Lithostratigraphy and sedimentology of the late Jurassic-early Cretaceous Mic Mac and lower Missisauga formations, offshore Nova Scotia, Canada.

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Canada
LITHOSTRATIGRAPHY AND SEDIMENTOLOGY OF THE
LATE JURASSIC-EARLY CRETACEOUS MIC MAC AND LOWER
MISSISAUGA FORMATIONS, OFFSHORE
NOVA SCOTIA, CANADA

by

PHILIP THOMAS NANTAIS

A Thesis
submitted to the Faculty of Graduate Studies
through the Department of
Geology in Partial Fulfillment
of the requirements for the Degree
of Master of Science at
University of Windsor

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1986
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To Pinky
ABSTRACT

Lithostratigraphy and Sedimentology of the Late Jurassic-Early Cretaceous Mic Mac and Lower Missisauga Formations, Offshore Nova Scotia, Canada

Recent frontier exploration has provided a large body of data which has permitted detailed study of the lithostratigraphy, sedimentology and lithofacies of the Lower Missisauga and Mic Mac Formations, offshore Nova Scotia. The East Sable Island area has a relatively high concentration of subsurface data and was selected for detailed study of sedimentology and reservoir geology.

Recognition of the transgressive nature of prominent deepening-upward limestone units and two shale tongues of the Lower Missisauga Formation in the central-basin area has permitted division of the succession into 7 depositional complexes bounded by slightly diachronous regressive surfaces. Lithofacies reconstruction defines two lobes of terrigenous clastics prograding from the northeast and northwest.

In the East Sable Island area, Mic Mac Formation sandstones form dominantly coarsening-upward units, enveloped in mudstone and siltstone, and deposited on a shallow marine shelf. Prograding clastic sediments comprising the Lower Missisauga Formation were laid down in lower delta-plain, delta marine-fringe complexes and prodelta environments. Coarsening-upward units form dominantly deltaic foreset deposits, comprising barrier-beach, river mouth bar, tidal delta/bar and nearshore marine sediments. These sandstones formed an almost continuous linear to arcuate body of sandstone around the entire perimeter of the delta.
The sandstone bodies form texturally heterogenous reservoirs with anisotropic properties inherited primarily from the depositional environment, but also modified by diagenesis. Porosity has been reduced by compaction, pressure solution and formation of authigenic minerals including early pore-lining chlorite, quartz as overgrowths and intergranular carbonate cement. Porosity has been enhanced by advanced alteration, replacement and dissolution of alumino-silicate framework grains, particularly volcanic rock fragments and calcic plagioclase. Subsequent selective dissolution of carbonate cement is responsible for the present distribution of porosity and permeability in reservoir facies. There is no petrographic evidence to indicate a different paragenetic sequence in normal pressured and overpressured sandstone reservoirs.
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TABLE OF CONTENTS

DEDICATION iv
ABSTRACT v
ACKNOWLEDGEMENTS vii
LIST OF TABLES xi
LIST OF FIGURES xii
LIST OF APPENDICES xvii

CHAPTER

1.0 INTRODUCTION 1
1.1 Study Area 1
1.2 The Problem 1
1.3 Previous Work 4
1.4 Scope of Study 7

2.0 REGIONAL GEOLOGICAL SETTING 13
2.1 General 13
2.2 Geological History 15
2.3 Lithostratigraphy 20
  2.3.1 General 20
  2.3.2 Mississauga Formation 21
  2.3.3 Mac Mac Formation 23
  2.3.4 Abenaki Formation 26
  2.3.5 Verrill Canyon Formation 31
2.4 Biostratigraphy 32
2.5 Structural Framework 33
  2.5.1 General 33
  2.5.2 Structures 34
  2.5.3 Post-Rifting Structural Framework 36
    2.5.3.1 Synsedimentary Faults 36
    2.5.3.2 Salt Structures 39
2.6 Hydrocarbon Occurrences 41
  2.6.1 General 41
  2.6.2 Overpressured zone 45
  2.6.3 Source Rock Analyses and Maturation Profiles 47

3.0 REGIONAL LITHOSTRATIGRAPHY 50
3.1 Introduction to Lithostratigraphic Problems 50
3.2 Lithostratigraphy 56
3.3 Unit A 60
  3.3.1 Sedimentology 64
  3.3.2 Age 65
3.4 Unit B
  3.4.1 Sedimentology
  3.4.2 Age
3.5 Unit C
  3.5.1 Sedimentology
  3.5.2 Age
3.6 Unit D
  3.6.1 Sedimentology
  3.6.2 Age
3.7 Unit E
  3.7.1 Sedimentology
  3.7.2 Age
3.8 Unit F
  3.8.1 Sedimentology
  3.8.2 Age
3.9 Unit G
  3.9.1 Sedimentology
  3.9.2 Age
3.10 Geological History And Paleogeography
  3.10.1 Depositional Episode A
  3.10.2 Depositional Episode B,C,D
  3.10.3 Depositional Episode E,F,G
4.0 Characterization of Potential Reservoir Facies
  4.1 Reservoir Heterogeneity and Sequence Elements
  4.2 Porosity and Permeability Relationships
    4.2.1 Sandstone-Limestone Element
    4.2.2 Well-Washed Sandstone Elements
    4.2.3 Bedded Shaly Sandstone Element
    4.2.4 Bioturbated Element
    4.2.5 Order of Occurrence
4.3 Petrography
4.4 Summary of Diagenetic Effects Controlling Reservoir Properties
5.0 Concluding Remarks
REFERENCES
APPENDIX
VITA AUCTORIS
LIST OF TABLES

2.1 Significant hydrocarbon discoveries on the Scotian Shelf. 42

4.1 Sequence elements in Lower Mississauga and Mic Mac Formation sandstones — Venture field, offshore Nova Scotia. 175

4.2 Hierarchy of reservoir heterogeneities. 179

4.3 Sequence elements, depositional environments and generalized fluid-flow characteristics in Lower Mississauga and Mic Mac Formation sandstones in the East Sable Island areas. 182

4.4 Summary of porosity and permeability relationships in well-washed sandstones — Type-II elements. 188

4.5 Summary of porosity and permeability trends in Type-IV elements. 207
<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Location of study area.</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Stratigraphic scheme for offshore Nova Scotia</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Well location map.</td>
<td>8</td>
</tr>
<tr>
<td>1.4</td>
<td>Cross-section index map.</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Tectonic elements and sediment thickness map.</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Isopach map of the late Middle-Late Jurassic Mic Mac Formation.</td>
<td>25</td>
</tr>
<tr>
<td>2.3</td>
<td>Structure contour map of the top of Mic Mac Formation.</td>
<td>26</td>
</tr>
<tr>
<td>2.4</td>
<td>Structure contour map of the top of Baccaro Member and equivalents.</td>
<td>29</td>
</tr>
<tr>
<td>2.5</td>
<td>Isopach map of the Baccaro Member and equivalent carbonates.</td>
<td>30</td>
</tr>
<tr>
<td>2.6</td>
<td>Major fault structures in the Sable Subbasin.</td>
<td>37</td>
</tr>
<tr>
<td>2.7</td>
<td>North-south seismic line through the East Sable Island area.</td>
<td>38</td>
</tr>
<tr>
<td>2.8</td>
<td>A hydrocarbon generation model for the Scotian Shelf.</td>
<td>49</td>
</tr>
<tr>
<td>3.1</td>
<td>Gamma-ray, sonic and electrical log curves for a portion of the Mic Mac Formation type section.</td>
<td>52</td>
</tr>
<tr>
<td>3.2</td>
<td>Gamma-ray, sonic and electrical log traces in a portion of the Mic Mac Formation in the Mobil et al. Venture H-22 well.</td>
<td>53</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic stratigraphic section illustrating lithostratigraphy in the Mic Mac and Lower Mississauga Formations.</td>
<td>58</td>
</tr>
<tr>
<td>3.4</td>
<td>Reference sections for lithostratigraphic units in the Mic Mac Formation.</td>
<td>59</td>
</tr>
<tr>
<td>3.5</td>
<td>Isopach map of Unit A.</td>
<td>61</td>
</tr>
<tr>
<td>3.6</td>
<td>Graphic log of core in the Shell Erie D-26 (2242.1-2251.25 m) well.</td>
<td>62</td>
</tr>
<tr>
<td>3.7</td>
<td>Isopach map of Unit B.</td>
<td>66</td>
</tr>
<tr>
<td>3.8</td>
<td>Isopach map of Unit C.</td>
<td>73</td>
</tr>
</tbody>
</table>
3.9 Graphic log of fluvial channel sandstones in the Shell Eire D-25, Mic Mac J-77 and Mobil TETCO Esperanto K-78 wells.

3.10 Isopach map of Unit D.

3.11 Isopach map of Unit E.

3.12 Graphic log of core from the Mobil et al. Venture B-52 (5537.9-5555.4 m) well.

3.13 Graphic log of core from the Mobil et al. Venture B-52 (5175.8-5190.3 m) well.

3.14 Graphic log of offshore and submarine shoal deposits cored in the Mobil et al. Venture H-22 (5397.15-5414.5 m) well.

3.15 Graphic log of tidally influenced shallow marine sandstone deposits in a core from the Mobil et al. Venture H-22 (5237.0-5234.8 m) well.

