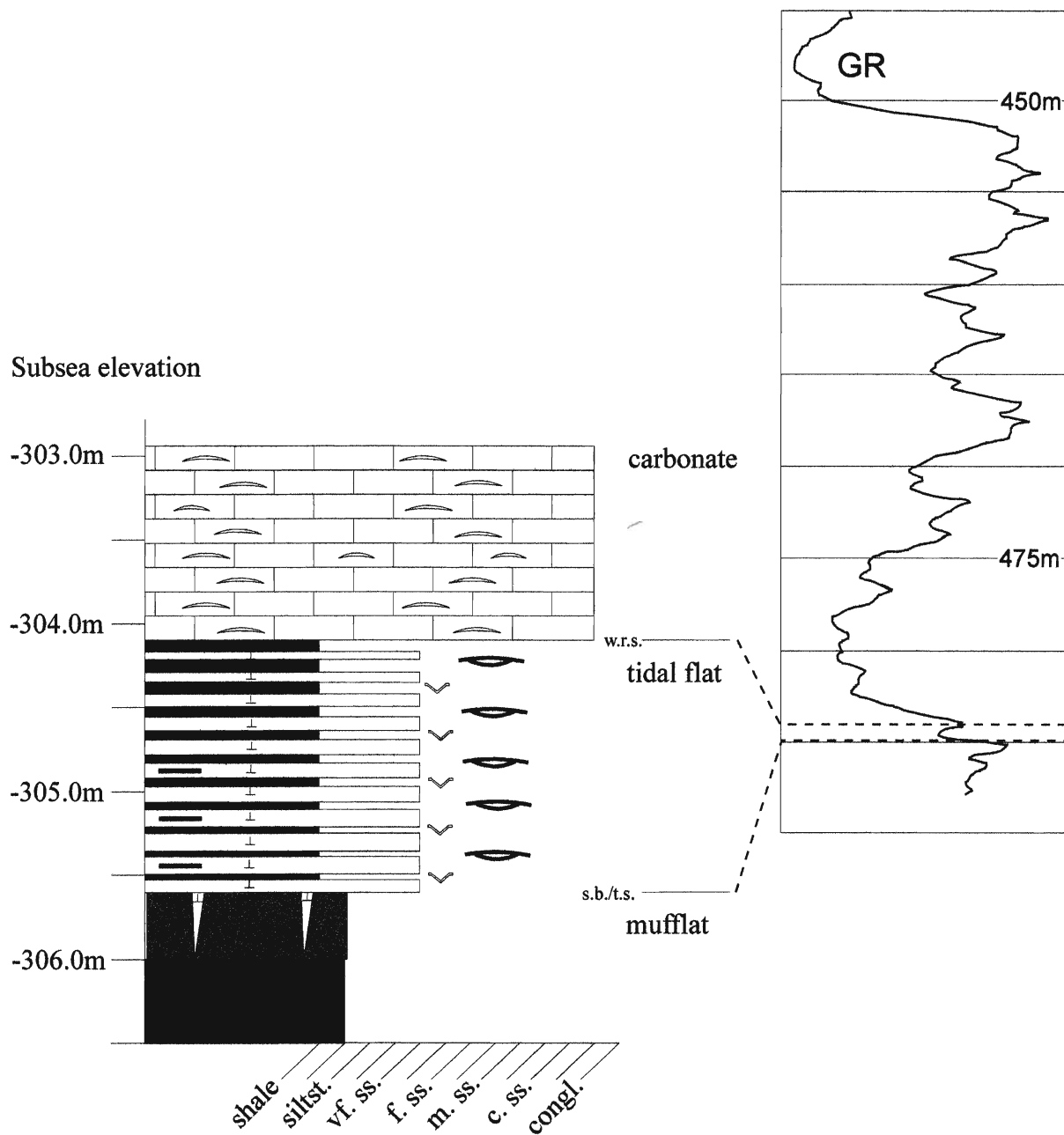


Well Name: Pembina Lake Erie #2 42-F  
 Block Number: 42-F  
 K.B. elevation: 180.4m a.m.s.l.

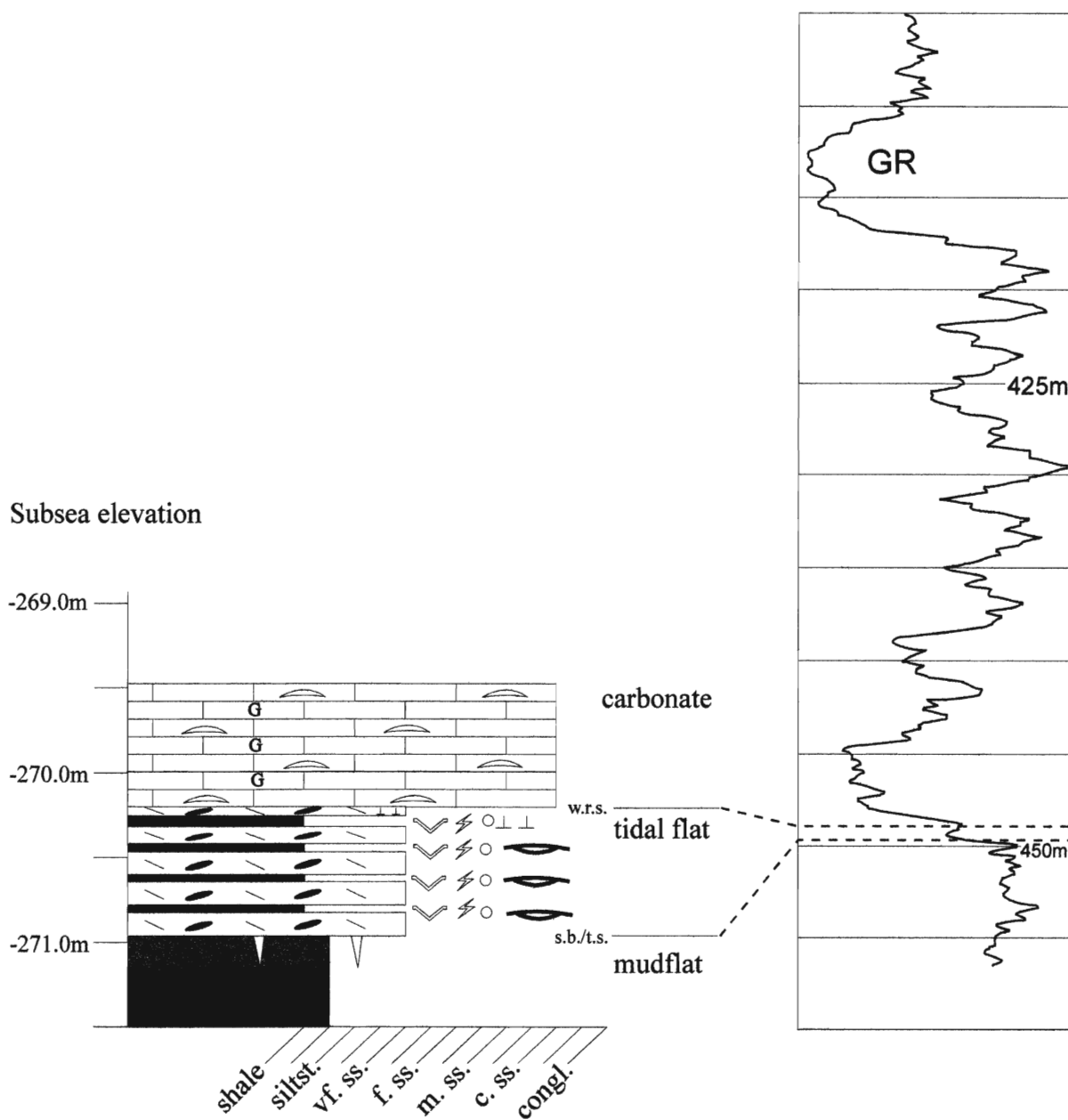
Subsea elevation



Well Name: Cons. Amoco Lake Erie 13076  
Block Number: 51-A  
K.B. elevation: 179.22m a.m.s.l.