3.16 Isopach map of Unit F.

3.17 Structure contour map of the top of Lower Mississippian Formation.

3.18 Graphic log of core from the #8 sandstone in the Mobil et al. Venture H-22 well.

3.19 Graphic log of core from the #7 sandstone in the Venture field area.

3.20 Graphic log of core from the #6 sandstone in the Venture field area.

3.21 Graphic log of core from the upper part of the #5 sandstone in the Mobil et al. Venture B-52 (4944.0-4959.45 m) and B-43 (4875-4879.2 m) wells.

3.22 Graphic log of prodelta and distal delta-front sediments cored in the Mobil et al. Venture H-22 (4899.05-4917.7 m) well.

3.23 Deformation structures observed in a prodelta and distal delta-front sequence cored in the Mobil et al. Venture H-22 (4899.05-4917.1 m) well.

3.24 Graphic log of core from the #3A sandstone and #3 limestone in the Venture field area.

3.25 Graphic log of core from the Mobil et al. Venture B-43 (4430.2-4442.45 m) well.
3.26 Isopach map of Unit G.

3.27 Graphic log of core from the Mobil Sable Island C-67 (4084.4-4093.3 m) well.

3.28 Graphic log of core from a shaly facies of the Missisauga Formation laterally equivalent to Unit G in the Petro-Canada et al. Banquereau C-21 (4473.0-4477.7 m) well.

3.29 Lithofacies map for Kimmeridgian time.

3.30 Lithofacies map for Tithonian time.

3.31 Percent limestone map for the Mic Mac Formation.

3.32 Percent coarse-grained sandstone map for the Mic Mac Formation.

3.33 Schematic correlation between the Mobil et al. Arcadia J-16 well and the Venture field area.

3.34 Lithofacies map for Lower Missisauga Formation.

3.35 A percent limestone map for the Lower Missisauga Formation.

3.36 Percent coarse-grained sandstone map for the Lower Missisauga Formation.

4.1 Core photographs of Type-II elements.

4.2 Core photographs of Type-III elements.

4.3 Core photographs of Type-IV elements.

4.4 Cumulative frequency plot of porosity values and their relationship to sequence elements.

4.5 Frequency and cumulative frequency plot of porosity and permeability for Type-I elements.

4.6 Porosity-permeability scattergram for Type-I elements.

4.7 Kn/Kv plot for Type-I elements.

4.8 Frequency and cumulative frequency plot of porosity and permeability for structureless sandstone.

4.9 Frequency and cumulative frequency plot of porosity and permeability for cross-bedded sandstone.
4.10 Frequency and cumulative frequency plot of porosity and permeability for cross-laminated sandstone.

4.11 Frequency and cumulative frequency plot of porosity and permeability for plane-laminated sandstone.

4.12 Porosity-permeability scattergram for structureless sandstone.

4.13 Porosity-permeability scattergram for cross-bedded sandstone.

4.14 Porosity-permeability scattergram for cross-laminated sandstone.

4.15 Porosity-permeability scattergram for plane-laminated sandstone.

4.16 Kh/Kv plot for structureless and plane-laminated sandstone.

4.17 Kh/Kv plot for cross-bedded and cross-laminated sandstone.

4.18 Porosity-permeability scattergram for bedded shaly sandstone and siltstone elements.

4.19 Frequency and cumulative frequency plot of porosity and permeability in wavy-bedded sandstone.

4.20 Frequency and cumulative frequency plot of porosity and permeability for lenticular-bedded sandstone/siltstone and thinly bedded mudstone and sandstone/siltstone.

4.21 Frequency and cumulative frequency plot of porosity and permeability for well-washed burrowed sandstone.

4.22 Porosity-permeability scattergram for well-washed burrowed sandstone.

4.23 Frequency and cumulative frequency plot of porosity and permeability in muddy bioturbated sandstone.

4.24 Porosity-permeability scattergram for muddy bioturbated sandstone.

4.25 Kh/Kv plot for muddy bioturbated sandstone and burrowed well-washed sandstone.

4.26 Two repetitive series of sequence elements commonly observed in the Venture field area.

4.27 Core photographs of sequence A.
4.28 Core photographs of sequence B.

4.29 Relationship between sequence elements porosity, permeability and log derived clay volume in core #7 from the Mobil et al. Venture B-52 (5266.6-5280.0 m) well.

4.30 Photomicrograph of a medium-grained sandstone from 4958.25 m (core depth) in the Mobil et al. Venture B-43 well.

4.31 Photomicrograph of a fine-grained sandstone from 4726.35 m (core depth) in the Mobil et al. Venture B-13 well.

4.32 Photomicrograph of a fine- to medium-grained sandstone cored in the Mobil et al. Venture B-43 (4965.7 m, core depth) well.

4.33 Photomicrograph of a poorly indurated, fine-grained sandstone from the normal pressured succession of the upper Mississauga Formation in the Shell Petro-Canada Penobscot B-41 (2656.9 m, core depth) well.

4.34 Photomicrograph of a well indurated, very fine- to fine-grained, glauconitic sandstone from the normal pressured succession in the Mobil et al. Venture B-43 (4433.55 m, core depth) well.

4.35 Photomicrograph of a glauconitic sandstone from the Mobil et al. Venture B-43 (4963.95 m, core depth) well.

4.36 Photomicrograph of an oolitic unit interbedded with fine-grained sandstone in the Mobil et al. Venture B-13 (4692.3 m, core depth) well.

4.37 Photomicrograph of an oolitic-bioclastic grainstone in the Mobil et al. Venture B-13 (4712.4 m, core depth) well.

4.38 Factors affecting reservoir quality and the paragenetic history of Mac Mac and Lower Mississauga Formation sandstones in the East Sable Island area.
LIST OF APPENDICES

1. List of stratigraphic tops. 246
2. Detailed core descriptions. 251
3. Rear pocket - Stratigraphic cross-sections.
1.0 Introduction

1.1 Study Area

The Late Jurassic-Early CretaceousMic Mac and Lower Missisauga Formations occur in the subsurface of offshore Nova Scotia. The Nova Scotia shelf is a glaciated platform, bounded in the northeast by the Laurentian Channel, in the southwest by the U.S./Canada border and the Georges Basin and landward by the subcrop of Paleozoic basement (Jansa and Wade, 1975). The width of the shelf varies between 225 km in the northeast to 130 km in the southwest. Water depths increase seaward and are typically less than 200 m, although several irregular depressions to several hundred metres and isolated banks are present.

The study area occupies 54,500 km$^2$ between 43$^\circ$N and 43$^\circ$45'N in the southwest; 44$^\circ$30'N and 45$^\circ$N in the northeast and bounded by the 57$^\circ$30'W and 62$^\circ$30'W meridians (Fig. 1.1). The study area is centred approximately 340 km east-southeast of Halifax, Nova Scotia.

1.2 The Problem

The geology of the lower part of the Missisauga Formation and the Mic Mac Formation, as well as adjacent or laterally equivalent units, has been interpreted on the basis of stratigraphic, structural and sedimentological relationships revealed by a detailed study of data from 54 wells. None of the succession is exposed onshore. The study units comprise a predominantly siliciclastic succession containing subordinate carbonate beds. Facies variation in the sequence is complex. The proportion of siliciclastic and carbonate components vary considerably according to position in the basin.
Figure 1.1. Geographical location of the study area, offshore Nova Scotia.
The lithostratigraphy was originally defined by McIver (1972) on the basis of 20 wells. Not all of the variations and complexities of the lithostratigraphy were represented in this data base. As of January 1986, 86 additional wells have been drilled, 54 of which penetrate the Mic Mac Formation. The lack of a comprehensive, up-to-date geological analysis of the Mic Mac Formation and Lower Missisauga unit has provided the impetus for this study. The study has two main components. The construction of cross-sections has permitted the establishment of a broad lithostratigraphic framework and regional lithofacies (Refer to Fig. 1.4). Secondly, the East Sable Island area has been selected for a detailed study of reservoir geology, since the drilling and coring has been considerably more intensive.

Despite the drilling of nearly 90 wildcat wells, the offshore Nova Scotia play is still in an early stage of exploration. Sixteen significant gas/condensate (and minor light oil) discoveries have been made in the vicinity of Sable Island since drilling commenced in 1967.

The Lower Missisauga unit and the Mic Mac Formation have proven to be the most prolific hydrocarbon-bearing strata. Currently one project, the Mobil et al. Venture Field with estimated gas reserves of 5.6-7 billion m$^3$(2-2.5 TCF) is being considered for development, with a target production date in the early 1990s, although delineation is incomplete (Globe and Mail, Nov. 7, 1985). Additional recent discoveries are currently being appraised or await further drilling.
1.3 Previous Work

Detailed accounts of the exploration history, early concepts and interpretations of the geologic, geomorphic and structural development of the Nova Scotia shelf are reviewed by Emery and Uchupi (1972), Sherwin (1973) and King and MacLean (1976). The following discussion is a brief synopsis of previous work, emphasizing particular milestones in the development of an understanding of the stratigraphic framework.