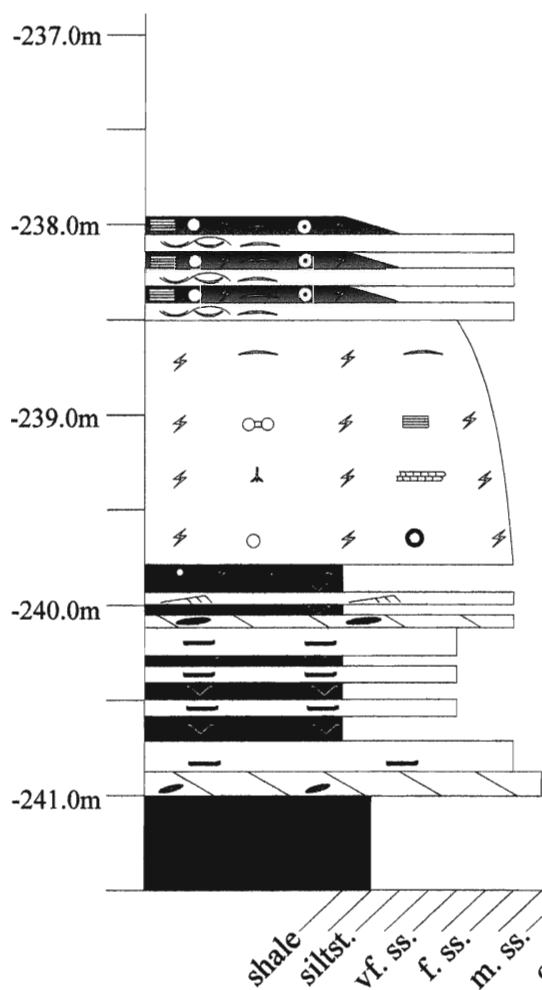


Well Name: Consumers Pan Am 13057  
 Block Number: 56-E  
 K.B. elevation: 178.91m a.m.s.l.



Well Name: Pembina #2 LE 64-P  
 Block Number: 64-P  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



offshore

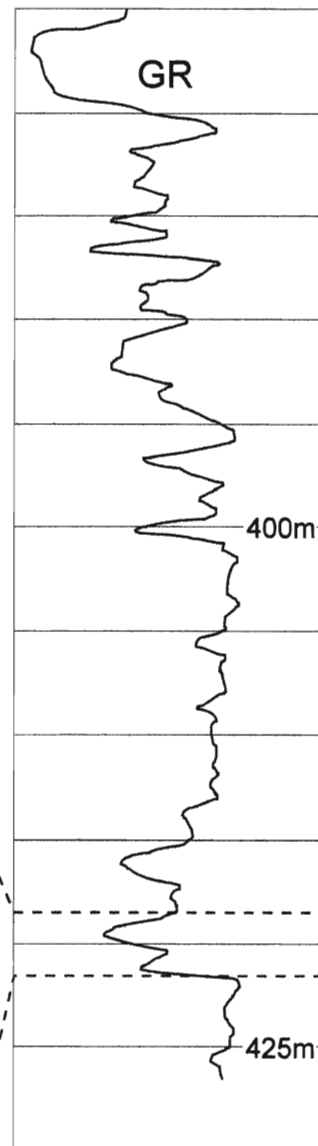
shoreface  
sandstone

w.r.s. backbarrier

tidal flat

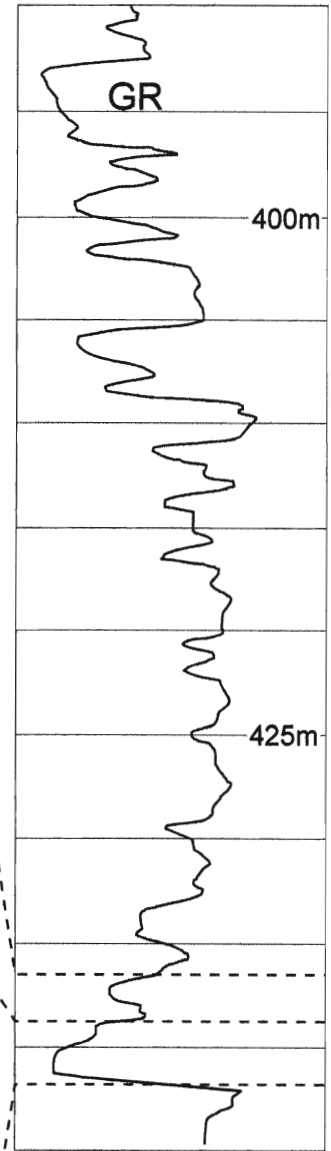
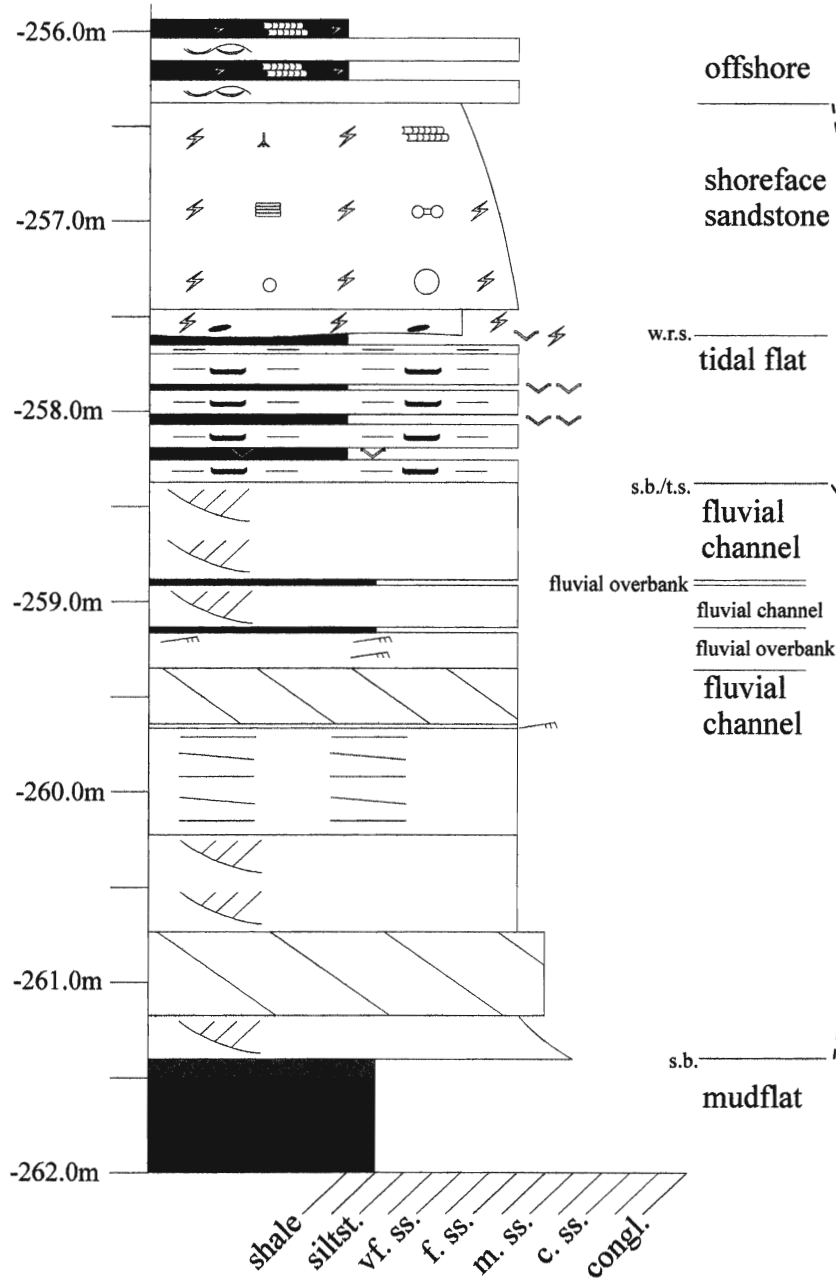
s.b./t.s. fluvial channel  
 s.b.

mudflat



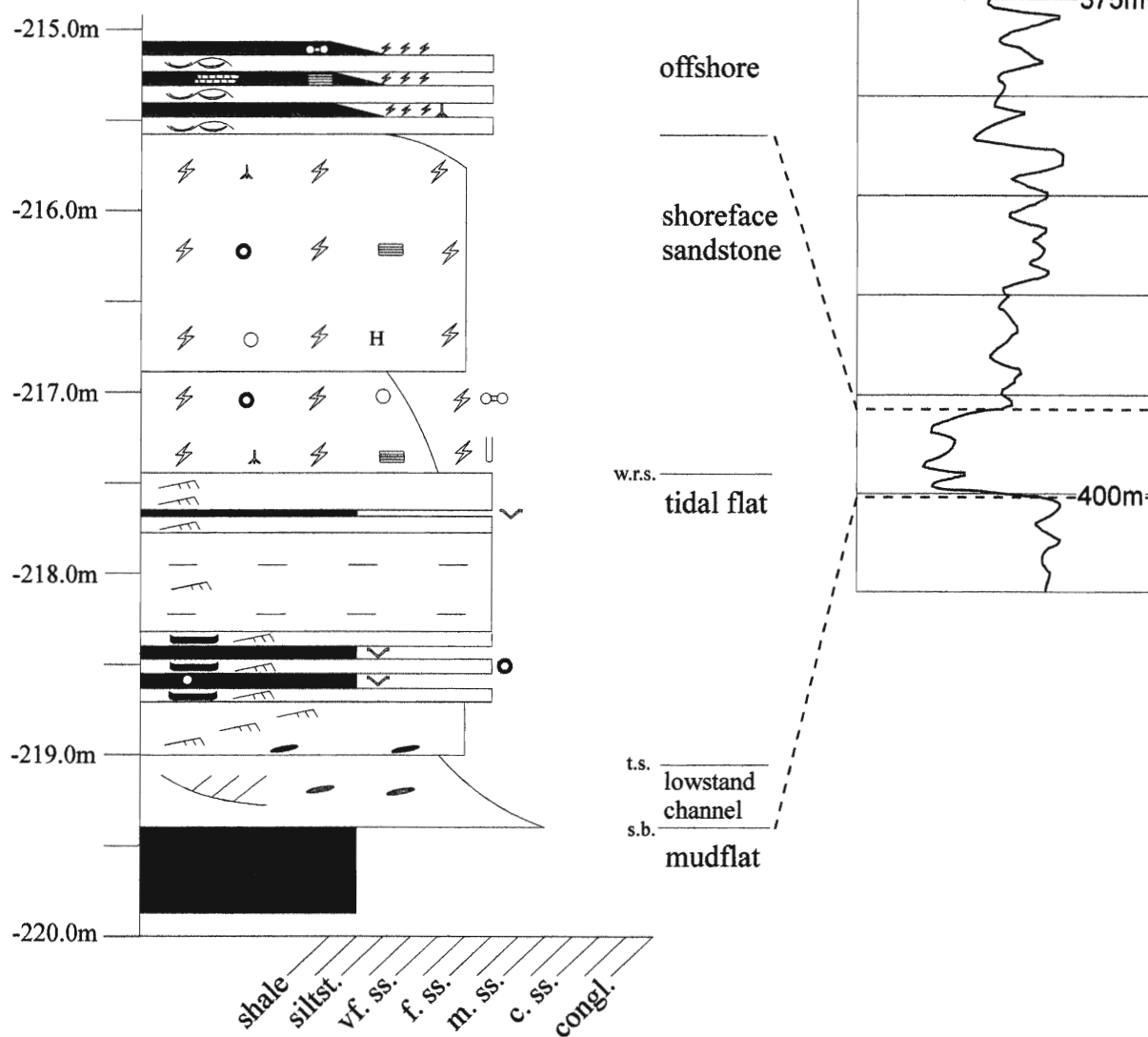
Well Name: Pembina Lake Erie 64-W-4  
 Block Number: 64-W-4  
 K.B. elevation: 180.4m a.m.s.l.

Subsea elevation



Well Name: Pembina Lake Erie 67-F-4  
 Block Number: 67-F-4  
 K.B. elevation: 180.5m a.m.s.l.