Knowledge of the Cenozoic-Mesozoic stratigraphy prior to 1968 was based on dredge samples, geophysical surveys and shallow boreholes. Modern marine geophysical techniques, including seismic refraction and reflection, gravity and aeromagnetic surveys were initiated in 1954 by Canadian and U.S. research institutes and government surveys. It soon became apparent that the thick, southeast trending wedge of prograding sedimentary rocks underlying the Scotian Shelf and Slope had all the prerequisites of a major, unexplored hydrocarbon province. Reconnaissance petroleum exploration began in 1959 and culminated in the drilling of the first wildcard well, Mobil Sable Island C-67 in 1967 to a total depth of 4604 m. The well encountered gas and light oil in 11 zones and over 600 m of Late Jurassic and Cretaceous sandstones with reservoir quality. Magnusson (1973) described the stratigraphic succession and identified 11 units, relating them to a broad regressive phase of sedimentation with indications of paralic, offshore-bar, beach and tidal environments taken to represent the distal elements of a broad Mesozoic delta. King (1970) systematized the stratigraphy of the unconsolidated Quaternary sediments of the Scotian Shelf.

McIver (1972) on the basis of subsurface information from 20 exploratory wells and seismic data, proposed a formal, generalized lithostratigraphic framework and designated type reference wells and nomenclature for the
Fig. 1.2. Stratigraphic scheme for Mesozoic-Cenozoic sediments, offshore Nova Scotia (modified slightly from Grant et al., 1985).
complete Mesozoic succession on the Scotian shelf. The underlying sedimentary rocks were subdivided into 3 groups, 12 formations and 4 members (Fig. 1.2). McIver's (1972) scheme defined (1) a basal Early-early Middle Jurassic unit of salt, overlain by dolomites and siliciclastics; (2) the Western Bank Group (late Middle-Late Jurassic) consisting of limestones with associated shales and subordinate sandstone; (3) the Nova Scotia Group (Early Cretaceous), a regressive wedge of sandstone and shale and (4) the Gully Group (Late Cretaceous) consisting of shales, thin carbonates, chalk and argillaceous sandstones. Subsequent seismic reflection studies combined with correlation of well data defined four unconformities within the Mesozoic-Cenozoic section (King et al. 1974).

The Mic Mac Formation is part of the Western Bank Group and consists of shale, sandstone and limestone. The unit interdigitates in a complex manner with laterally equivalent carbonates of the Abenaki Formation and passes basinward into shale of the Verrill Canyon Formation. The Missisauga Formation is the basal unit of the Nova Scotia Group and overlies the Mic Mac Formation or basinward, the Verrill Canyon Formation. The Mic Mac Formation has been well defined on the upper shelf by earlier studies. Previously, the study unit was not delimited in seaward wells in the vicinity of Sable Island owing to the relatively shallow depth of wells and complex facies relationships.

The lithostratigraphy outlined by McIver (1972) was subsequently revised. Jansa and Wade (1975) reduced the Naskapi Formation to member status, designated one new unit, the Late Triassic Eurydice Formation, defined two informal units and adjusted the ages for several formations. Given (1977) used a prominent seismic event, an oolitic carbonate interval termed the '0' Marker to informally subdivide the Missisauga Formation into
an upper and a lower unit. She also redefined the Mohawk Formation. On the western shelf, the Mohawk Formation was placed in the Western Bank Group. The Mohican Formation was proposed for that part of the former Mohawk Formation occurring below the Western Bank Group on the eastern shelf and in the sub-basins. Eliuk (1978) studied the facies relationships of the Abenaki Formation and proposed an informal unit, the Artimun Member of the Abenaki Formation, overlying the Baccaro Member on the western shelf.

The correlation of well data allowed Jansa and Wade (1975) and Given (1977) to construct broadly based lithofacies maps for various time slices throughout the Mesozoic. Variations between the two sets of lithofacies maps can be ascribed to increased well control in later studies. Eliuk (1978) presented lithofacies maps specifically for the Abenaki Formation (late Middle to Late Jurassic) and laterally equivalent siliciclastics. The major emphasis however, was on the proportion of carbonate components.

1.4 Scope of Study

This study combines petrophysical well log correlation and interpretation with detailed lithologic description of 581 m of cored sections from 11 wells. The geologic data for the Mic Mac Formation has been provided by 74 wells with non-confidential status within the study area (Fig. 1.3). However, only 54 of these penetrate the study unit and their lateral equivalents. A major concentration of wells outlining the Venture field occurs in the vicinity of Sable Island. The lower part of the Mic Mac Formation is only represented in wells on the upper shelf that lie on the platform and immediately basinward of the east trending basement hinge line. The upper part of the study unit is encountered in the East Sable Island area, but tends to abruptly shale out basinward to the south.
Fig. 1.3. Well location map of the Scotian Shelf showing wells used in this study.
Typically, a full suite of electrical, radioactivity and acoustic logs was run in all wells used in the present study. Dipmeter logs were also available for a limited number of wells. Lithologic control in non-cored sections was provided by the descriptions of drill cuttings and sidewall cores in well history reports, combined with lithologs prepared by Canadian Stratigraphic Services Limited. Cuttings samples are described in well histories at either specified intervals, commonly 3 or 5 m, or at random intervals based on the dominant lithology and texture. Seismic control was obtained from the publications of Jansa and Wade (1975), Given (1977), Eliuk (1978) and Schlee and Jansa (1981), as well as from personal communications of J. Wade and B. MacLean of the Atlantic Geoscience Centre. The seismic data were particularly important in illustrating the structural and regional sedimentological framework of the platform-to-basin transition, a task complicated by the dramatic thickening of sedimentary units basinward, as a result of peneccontemporaneous faulting along the east trending hinge zone.

The wells used in this study are those for which confidentiality restrictions have expired in accordance with the Canada Oil and Gas Lands Drilling Regulations. Information is released from confidential status 2 years following the termination of an exploratory well and 90 days after a delineation well. Seismic data remain under confidential status for 5 years. Several additional wells have recently been drilled in the East Sable Island area. The data from these wells are not available. However well control in the area is sufficient to present a detailed geologic study.

Three main aspects of the geology in the Lower Mississauga unit and the Mic Mac Formation are addressed, representing a progressive reduction in the scale of investigation from regional to microscopic. The task of erecting a regional lithostratigraphic framework for the Lower Mississauga unit and Mic
Mac Formation was based on recognition of time-stratigraphic equivalent units or systematically diachronous horizons. This was complicated by basinward thickening of coeval sediments, and by the fact that no definitive time-stratigraphic marker units, such as bentonite beds, have been recognised on the Scotian Shelf.

Marker units which are environmentally controlled, such as limestone units within dominantly siliciclastic sequences, are generally readily recognised and have been used in this study. Busch (1971) noted that thin limestone beds are deposited on marine shelves parallel and adjacent to successive positions of the shoreline. The carbonates reflect a local decrease in siliciclastic input and have demonstrably regional significance in the context of transgressive-regressive events. The role of the stratigrapher is to distinguish between these regionally significant events and lateral facies variations, while considering the possible diachronism of such markers. Fortunately the carbonates in the study area are extensive. However, it is usually difficult to trace these markers into the laterally equivalent, predominantly limestone sections of the Abenaki Formation.

Limited paleoenvironmental reconstructions between wells in the East Sable Island area were undertaken. Cores provided the best means for definition of depositional environments, owing to the preservation of sedimentary structures and the vertical sequence of lithologic associations. Each descriptive unit observed in the cores examined was correlated to well-log signatures, providing the basis for a powerful predictive tool when used with the appropriate facies model in areas without cores. Drill cuttings were used in conjunction with well logs to ascertain grain texture, mineralogy and cement. The relative scarcity of cored wells provides difficulties in determination of the precise configuration and geometry of
particular facies and potential reservoirs. Additional complications arise from composite depositional units, local deviations from idealized facies models and diagenetic effects on log response.

The establishment of general lithofacies has allowed the forecasting of reservoir trends. Primarily textural heterogeneities modified by diagenesis impart a natural anisotropy to potential reservoir facies. It is important to understand the distribution of different types and scales of subtle, facies-related heterogeneities, which affect porosity and permeability gradients. These reservoir heterogeneities are represented on a variety of scales ranging from grain-pore distributions and bedding character to large-scale lithologic variations. The effect of biogenic activity on the enhancement or deterioration of reservoir properties is an important consideration.

Sedimentary layer characteristics and gross lithology, combined with commercial core analyses, were used to determine the variation in porosity and permeability within particular depositional units. The core analyses are obtained from well history reports. Approximately 50 thin sections yielded data on mineral composition and texture.
2.0 Regional Geological Setting

2.1 General

The sedimentary basin off Nova Scotia Basin represents part of a mature Atlantic-type rifted continental margin. It evolved during Mesozoic-Cenozoic time and was initiated with the opening of the North Atlantic Ocean on separation of North America from Africa. The Scotian Basin and adjacent platforms are structurally bounded by the Yarmouth Arch in the southwest and the Avalon Uplift in the northeast (Fig. 2.1). The basin is flanked to the northwest by the Nova Scotian uplands, part of the Appalachian Orogen. The basin overlies oceanic crust seaward of the continental slope and rise. It is located offshore and covers nearly 275,000 km$^2$, being in excess of 1000 km long and 250 km wide. Sediments prograding over basement highs, platforms and into the subbasins, have formed a broad sedimentary terrace, adjacent to the continent. The top of this terrace is the present-day continental shelf.