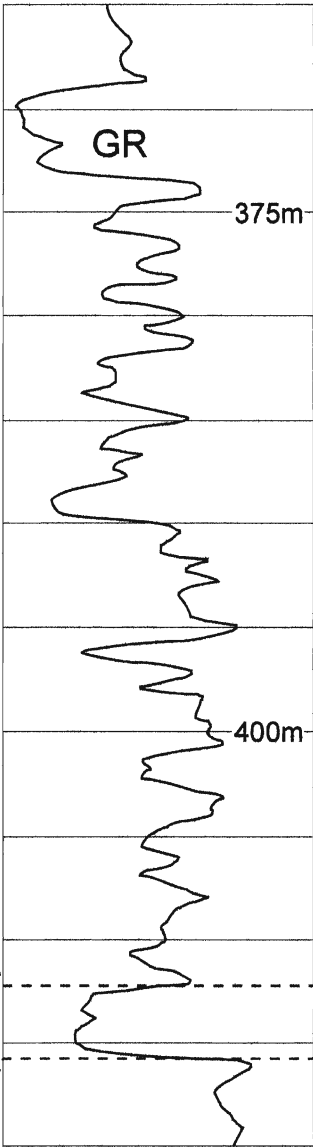
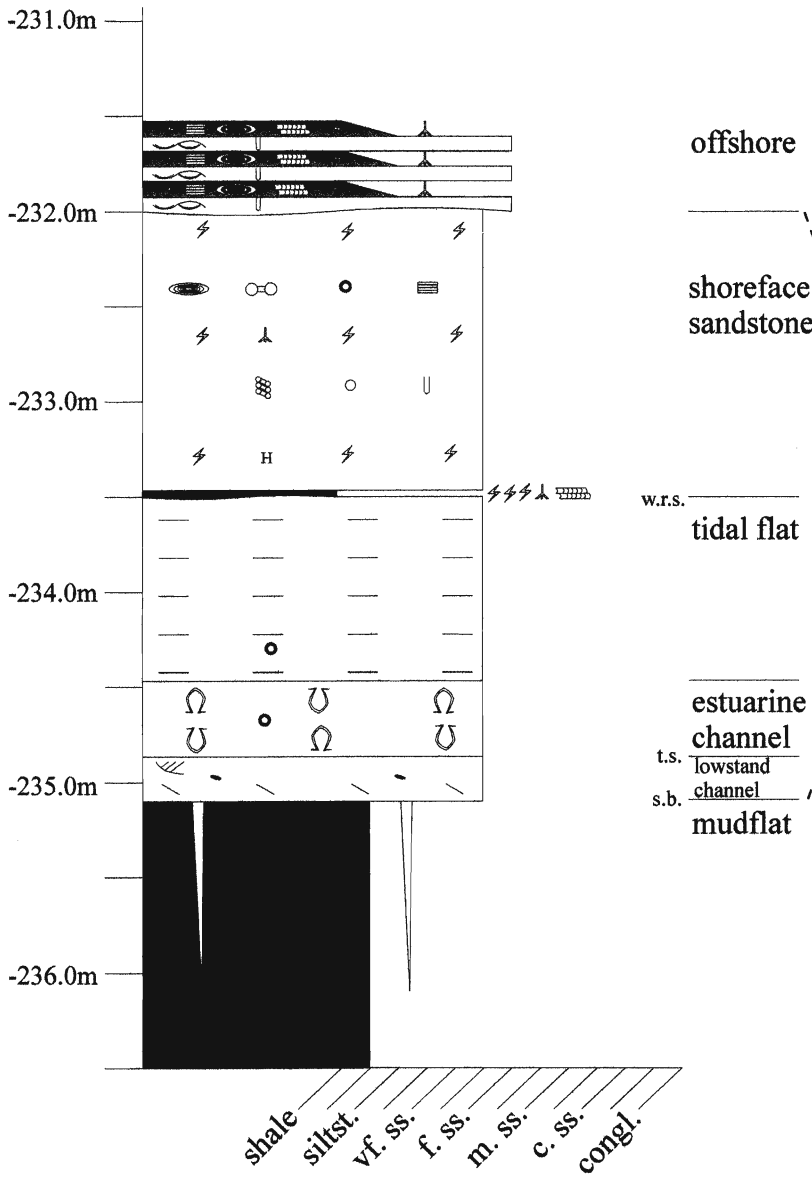
Subsea elevation





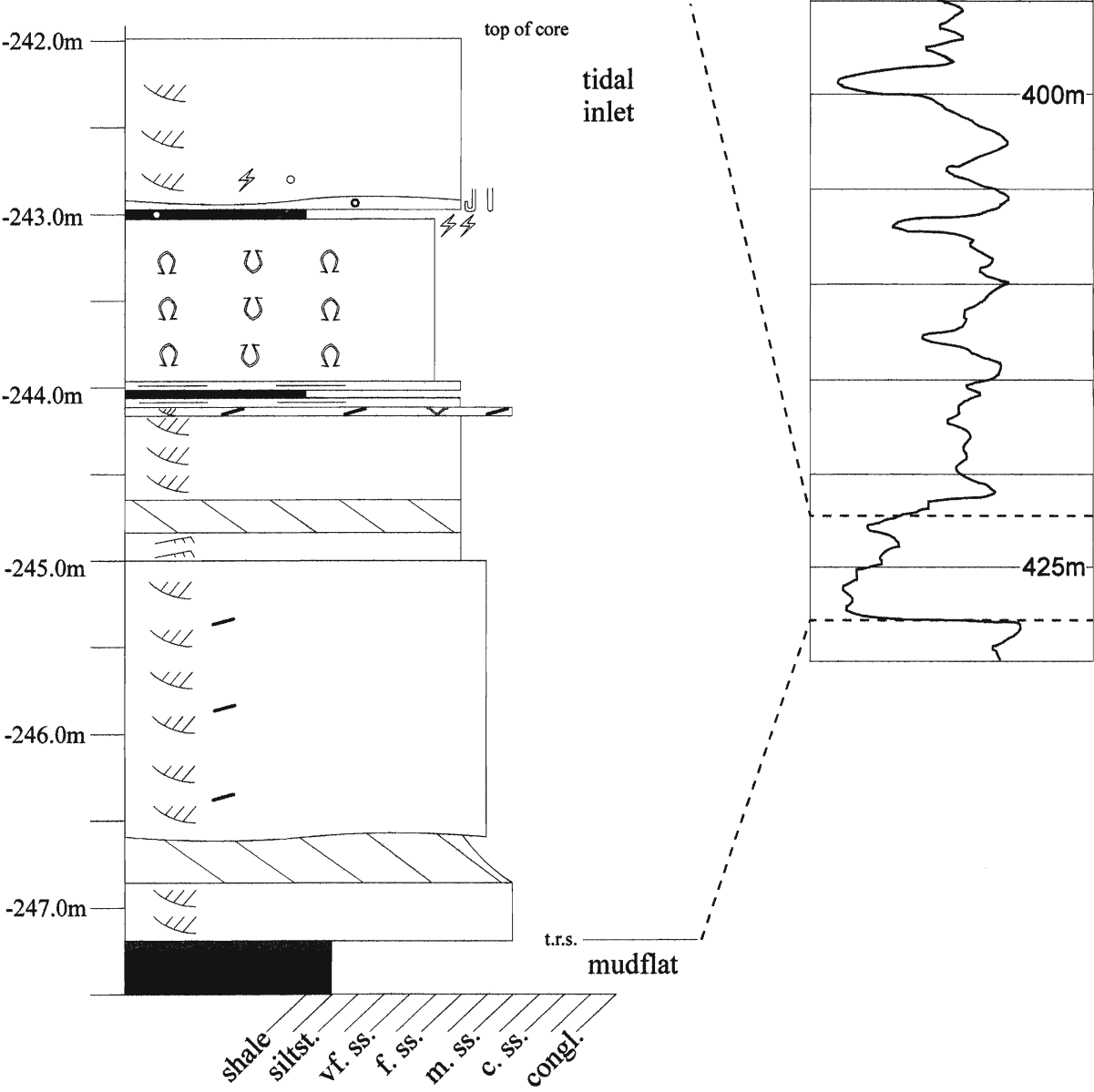
Well Name: Pembina East Lake Erie 67-P-2  
Block Number: 67-P-2  
K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