The structural trend of the Scotian Basin is dominantly northeast, swinging east-west in the vicinity of the Canso Ridge. The Canso Ridge was an emergent stable basement feature for most of Triassic and Jurassic time and is onlapped by Late-Middle Jurassic and younger sediments (Purcell et al., 1980). The LaHave platform was a regionally stable area throughout Mesozoic-Cenozoic time. Two areas of thick sediment accumulation occur south of the Canso Ridge. The Abenaki Subbasin lies south of the Canso Ridge and plunges southeast. The landward margin is defined by the basement hinge zone and the basinward limit by a postulated structural element, the North Sable High. The landward-dip of seismic reflectors seen in the area is presumably a consequence of draping over this feature (Jansa and Wade, 1975). The Sable Subbasin is bordered in the north-northwest by the North Sable High and the
basement hinge zone. The subbasin represents a structurally embayed monocline, and the seaward boundary is not defined.

A relatively conformable succession of Late Triassic to Recent sediments attains a thickness in excess of 12 km beneath the outer continental shelf and upper slope. This sedimentary wedge overlies peneplained Paleozoic basement, comprising slightly metamorphosed Cambro-Ordovician sediments, Devonian granites and unmetamorphosed, mildly deformed Permo-Carboniferous sedimentary strata (Jansa and Wiedmann, 1982). The overall framework of sedimentation reflects wedge-shaped upbuilding and southeasterly progradation on a slowly subsiding continental margin, complicated by the interaction of tectonic activity, subsidence, compaction, variation in sediment supply and sea-level fluctuation.

Stratigraphic terminology and nomenclature used in this study are those of McIver (1972), as subsequently modified by Jansa and Wade (1975) and Given (1977). Detailed stratigraphic descriptions of the Mesozoic-Cenozoic strata of offshore Nova Scotia were given by McIver (1972), Sherwin (1973), Austin (1973), Jansa and Wade (1975), King et al. (1975), Given (1977), Eliuk (1978), Purcell et al. (1980), Wade (1981) and Jansa and Wiedmann (1982). The following summary of the geological history of the Scotian continental margin is derived from these publications.

2.2 Geological History

The development of the present continental margin off of Nova Scotia began in Triassic time, but possibly as early as Late Permian time, with an initial phase of graben evolution and sediment infilling accompanied by diabasic, basaltic and doleritic volcanic activity (Jansa and Wiedmann, 1982). Major Late Triassic/Early Jurassic extensional tectonics resulted in
a system of northeast-trending grabens and horsts. This provided a structural fabric of basement highs and subbasins that ultimately controlled early sedimentation.

The location of early sedimentary basins and basement highs reflects Paleozoic structural trends in the Appalachian orogenic belt (Jansa and Wade, 1975). Basal, reddish silty shales, sandstones and minor conglomerates (Eurydice Formation) were deposited in continental, fluviatile and lacustrine environments. Middle and Early Jurassic sediments appear to have been concentrated in structurally low areas. However, they gradually filled the basins and spread over the stable platform. In the northwest part of the basin, the oldest deposits are late Early Jurassic, seaward Triassic sediments are postulated (Purcell et al., 1980).

During Early Jurassic extension and subsidence of the initial rift margin, a narrow, shallow, semi-restricted epicontinental seaway was developed. This resulted in the deposition of up to 3 km of salt incorporating minor redbed intercalations. These evaporites of the Argo Formation have not been observed on the landward flank of the basin, but appear to be restricted to the subbasins. The formation has been dated palynologically as Rhaetian to Hettangian-Sinemurian (Barss et al., 1979).

Salt deposition abruptly ceased in Early Jurassic time. The Argo Formation is overlain locally by nearshore sabkha and subtidal carbonate deposits of the Iroquois Formation, which are succeeded upward and laterally by continental and marine siliciclastic rocks of the Mohican Formation.

The Iroquois Formation consists of fine- to micro-crystalline dolostones with nodular anhydrite and stromatolitic beds, grading up into dolomitized, pelleted, oolitic and skeletal limestones (Jansa and Wiedmann, 1982). The vertical sequence indicates a gradual decrease in restriction of the
environment from a hypersaline, semi-restricted tidal-flat setting to open
marine, subtidal conditions. The siliciclastic strata of the Mohican
Formation include alternating fine- to coarse-grained sandstone and
variegated shales with rare, distal intercalations of algal limestone (Jansa
and Wade, 1975). These indicate continental, marginal-marine conditions.
Mohican Formation siliciclastics become marine seaward of the hinge zone (J.
Wade, pers. comm.) The deposition of this clastic wedge has been correlated
with the rejuvenation of source areas upon the initiation of seafloor
spreading in early Middle Jurassic time (Jansa and Wade, 1975). Uplift of
the southwest portion of the nearshore platform resulted in a major
unconformity. Also, local intrusion of basaltic dykes and sills accompanied
early seafloor spreading (Grant et al., 1985). The unconformity has not been
recognized extensively south of the hinge zone and deposition in the basin
may have been relatively continuous (Jansa and Wiedmann, 1982).

Siliciclastic deposition giving rise to the Mohican Formation ended
abruptly with a widespread transgression. The initiation of normal marine
conditions in late Middle Jurassic time resulted in a second stage of
carbonate platform and bank development on the LaHave Platform. The
deposition of extensive carbonate facies indicates a change in the structural
behaviour of the continental margin, whereby dominantly vertical tectonics
was replaced by regional downwarping, resulting in low to moderate
topographic relief. Presumably, precontinental-drift marginal basins were
filled by this time (Given, 1977). Two facies accompanied the development of
platformal and shelf-margin carbonates, an updip, nearshore siliciclastic
facies (Mic Mac Formation) and a basinal shale facies (Verrill Canyon
Formation). Siliciclastic deposits became increasingly abundant landward
toward the north. Interdigation of these laterally equivalent, lithologic units is extremely complex.

Carbonate sedimentation began during Bathonian time when a transgressive sheet of sandy, oolitic grainstones and packstones was deposited along the outer margin in close proximity to a siliciclastic shoreline (Jansa and Wiedmann, 1982). These strata constitute the lowermost unit of the Abenaki Formation and are known as the Scatarie Member. Carbonate deposition was briefly interrupted in Callovian time when the Missaine Member, consisting primarily of marine shale, was deposited. In Late Jurassic time, thick, locally reefal carbonate strata were restricted to a narrow zone at the shelf margin.

During deposition of the carbonate complex, lime mudstone was accumulating landward and an association of shale, limestone and thin quartzose sandstones (Mic Mac Formation) was prograding in back-bank and shelf areas. In the Sable Island area, sandstones and shales were laid down adjacent to the Baccaro carbonate bank. To the northeast, carbonate sediments interfinger with siliciclastic rocks of the Mic Mac Formation.

In late Early Kimmeridgian time, the depositional environment on the LaHave platform deepened, and high-energy oolitic and skeletal carbonates were replaced by skeletal wackestones, biomicrites and lime mudstones (Eliuk, 1978; Jansa, 1981). By Late Kimmeridgian time, a new regressive phase gave rise to a decrease in shalliness with re-establishment of isolated coral-stromatoporoid bioherms and possibly reefs near the shelf margin (Jansa and Wiedmann, 1982; Jansa, 1981). This regression has been attributed to rejuvenation of source areas, including the elevation of the Avalon Uplift. This tectonic activity has been correlated with the final separation of the North American and European plates (Jansa and Wade, 1975). This resulted in
the development of major drainage systems that deposited thickly bedded, fine-grained to conglomeratic sandstones and relatively thin shales. Seaward progradation of these clastic sediments caused segmentation and seaward retreat of the Abenaki carbonate bank toward the south.

Massive carbonate deposition was essentially terminated in the Late Tithonian-Berriasian as a fluvial-deltaic complex prograded south across the basin margin. The Missisauga Formation forms a large delta complex, consisting of a suite of associated depositional systems including alluvial-plain, lower delta-plain, delta-fringe and barrier-coast environments. Minor Jurassic carbonate facies persisted in the southwest and in deeper water adjacent to active delta lobes. Seaward, these facies grade laterally into Verrill Canyon shales. A brief marine incursion in Hauterivian time resulted in widespread deposition of intercalated oolitic limestone and sandstone in an otherwise siliciclastic sequence.

Deposition of the Missisauga Formation ceased in Aptian-Barremian time with a marine transgression, which gave rise to the Naskapi Shale Member of the Logan Canyon Formation. The Logan Canyon Formation represents a second stage of siliciclastic deposition. However, identification of a discrete deltaic complex is difficult. Morphologically, the unit may have consisted of a large coastal plain with small fluvial systems and marine embayments, estuaries and tidal channels (Given, 1977). Regionally, a slow transgression is expressed as a progressive upward decrease in the thickness and proportion of sandstone bodies and average grain size (Grant et al., 1985).

A major transgression was in evidence by Cenomanian time, flooding the coastal plain and arresting sandstone deposition except in marginal areas of the basin. The deposition of marine shale facies of the Dawson Canyon
formation was interrupted twice by periods of chalky carbonate sedimentation during brief rises in sea level.