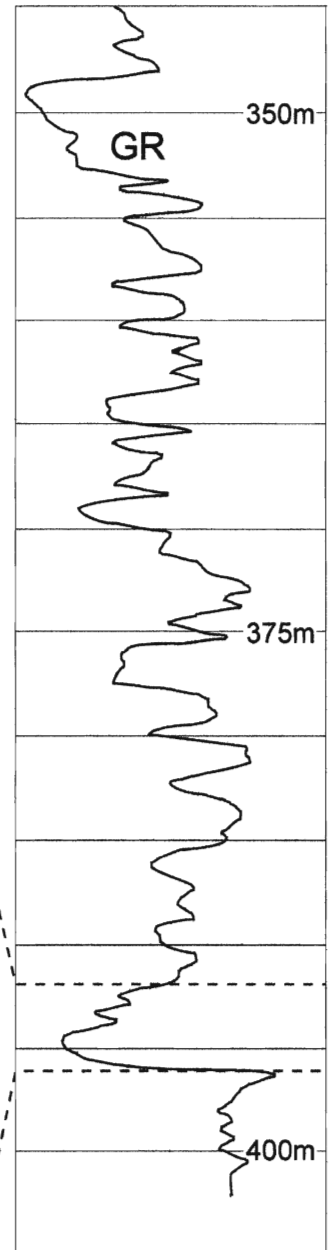
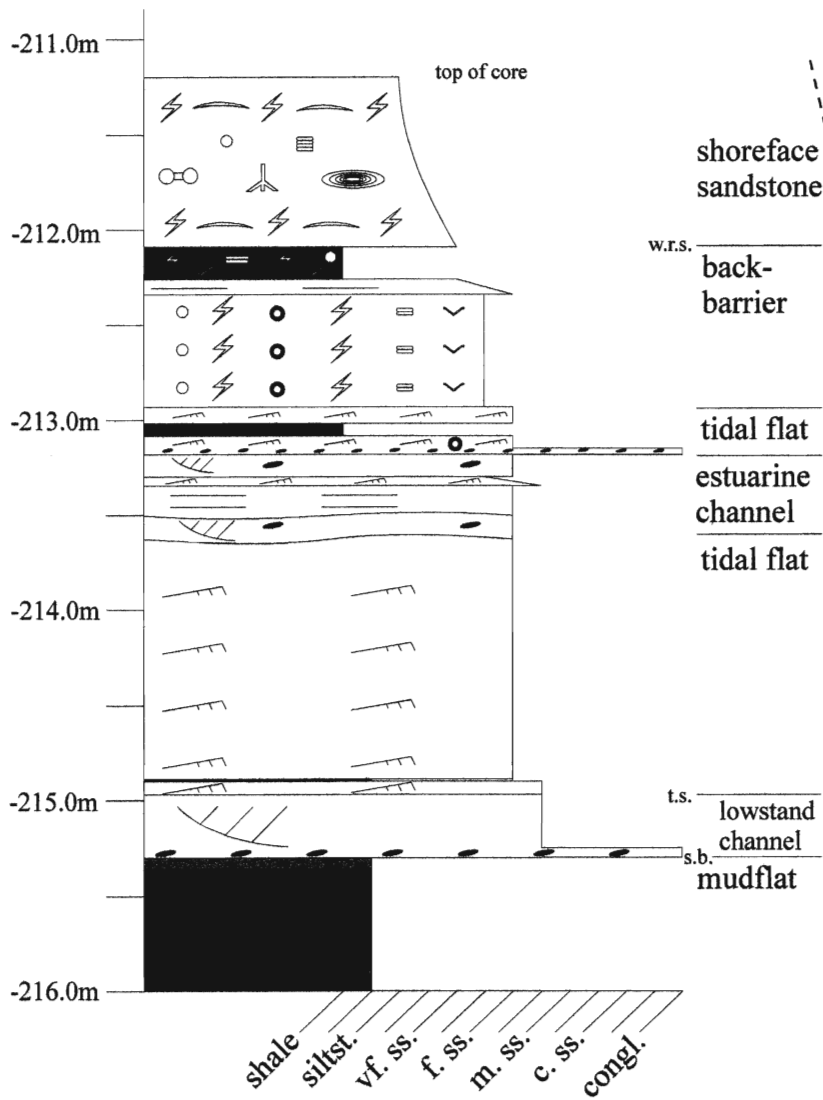
Well Name: Pembina #2 LE 68-Q-2A  
Block Number: 68-Q-2  
K.B. elevation: 180.6m a.m.s.l.

Subsea elevation



Well Name: Pembina Lake Erie 69-F-2  
 Block Number: 69-F-2  
 K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



Well Name: Pembina Lake Erie 71-I-3

Block Number: 71-I-3

K.B. elevation: 180.7m a.m.s.l.

Subsea elevation

-242.0m

-243.0m

-244.0m

-245.0m

-246.0m

-247.0m

-248.0m

-249.0m

offshore

w.r.s.

back-  
barrier

tidal flat

s.b./t.s.

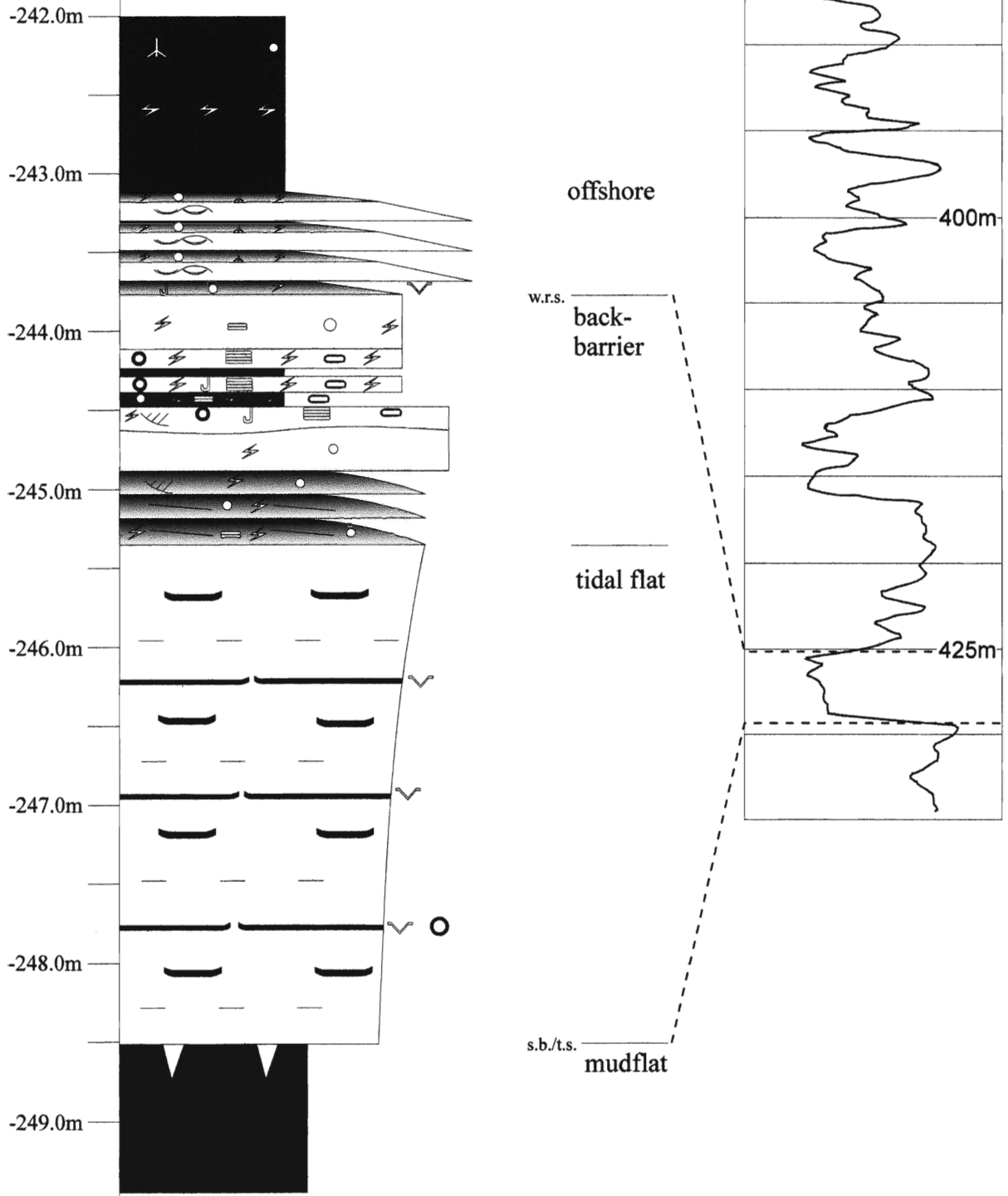
mudflat

shale  
siltst.  
vf. ss.  
f. ss.  
m. ss.  
c. ss.  
congl.