Outer-shelf and continental-slope conditions persisted to Late Eocene-Oligocene time (Jansa and Wiedmann, 1982; Doeven, 1983). A regional marine regression commenced in response to outbuilding of the shelf margin and eustatic lowering of sea level. Siliciclastics were mainly deposited as a prograding wedge, which resulted in construction of the present-day shelf. Coarse siliciclastic deposition during Late Miocene-Pleistocene time was related to glaciation, when much of the shelf was subaerially exposed. This resulted in the erosion of the proximal part of the clastic wedge, locally down to Lower Cretaceous sediments (Jansa and Wade, 1975).

Though recent petroleum exploration drilling has provided much new stratigraphic information, many questions remain. Mesozoic sediments underlying the continental slope and rise remain virtually unexplored. Little is known of the origin, nature and spatial distribution of deposits laid down prior to seafloor spreading. Undoubtedly continued exploration in the offshore will ultimately provide an understanding of a variety of geologic and stratigraphic problems.

2.3 Lithostratigraphy.

2.3.1 General

The onset of seafloor spreading coincided with the establishment of normal marine conditions in Middle and Late Jurassic time. A complex succession of coeval clastics, basin-margin carbonates and basinal shales was deposited during widespread marine transgression. These sediments comprise what McIver (1972) and Given (1977) defined as the Western Bank Group.
consisting of the Mohawk, Mic Mac, Abenaki and Verrill Canyon Formations. These sediments are overlain by and in part equivalent to, a thick, terrigenous siliciclastic sequence, called the Nova Scotia Group. The lowermost part of the basal formation (Missisauga Formation) of the Nova Scotia Group and the clastic formation of the Western Bank Group are considered in this study.

The depositional framework for the Western Bank Group is characterized by complex lateral relationships between nearshore marine shelf and basinal facies. In the Abenaki and Sable Subbasins, deltaic and prodeltaic siliciclastic deposits prograded basinward throughout sedimentation of the Western Bank Group. Peripherally, a contemporaneous, carbonate bank was formed along the basin margin in the southwest. A transitional area with mixed carbonate-siliciclastic sediments separated these two principal facies. Further seaward, slope and basinal shales, argillaceous lime mudstones and possibly turbidites were deposited.

The regional uniformity of the siliciclastic part of the sedimentary wedge results in problems concerning stratigraphic nomenclature. The updip sandy facies are generally too homogeneous to be differentiated exclusively on the basis of lithologic criteria. Distally, units pass laterally to dominantly argillaceous facies. In the central portion of the basin, formations can be distinguished on the basis of well defined transgressive and regressive events.

2.3.2 Missisauga Formation

The Missisauga Formation in the Abenaki and Sable Subbasins reflects deposition in an Early Cretaceous, prograding delta complex, comprising a broad spectrum of associated depositional environments. The formation
consists of thick, massive sandstones separated by relatively thin shale intercalations in the upper shelf and central shelf regions, grading into thinner sandstone units basinward, with concomitant thickening of the intervening shales. The updip type section was defined by McIver (1972) in the Shell Missisauga H-54 well (44°23'19.38"N; 59°22'27.6"W) between 2388-3511 m subsea (7855–11520 ft). The section consists of approximately 60% fine-grained to conglomeratic sandstone in units 60 to 90 m thick, interbedded with subordinate laminated, carbonaceous shales and siltstones. The sandstones are friable, and vary from clean and well-sorted to argillaceous and poorly-sorted, with fining-upward sequences common. Nearly 60% of the sandstones are porous with average porosities in excess of 20% (Given, 1977).

The type section in the basinward facies was defined in the Shell Cree E-35 well (43°44'20.71"N; 60°35'55.9"W) between 2551.0–3718.5 m subsea (8370–12200 ft). The interval included decreasingly common sandstone (35%) in units 6 to 15 m thick, with intervening siltstones and shales that are commonly burrowed and fossiliferous. The sandstones are predominantly fine- and very fine-grained, clean to slightly argillaceous, moderately indurated with sporadic burrows and thin coal seams or partings evident. Limestone beds are locally common and are typically arenaceous, oolitic, skeletal grainstones and packstones with rare sandy lime mudstones. The lower contact is defined at the base of the lowermost sandstone with a sharp, cylindrical spontaneous potential log response. Where sandstone units are less common, the position of the basal contact becomes somewhat arbitrary. The upper contact is sharp and defined at the base of the distinctive Naskapi Member shale, which normally coincides with the top of the first massive sandstone of the Missisauga Formation. The Naskapi Member is a varicoloured shale unit
and is frequently reddish brown and pale red near the base. Because of its distinctive lithologic character, the base of the Naskapi shale has been used as a stratigraphic datum for the cross-sections in the present study. If the Naskapi shale is absent, as in the updip regions of the shelf, the sandstone-shale sequences of the Logan Canyon Formation cannot be readily distinguished from the Missisauga Formation on the basis of lithology.

The Lower Missisauga unit is not a formally defined lithostratigraphic unit. Given (1977) used the 'O' Marker to subdivide the Missisauga Formation into upper and lower units. The 'O' Marker is a distinctive lithostratigraphic unit, and seismic reflector in the upper part of the Missisauga Formation. The 'O' Marker limestone unit consists of oolitic and skeletal grainstones and interbedded siliciclastic rocks (Jansa and Wade, 1975).

Recent drilling has confirmed the presence of a shale unit in the lowermost part of the Missisauga Formation. This facies is best developed in the mid-shelf region, where a thick shale occurs within a dominantly sandstone succession. Basinward where sandstone units are commonly separated by relatively thick shales, the position of the shale unit becomes less clear. Updip the shale unit thins, but remains lithologically distinctive. In this study, the top of the Lower Missisauga unit is picked at the top of this shale unit. One objective of the present study is to demonstrate the lithostratigraphic utility of the shale unit.

2.3.3 Mic Mac Formation

The type section of the Mic Mac Formation was established by McIver (1972) in the Shell Mic Mac-H-86 well (44°35'28.87"N, 59°27'02.47"W) between 3086.0-4381.5 m subsea (10125-14375 ft.). The unit represents shallow marine
and in part nearshore and terrigenous environments. The type section of the formation comprises approximately 15% sandstone, 13% limestone and 72% shale. The shales are medium to dark brown to olive gray and rarely reddish brown, silty, calcareous, slightly carbonaceous and commonly burrowed and fossiliferous. The sandstones occur in beds 3 to 9 m thick and are very fine- to fine-grained, slightly argillaceous, calcareous to siliceous, well indurated and less commonly carbonaceous, pyritic sideritic, fossiliferous, glauconitic and burrowed. About 30% of the sandstones exhibit good reservoir quality with porosities, ranging from 10% to 28% and averaging about 16% (Given, 1977). Carbonate units consist of sandy lime mudstone, sandy bioclastic wackestone and thin oolite and fossil packstones or grainstones in beds from 3 to 6 m thick.

The Mic Mac Formation interdigitates with Abenaki carbonates in the central shelf region and grades basinward into shale. Overall, the formation is interpreted as an updip and lateral clastic facies of the Abenaki Formation. The Mic Mac Formation continually prograded south throughout Late Jurassic time.

The upper contact of the Mic Mac Formation is at the base of the lowest unit of the Missisauga Formation. Where the Lower Missisauga Formation sandstones are less well developed, the contact becomes somewhat arbitrary. Alternatively, the base is picked where the succession becomes dominantly limestone (top of the Abenaki Formation). The contact between the base of the clastics and the top of the carbonate is clearly diachronous (Given, 1977).

The Mic Mac Formation attains a maximum known thickness of 1797 m in Petro-Canada et al. West Esperanto B-78. Isopach and structural trends indicate that the thickest accumulation is in the central portion of the
Fig. 2.2. Isopach map of the late Middle-Late Jurassic Mic Mac Formation. The contours define a thick clastic wedge centred in the Abenaki Subbasin with a lobe extending into the Sable Island area. The southern limit is undefined since the succession gradually shallows basinward.
Abenaki Subbasin (Fig. 2.2). The formation thins over the LaHave Platform and Canso Ridge. The unit shales out basinward, gradually in the southeast but, rather abruptly in the southwest where it overlies the Baccaro carbonate bank. The deflection and convergence of structure contours in the southwest reflect the influence of the underlying Baccaro Member on deposition of the Mic Mac Formation (Fig. 2.3).

2.3.4 Abenaki Formation

The Middle to Late Jurassic Abenaki Formation comprises four members: the basal Scatarie Member, the Missaine Member, Baccaro Member and the Artimon Member. Eliuk (1978) has recognized at least four deepening-upward cycles, followed by abrupt shoaling in the Abenaki Formation. These units display complex vertical and lateral variations in composition and texture as well as in their relationship to coeval siliciclastic sediments.

The Scatarie Member marks a widespread, late Middle Jurassic transgression. Up to 180 m of medium gray oolitic, pisolithic and oncotic grainstone and packstone interbedded with skeletal-peloidal wackestone was deposited in high-energy, very shallow water, marine environments (Jansa and Wade, 1975). The type section has been designated in the Shell Oneida 0-25 well between 3716-3820.5 m subsea (12192-12535 ft.). The unit is overlain by the Mic Mac Formation in the nearshore ridge area and basinward by the Missaine Member.