GR

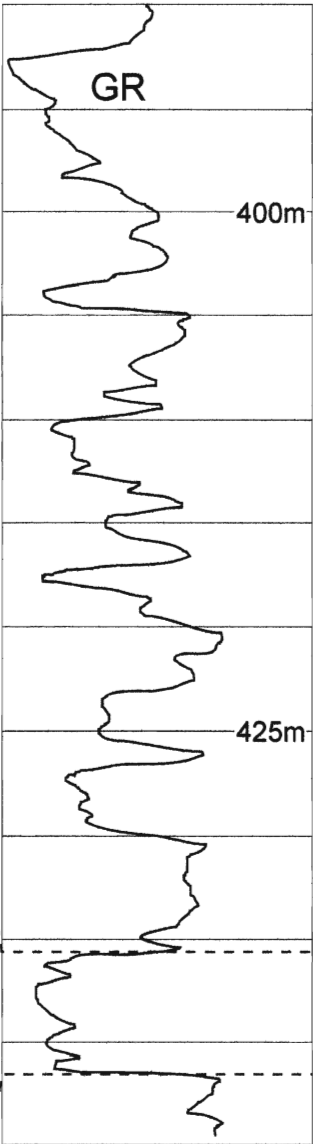
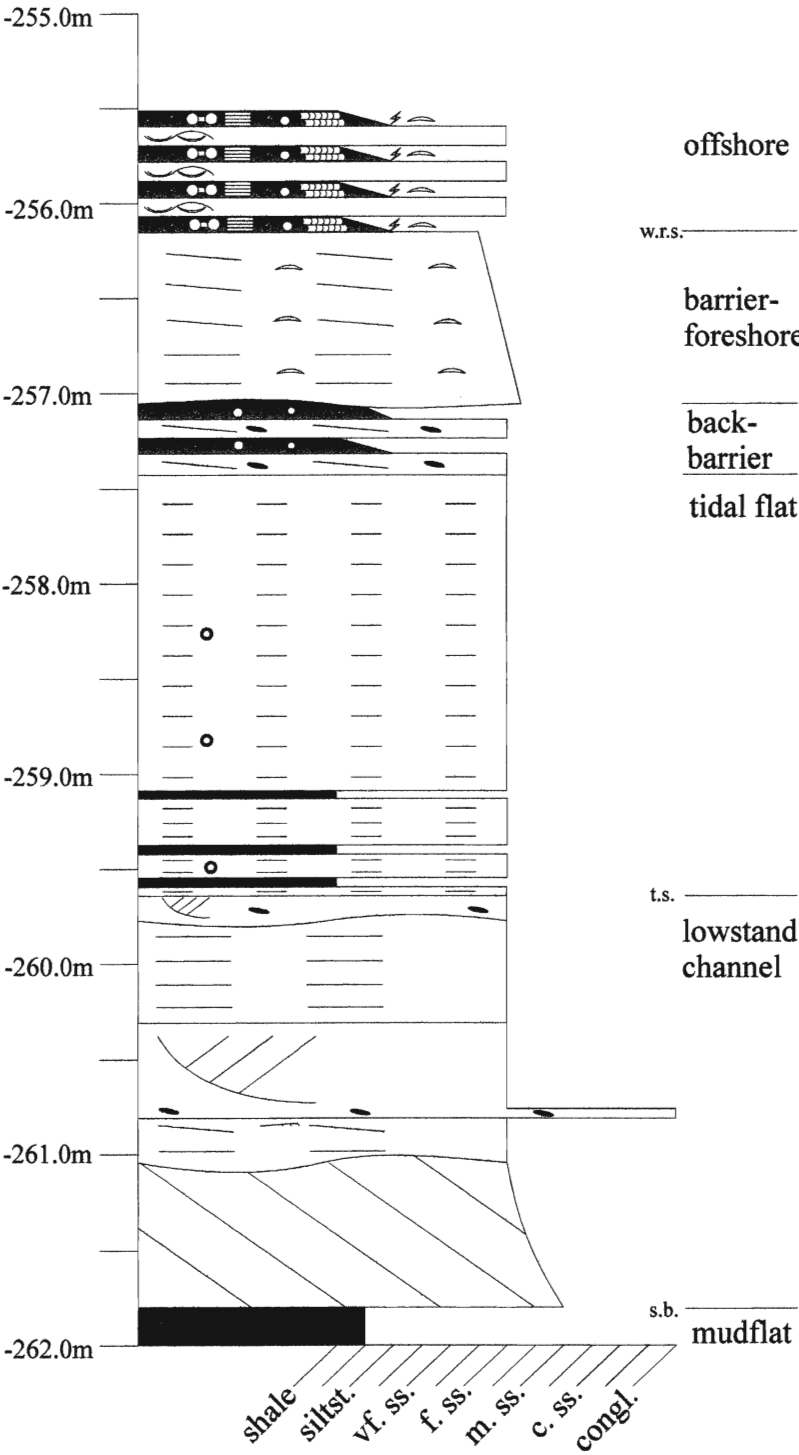
400m

425m



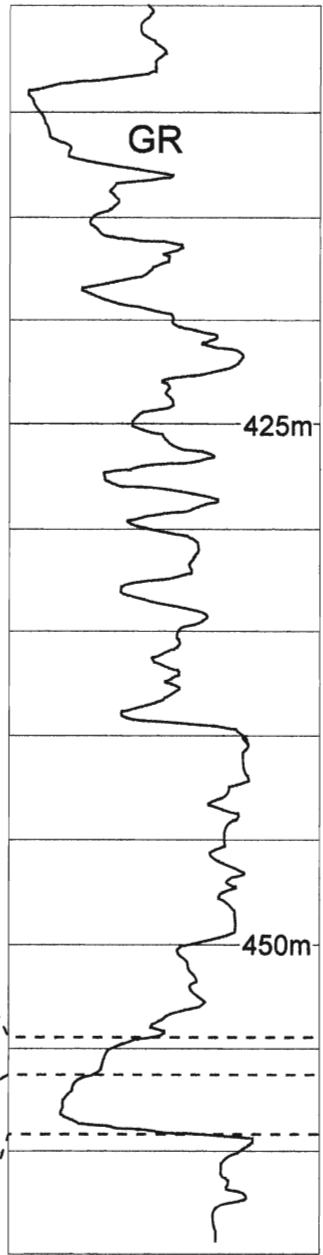
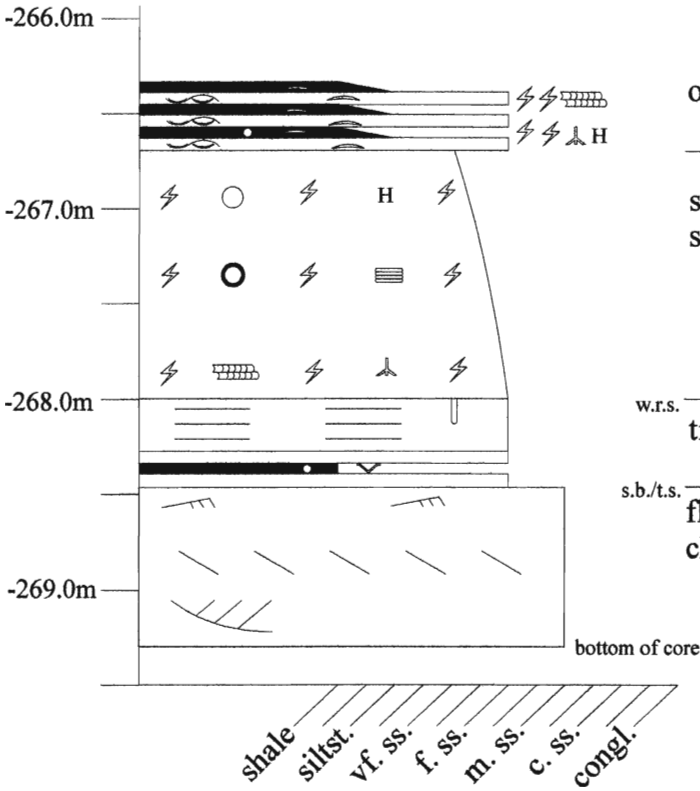
Well Name: Pembina Lake Erie 72-O-1  
Block Number: 72-O-1  
K.B. elevation: 180.7m a.m.s.l.

Subsea elevation



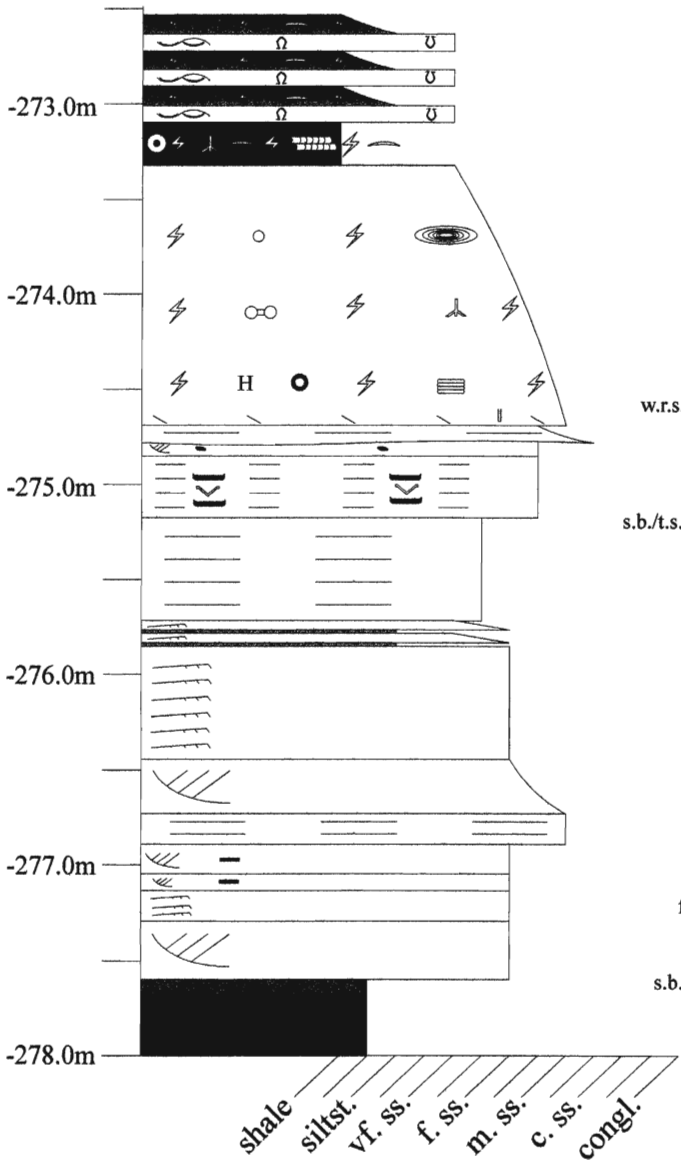
Well Name: Anschutz-B Lake Erie 89-D  
Block Number: 89-D  
K.B. elevation: 187.76m a.m.s.l.

Subsea elevation



Well Name: Pembina Lake Erie 89-H-2  
Block Number: 89-H-2  
K.B. elevation: 180.4m a.m.s.l.