The Missaine Member records a continuing late Middle Jurassic transgression and a return to siliciclastic deposition in inner to outer neritic environments (Eliuk, 1978). The shale unit is typically 46 to 122 m thick, light olive gray, laminated, calcareous to micritic with rare thin skeletal-peloidal limestone beds. The type section has been described by
McIver (1972) in the Shell Oneida 0-25 well (43°14'57.5"N; 61°33'36.4"W) between 3644-3716 m subsea (11955-12192 ft.). The unit appears to be entirely Callovian in age. The Misaine is only recognized where it is overlain by the Baccaro Member. However, equivalent shales were deposited as the basal beds of the Mic Mac Formation.

McIver (1972) described the type section of the Baccaro Member in the Shell Oneida 0-25 well for the interval 2857.5-3644.0 m subsea (9375-11955 ft.). The interval is as dated Oxfordian-Kimmeridgian to Berriasian-Valanginian (Barss et al., 1979). The unit is essentially massive carbonate, partially consisting of high-energy grainstone with subordinate shale and sand interbeds. The type section is oolitic grainstone, alternating with peloidal lime mudstone and calcareous shale (McIver, 1972). The limestone is sporadically porous but rarely permeable.

The Baccaro Member was deposited locally in a restricted belt along the basin hinge zone in the southwest, representing the paleocontinental shelf edge adjacent to the siliciclastic deposits of the Mic Mac Formation. Seaward of the limestone platform, deep marine shales, marls, chalks and possibly turbidites are anticipated. The nearshore sandy facies were separated from the Baccaro platform carbonates by a neritic moat zone, containing lime mudstone, peloidal mudstone, rare oolitic beds and possible fringing patch reefs (Eliuk, 1978). Cyclic associations of oolitic grainstone and skeletal/peloidal wackestone beds were developed along with bioherms near the shelf margin (Jansa, 1981). The Baccaro skeletal, reefal facies was confined to the shelf edge in the southwest. Coral-stromatoporoid and sponge bioherms were a relatively rare component of the offshore banks (Jansa, 1981). The non-skeletal facies occupied the inner platform and nearshore settings with common, siliciclastic-rich carbonates. The
Fig. 2.4. Structure contour map of the top of Baccaro member (Abenaki Formation) and lateral equivalents. The structure contours in the east define the configuration of the top of a partially equivalent limestone intermixed with subordinate siliciclastics.
Fig. 2.5. Isopach map of the Baccaro Member (Abenaki Formation) and equivalent carbonates. The Baccaro Member is restricted to the west. The eastern area consists of intermixed limestone and subordinate siliciclastics of the Mic Mac Formation.
morphology, areal extent and composition of the shelf-margin carbonate bank was ultimately dependent on bathymetry and proximity to a source of siliciclastic material.

The upper boundary of the Abenaki Formation is diachronous. The contact is generally gradational where the unit is overlain by the Mic Mac Formation. Toward the southwest, the Verrill Canyon Formation overlies the Baccaro limestone with a sharp contact. In some of the recently drilled wells, several thick Late Jurassic Baccaro equivalent carbonate units are separated by equally prominent siliciclastic successions. At these locations, the lithostratigraphy is presently undefined. This problem is addressed in a later chapter.

The Baccaro carbonate bank is initially a northeast trending unit, gradually turning east-northeast (Fig. 2.4). The eastward deflection of structural contours reflects basement influences. Isopach trends indicate the thickest accumulation is in the southwest in Chevron PEX Shell Acadia K-62 where the thickness exceeds 1370 m (Fig. 2.5). The carbonate bank in the southwest displays a steep platform profile on its seaward margin. A gently inclined ramp profile is characteristic of the eastern portion of the carbonate platform.

2.3.5 Verrill Canyon Formation

The Verrill Canyon Formation represents coeval, shallow to moderately deep marine shelf and slope-to-basinal shale facies of the Mississauga, Mic Mac and Abenaki Formations. The formation consists of medium gray to brown, carbonaceous shale with subordinate thin, well sorted, very fine-grained sandstone and siltstone, which may contain scattered ooids, pellets, shell debris and pyrite (McIver, 1972). Depending on the proximity of the
carbonate bank, the shales are often calcareous and may incorporate variable amounts of micritic, argillaceous limestone (Jansa and Wade, 1975).

The type section was defined in the Shell Oneida 0-25 well between 2498.0-2857.5 m subsea (8195-9375 ft.). This interval has been dated palynologically as Hauterivian to Aptian (Williams, 1975). This interval is younger than the sediments considered in this study. Only the upper part of the formation is known, and the base has not been penetrated. The upper contact is diachronous and gradational, since it interdigitates updip with carbonate and siliciclastic sediments. The formation top is picked where the sequence becomes dominantly shale.

2.4 Biostratigraphy

Microfossils have been studied by a number of researchers to paleontologically subdivided and correlate subsurface lithologic units on the Scotian Shelf (Ascoli, 1976; Given, 1977; Bujak and Williams, 1977, 1978; Barss et al., 1979; Jansa et al., 1979). These studies have focused on foraminifera and palynomorphs. Detailed correlation of biohorizons have been restricted by sample quality and the employment of different biostratigraphic techniques. Discrepancies in zonation often exist at the stage level.

Microfossils have been mainly extracted from ditch cuttings and studied at approximately 20 m intervals down a given well. Because of potential problems due to cavings, only tops or first occurrences are selected. These biozonalions have been called assemblage zones (Ascoli, 1976; Barss et al., 1979). However, Doeven (1983) proposed they be called interval zones, because the boundaries are defined exclusively by tops. The tops are generally considered approximate owing to the relatively large sample interval, possible reworking and the commonly sparse nature of the
assemblages. In deeper wells, indigenous microfossils may suffer thermal degradation which hampers identification, but often permits recognition of cavings.

Recently, combined conventional and quantitative (probabilistic) biostratigraphic techniques have been applied to the Scotian Shelf (Agterberg and Gradstein, 1981; Agterberg and Nel, 1984a,b). This approach is still in the developmental stage and cannot at this time be practically applied to the resolution of lithostratigraphic problems.

Partial biostratigraphic control for this study has been extracted from the publications cited above. Additional biostratigraphic data, particularly for the most recently drilled wells, has been provided in personal communications from P. Ascoli and R. Fensome of the Atlantic Geoscience Centre, Dartmouth and E.H. Davies, currently with the Geological Survey of Canada, Ottawa. Biozonations outlined in well histories were also employed. It was often necessary to integrate biostratigraphic data and formulate a 'best' pick. Comments pertaining to relative sample quality were carefully weighed. The biozonations often include broad paleoenvironmental interpretations based on the microfossil assemblage.

2.5 Structural Framework

2.5.1 General

The structural development of the Nova Scotian part of the continental margin can be broadly divided into two phases: rifting and post-rifting seafloor spreading. Each structural stage has a unique style which affected the subsidence and tectonic history. Early rifting controlled the general basement structure and the initial sedimentation patterns. Structural
elements of the post-rifting phase are the consequence of renewed basement movements and more importantly, sedimentary loading on thick, mobile salt. Diapiric structures and synsedimentary growth faults are major structural features on the Scotian shelf.

2.5.2 Structures Associated with Early Rifting

The major basement structural elements of the Scotian margin are defined by a series of fault-bounded basement blocks, created during the continental breakup of North America and Africa in Early Mesozoic time. Faulting was characterized by subsidence of basement blocks in a tensinal stress regime. This created a series of elongate troughs and marginal flexures on the crests of regional arches. On the stable platforms, subsidence was dominantly flexural with minor faulting on the crests. Structure contours on peneplained Paleozoic basement of the nearshore ridge and platform indicate a gently seaward-dipping surface which plunges south-southwest (Given, 1977).

The location of early subbasins and basement highs reflects reactivation of older, northeast-trending Paleozoic structures in the Appalachian fold belt (Jansa and Wiedmann, 1982). Basins are located seaward of older structural embayments and the platforms adjacent to the structural promontories. The Orpheus Graben is apparently a consequence of varying degrees of subsidence associated with the lateral extension of a transform fault, located south of the Grand Banks along a Paleozoic zone of weakness (Jansa and Wade, 1975). The distribution of early fluviatile, lacustrine and alluvial-fan redbeds was controlled by graben geometry and relative subsidence rates.

Since the onset of seafloor spreading, the Scotian margin has subsided passively in response to sedimentation and conductive cooling of the
lithosphere (Beaumont et al., 1982). During this period, local tectonic adjustment and tilting of large fault blocks dramatically altered local sedimentation patterns. Isopach maps of Cretaceous and Tertiary strata indicate a lateral shift of depocentres to the southeast, presumably due to tilting of basement fault blocks along the margin of the basin (Jansa and Wade, 1975). A late Early Jurassic age unconformity on the northwest flank of the Scotian margin reflects a period of readjustment and rebound, which has been correlated to final plate separation (Jansa and Wade, 1975). Paleocene diastems have also been attributed to the response of fault blocks to loading, particularly at the shelf edge (Doeven, 1983).

The distinctive, sinuous, northeast-trending basement hinge zone separates the relatively stable platform from the actively subsiding marginal basin. The creation of the hinge zone corresponded to the initial phase of subsidence, related to rifting. The hinge zone is a series of eastward-dipping en echelon normal faults and marginal flexures in the basement. The style of the shelf edge flexure changes along its length (Eliuk, 1978). Southwest of Sable Island, the shelf edge displays a steep platform morphology sloping some 20–30° seaward. To the east, the margin dips gently seaward and takes on a ramp profile. This difference in shelf morphology resulted in a discordant paleobathymetric gradient between the two areas. The variation was particularly accentuated through Late Jurassic time.

The hinge zone has been very influential in controlling platform-to-basin sedimentation throughout Mesozoic and Cenozoic times. The southwest edge of the stable platform in Late Jurassic time controlled the distribution of carbonate shelf sediments. Basinward thickening of siliciclastic units across the margin complicate the stratigraphy. The influence of the hinge zone on deposition decreased as siliciclastic sediments prograded across the
structure. However, periodic, local movements on the hinge zone disrupted normal patterns of deposition.

2.5.3 Post-Rifting Structural Framework

Up to 7 km of carbonate and siliciclastic sediments overlie basin evaporites, which themselves may approach several kilometres in thickness. The instability created by loading a thick siliciclastic wedge on mobile salt and sediment outbuilding on a tilting continental terrace has created a variety of structures which include piercement salt diapirs and listric or normal synsedimentary growth faults.

2.5.3.1 Synsedimentary Faults

Synsedimentary faults and associated rollover anticlines are common, major structural features and exploration targets on the Scotian shelf (Fig. 2.6). The abrupt thickening of lithologic units on the downthrown sides attests to the contemporaneous nature of the faulting and sedimentation. The faults are normal, concave towards the centre of the basin and dip approximately 45° typically flattening with increasing depth (Fig. 2.7).

The throw is maximum in the centre of the fault slice and diminishes laterally and vertically. The internal side of the downthrown block generally displays a slight rollover. The faults are most prominent on the shoreward edge of the depocentre and migrate basinward concomitantly with the depocentre. Commonly, the faults are perpendicular to thickness gradients and parallel to facies boundaries (Perrodon, 1983).

On the Scotian margin, normal growth faults are probably basement controlled and typically occur on the updip basin periphery in the vicinity
Fig. 2.6. Major fault structures in the Sable Subbasin (modified from Dingwall, 1984).
Fig. 2.7. A north-south multi-channel seismic line through the East Sable Island area shows fault-bounded anticlinal rollover structures and thickening of the succession to the south (modified slightly from B. MacLean, pers. comm., 1985). The most prominent reflectors define limestone units in the dominantly siliciclastic sequence. These can be utilized to various degrees for stratigraphic correlation.
of the hinge zone. Fault patterns are relatively complex and consist of one or more growth faults with at least several antithetic displacements related to the rotation of the sediment wedge. The crests of the rollover shift down dip with depth. Growth faults tend to remain active as long as the depositional axis is maintained along the same line (Bruce, 1973). Oversteepening of the siliciclastic wedge at the shelf margin has been important in initiating normal listric faulting on the outer shelf in Tertiary time (Jansa and Wade, 1975).

The initiation of growth faulting has been attributed to deep-seated salt withdrawal associated with diapirism (Purcell et al., 1980). The weight of thick post-Jurassic sediments beneath the outer shelf probably initiated seaward movement of low-density material, resulting in salt diapirs and ridges in the Sedimentary Ridge Province. Similarly, sliding at the toe of growth faults gave rise to compression, leading to diapirism.

One of the largest structural features in the area occurs south of the LaHave Platform. A zone approximately 16 to 32 km wide and up to 320 km long bordering the shelf edge is interpreted to have moved seaward in Late Tertiary time. This movement has been attributed to oversteepening of the shelf margin (Jansa and Wade, 1975). The en echelon series of sinuous, arcuate faults dip up to 20° seaward. The greatest movements on these faults have been correlated to periods of low regional subsidence and high sedimentation (Jansa and Wade, 1975),

2.5.3.2 Salt Structures

Various forms of salt diapirs, swells and pillows occur in the Orpheus Graben, Abenaki Subbasin and Sable Subbasin on the Scotian shelf. Mobile salt masses are also a feature of the Sedimentary Ridge Province beneath the
Scotian Slope. The updip limit of the Argo Formation salt appears to coincide with the basement hinge zone. Diapirs rise as much as 9.1 km through the Upper Jurassic to Upper Tertiary sedimentary column and cover areas from 4 to 31 km² (Jansa and Wade, 1975). The intensity of diapirism has caused various discontinuities in the sediments. In many places the Argo Formation salt may be absent completely owing to its localization in diapiric structures.

The oldest documented salt occurred in Late Jurassic time (Eliuk, 1978). The timing of diapirism varied across the basin. The main phase of upward growth appears to have occurred during Early Cretaceous time (Keen, 1983). Growth proceeded as intermittent pulses, resulting in doming, faulting and local thinning of Late Cretaceous–Early Tertiary sediments. Many of the local hiatuses at the time are attributed to periods of salt movement (Jansa and Wade, 1975). Doeven (1983) using nannofossils, detected several local hiatuses in Upper Cretaceous sediments and correlated them to salt tectonism. Salt withdrawal has also resulted in local thick accumulations of Tertiary and Quaternary sediments adjacent to some diapirs.

Two types of diapiric structure have been recognized on the Scotian margin. Circular, salt-cored structures are found in each of the subbasins and the Orpheus Graben. Elongate ridges of salt are found in the Sedimentary Ridge Province. The seaward limit of the diapiric structures appears to coincide with the transition from continental to oceanic crust (Jansa and Wiedmann, 1982). A caprock facies is associated with most salt domes are associated with some form of caprock, representing a residuum of insoluble material left behind as the salt rose and was contemporaneously dissolved at the crest by subsurface fluids.
A variety of subsidiary structures are associated with diapirism. The features range from simple doming to complex faulting and localized subsidence. In the Scotian Basin, deformation is relatively minimal, expressed as rim synclines, sharply upturned strata and some flanks and crestal faulting (Jansa and Wade, 1975). However, faulting has been sufficiently complex to prohibit correlation of pay zones and lithologic units associated with the West Sable Island diapiric structure (Smith, 1975).

2.6 Hydrocarbon Occurrences

2.6.1 General

Hydrocarbons in the Scotian Basin have been discovered in reservoirs ranging in age from Late Jurassic to Late Cretaceous. A total of 16 significant discoveries and a number of interesting shows have been encountered (Table 2.1). Initial exploration efforts in the Scotian Basin concentrated on potential traps associated with shallow piercement salt structures which were easily discerned on seismic records. Several significant discoveries were subsequently recorded for wells testing deep-seated anticlinal and rollover structures on the down-thrown side of listric or normal faults. The potential of the overpressured zone play was successfully tested at the Venture prospect in 1979. This prospect contains the first potential commercially viable discovery to date.

The main discoveries are located exclusively in the Sable Subbasin and lie principally near the centre of maximum deposition in the vicinity of Sable Island. The shallower hydrocarbon discoveries on the Scotian Shelf are typically associated with diapiric structures. Diapiric structures have proven to be complexly faulted and the hydrocarbon distribution erratic
<table>
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<tr>
<th>Well</th>
<th>Intervals Tested (m)</th>
<th>Reservoir Formation</th>
<th>Structure</th>
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<tr>
<td>Shell Onondaga E-84 (1969)</td>
<td>untested</td>
<td>Missisauga</td>
<td>Salt dome</td>
<td>gas; 3 delineation wells</td>
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<td>1365-1450 1454-1464 1637-1682 1682-2320</td>
<td>Dawson Canyon Logan Canyon</td>
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<td>Wyandot Logan Canyon</td>
<td>Salt dome oil, gas/condensate; 2 delineation wells</td>
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<tr>
<td>Mobil TETCO Thebault P-84 (1972/73)</td>
<td>3213-3404 3830-3837</td>
<td>Missisauga Anticlinal closure on downthrown side of normal fault</td>
<td>gas, minor condensate; 2 delineation wells; normal and over-pressured reservoirs</td>
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<td>1861-1866 1968-1973 2248-2255</td>
<td>Logan Canyon Missisauga Drape over carbonate bank</td>
<td>oil, gas; 2 delineation wells</td>
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<td>Location</td>
<td>Horizon</td>
<td>Description</td>
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<tr>
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<td>I-59 (1974)</td>
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<td>Mic Mac</td>
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<td>Rollover anticline; associated with a listric fault</td>
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<td>Mississauga</td>
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<td>O-59 (1982)</td>
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<td>Rollover anticline; associated with a listric fault</td>
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<td>Company</td>
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<tr>
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<td>Mic Mac</td>
<td>Anticlinal gas/condensate; normal and over-pressured reservoirs</td>
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<td>3062-3065</td>
<td>Logan Canyon</td>
<td>Rollover gas/condensate; 1 delineation well; associated...</td>
<td></td>
</tr>
<tr>
<td>Shell Petro-Canada et al. North Triumph G-43 (1985)</td>
<td>3835-3846</td>
<td>Missisauga</td>
<td>Anticlinal gas/condensate; 1 delineation well;...</td>
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(Smith, 1975). Down-to-basin faulting parallel to, but seaward of the Baccaro carbonate bank has also been tested in addition to salt diapirs and rollover structures. Some basement-relief-controlled features are known along the hinge zone. Faulting and drape features due to differential compaction are characteristic of siliciclastics overlying the Abenaki carbonate bank. A variety of stratigraphic traps including sand and porosity pinchouts are anticipated (Meneley, 1981).