Subsea elevation



offshore

shoreface sandstone

w.r.s. tidal flat

s.b./t.s. fluvial channel

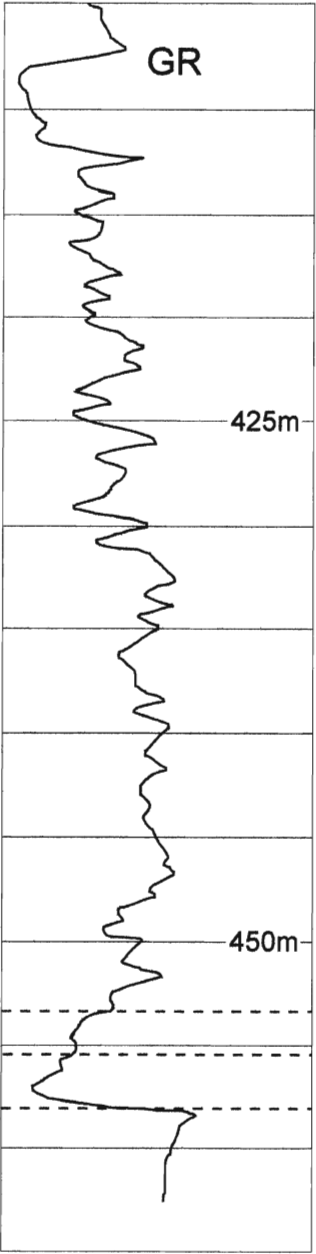
fluvial overbank

fluvial channel

fluvial overbank

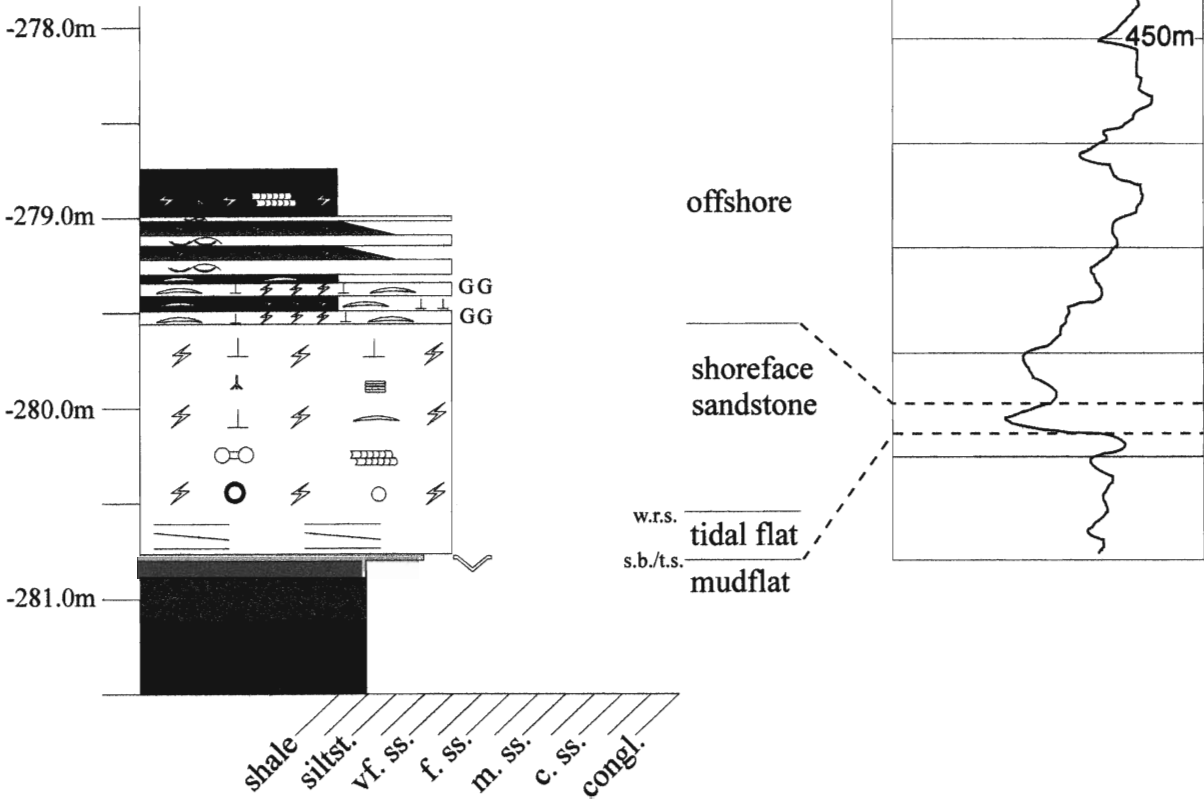
fluvial channel

s.b. mudflat



Well Name: Anschutz Lake Erie 92-N  
Block Number: 92-N  
K.B. elevation: 188.06m a.m.s.l.

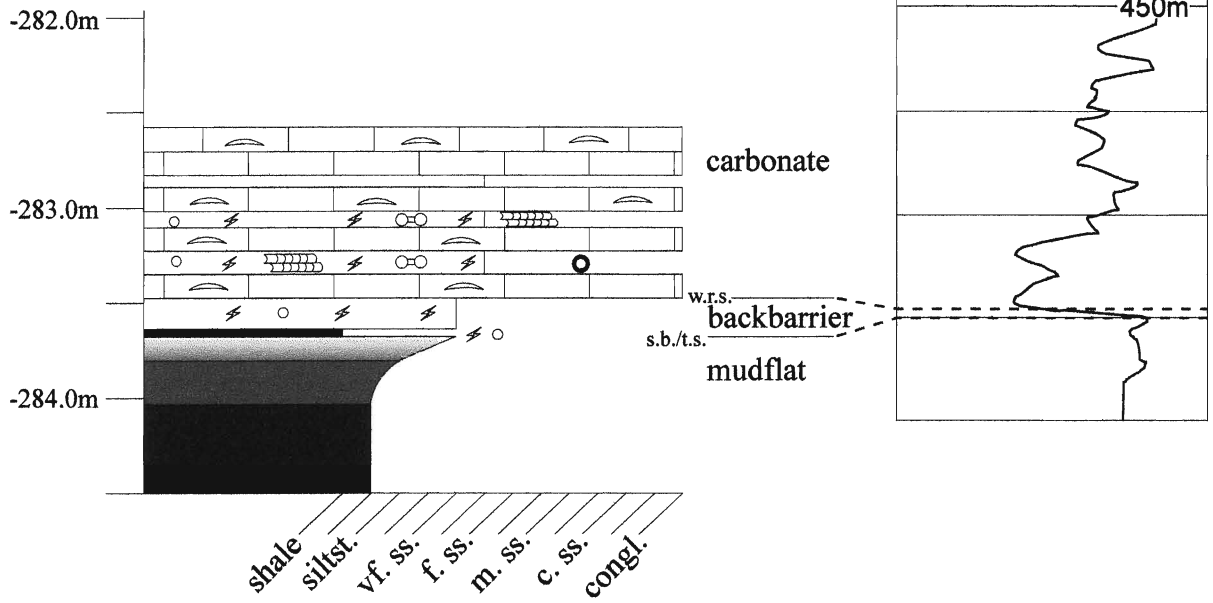
Subsea elevation





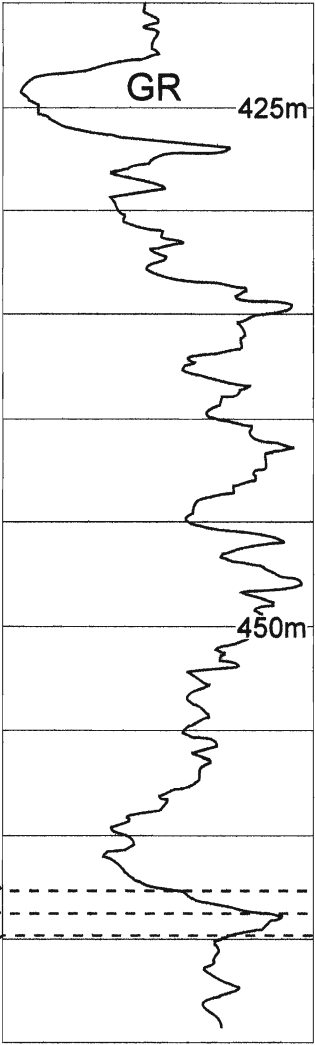
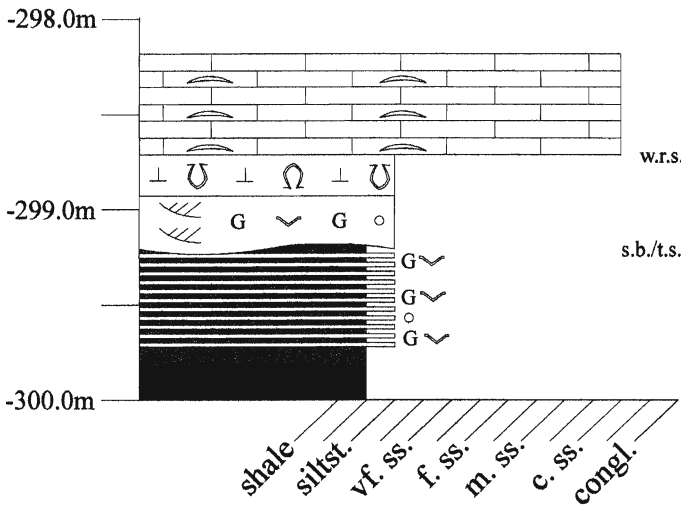
Well Name: Telesis 13922  
 Block Number: 95-H-4  
 K.B. elevation: 181.2m a.m.s.l.

Subsea elevation



Well Name: Con Amoco 13102  
Block Number: 96-D  
K.B. elevation: 179.22m a.m.s.l.

Subsea elevation



Well Name: CPOG Haldimand No. 1  
Block Number: 131-G-4  
K.B. elevation: 182.58m a.m.s.l.

Subsea elevation