Abundant fluvial and deltaic sandstones of the Logan Canyon, Mississauga and Mic Mac Formation have excellent reservoir potential. Porosities can locally exceed 30% and average greater than 15% (Given, 1977). Updip, the sequences contain prolific potential reservoir facies and the presence of an effective seal becomes a factor (McIver, 1972). Abenaki Formation carbonates have proven to be essentially nonporous (Eliuk, 1978). Chalk of the Wyandot Formation over the Primrose salt diapir contains light oil and gas (Table 2.1). Potential Triassic and Early to early Middle Jurassic siliciclastic and carbonate rocks have not been tested to ascertain their reservoir properties. However, preliminary observations indicate reservoir quality porosity and permeability exist (Jansa and Wade, 1975).

2.6.2 Overpressure Zone

Within the Sable Subbasin, a significant proportion of the section equivalent to the Lower Mississauga succession and Mic Mac Formation is overpressured. Several early wells penetrated the top of the abnormally pressured section and drilling was terminated owing to technological limitations and later, the belief that overpressuring indicated a paucity of reservoir conditions as in the U.S. Gulf Coast. In 1979, the Mobil TETCO Venture D-23 wildcat well in testing the overpressured zone, encountered a
thick sequence of gas- and condensate-bearing sandstone reservoirs in a deep-seated rollover structure. Formation pressures were nearly twice the extrapolated hydrostatic pressure (Grant et al., 1985). Several subsequent wells have penetrated over 1500 m of overpressured section without encountering the base.

Overpressuring is a relatively common phenomenon in the deeper parts of dominantly regressive clastic sequences worldwide. Overpressuring has been attributed to a number of interacting mechanisms, which include undercompaction of shales, thermal expansion of fluids, water liberated by clay transformation and hydrocarbon generation (Gretener, 1977). The abnormally high subsurface pressures are generally expressed physically in the sediments by reduced shale resistivity, density and acoustic velocity and apparent increased shale porosity and reduced formation-fluid salinity. An overall "by-passing" of diagenetic processes is normally apparent. In the U.S. Gulf Coast, overpressuring is usually associated with a deficiency of porous reservoirs.

The overpressured strata encountered in the Ventura field and elsewhere are atypical in that they contain abundant reservoir facies, are fully lithified and have undergone development of secondary porosity. Detailed shale analyses indicate the overpressured interval is normally compacted (Rodrigue et al., 1985). There does appear to be a slight reduction in average shale resistivity (Grant et al., 1985). The reduction in shale resistivity can usually be attributed to a slight increase in water saturation (Timmerman, 1982). The overpressures in the Sable Subbasin have been interpreted to be a 'hardrock' overpressure that may have originated relatively recently owing to the generation of gaseous hydrocarbons, possibly accompanied by the thermal expansion of fluids in what are effectively sealed
reservoirs. The possibility that gas generation in the Scotian Basin may have stimulated porosity enhancement within associated sandstones has been suggested by Meloche (1985).

A regional sealing horizon has not been identified in the Scotian Basin. Presumably, shale intervals at various depths within the Lower Missisauga and Mic Mac Formations perform this function. The seals must be moderately extensive since sandstone bodies within the overpressured zone may be correlated between structures. The updip seal probably occurs at the down-to-basin fault system bounding the northern edge of the subbasin (Grant et al., 1985).

2.6.3 Source Rock Analysis and Maturation Profiles

The formation of oil and gas is essentially a function of time and temperature, given sufficient quantities of organic matter capable of generating hydrocarbons. The quantity and type of hydrocarbon product is related to the relative proportion of various types of terrestrial and marine derived organic components and the thermal maturation history. Potential source rocks and their maturation in the Scotian Basin were recently studied by Bujak et al., (1977), Barse et al. (1980), Powell (1982), and Nantais (1983).

Geochemical data indicate that there are sufficient quantities of organic matter in sediments in the Scotian Basin to provide a source for hydrocarbons. However, the organic matter is dominantly reworked, degraded, terrestrially derived and thus gas prone. Type-III organic matter dominates mid-Cretaceous and older sediments. Type-II organic matter capable of generating significant quantities of liquid hydrocarbons has been identified in younger sediments. This material has proven to be thermally immature.
The source rock for much of the discovered gas-condensate is believed to be basinal shales in the Sable Subbasin. The close juxtaposition of reservoir facies and potential source rocks bode favorably for the accumulation of significant quantities of hydrocarbons.

Maturation has been evaluated and calibrated using a variety of techniques including geothermal gradient, vitrinite reflectance (\% Ro), thermal alteration index (TAI), and time-temperature index (TTI) (Fig. 2.8). The difference in depth between the top of the mature zone as indicated by cuttings gas analysis (0.45 \%Ro) and other means (0.70 \%Ro) has been referred to as the marginally mature zone. This zone is 1500-2000 m thick on the Scotian Shelf and is considered incapable of generating significant volumes of hydrocarbons. The top of the fully mature zone occurs at 0.7 \%Ro and the base at 1.3 \%Ro. Only potential source rocks within this zone are capable of generating significant quantities of gas. This does not preclude early hydrocarbon generation and subsequent vertical migration from source rocks now in the overmature zone.

Sediments on the nearshore ridges and platform are immature to the depths of basement. In the Abenaki Subbasin, full maturity is reached within the lower portions of the Mic-Mac and Abenaki Formations. Full maturity is attained within the Lower Missisauaga Formation in the Sable Subbasin. This variation is due to the relative subsidence and depth of burial. The presence of the overpressured zone tends to cause an increase in the thermal and maturation gradient, owing to a decrease in the thermal conductivity of the sediments. This results in a narrowing of the fully mature zone. The thermal anomaly recorded over the Primrose salt diapir has resulted in the generation of oil from Late Cretaceous sediments at moderate levels of maturity.
HYDROCARBON POTENTIAL

RELATIVE IMPORTANCE OF GENERATION

FULLY MATURE Main zone of generation for present day discoveries
MARGINALLY MATURE Shows only
PRIMROSE
DRI G AS ONLY
DRI G AS ONLY

% Ro, VITRINITE REFLECTANCE
GAS / OIL RATIO

GAS - CONDENSATE ZONE
LIGHT WAXY OIL (occurs only where lipid rich source rocks are found)
GAS - CONDENSATE - Principally from the thermal degradation of previously generated hydrocarbons

HYDROCARBON MODEL FOR THE SCOTIAN SHELF
(Diagramatic)

Fig. 2.8. A hydrocarbon generation model for the Scotian Shelf (from Nantais, 1983).
3.0 Regional Lithostratigraphy

3.1 Introduction to Lithostratigraphic Problems

Several aspects of Late Jurassic-Early Cretaceous lithostratigraphy on the Scotian Shelf are problematical. The principal concerns arise from outdated or inadequate definition of these lithostratigraphic units on the basis of limited information. The lithostratigraphy was originally defined by McIver (1972) on the basis of data from 20 wells. In the intervening years, over 85 additional wells have been spudded. The variations in lithology would not have been represented in the 20 wells originally used to outline the lithostratigraphic framework. This is particularly evident for the Late Jurassic Mic Mac and Lower Mississauga Formation sandstones encountered in the Sable Subbasin. The drilling of the Mobil TETCO Venture D-23 well in 1979 supplied the first substantiation of a thick, Late Jurassic siliciclastic sequence in the Sable Subbasin. Subsequent wells confirmed the presence of this sequence, encountering a laterally equivalent section in excess of 1400 m thick. Previously, Late Jurassic age siliciclastic sediments in the Sable Subbasin were believed to be predominantly shales of the Verrill Canyon Formation. There is a need to clarify and perhaps redefine Late Jurassic lithostratigraphic units and outline lithologically distinct mappable subunits within the context of this larger framework.

Problems have developed in the application of conventional lithostratigraphic terminology owing to recognition of lateral facies changes and stratigraphic complexity related to penecontemporaneous faulting along the basin margin. Various companies engaged in active exploration and government surveys have adopted different criteria for recognition and definition of some units. This has resulted in the lack of a general
consensus on stratigraphic picks and, indeed, some major discrepancies with regard to definition of the main units. These problems have been resolved in this study by utilizing the present stratigraphic nomenclature and commonly accepted lithostratigraphic principles.

The Mic Mac Formation is 1295.5 m thick in the type section and consists of approximately 15% sandstone, 13% carbonate, and 72% shale (McIver, 1972). Janse and Wade (1975) indicate that the Mic Mac formation has an average composition of 78% shale, 18% sandstone, and 4% limestone. The Mic Mac equivalent sequence penetrated in the East Sable Island area superficially appears much sandier on gamma-ray and spontaneous potential logs, than is indicated in the Mic Mac Formation type section well defined by SP logs. (Fig 3.1 and 3.2)

The problem in recognition of the Mic Mac Formation in the East Sable Island area arises in part, from inherent limitations of the original type section as defined by spontaneous potential log responses. The spontaneous potential log response is essentially a function of permeability. There is no direct relationship between porosity–permeability and the magnitude of the spontaneous potential deflection (Timmerman, 1982). Similarly, there is no direct indication of lithology. The magnitude of the spontaneous potential response is influenced by bed thickness and resistivity, drilling fluid invasion, borehole diameter, shale content and the Rmf/Rw ratio (Asquith, 1982). The SP deflection is suppressed by thin beds (<3 m), shaliness and the presence of gaseous hydrocarbons. The lithostratigraphy on the Scotian Shelf was defined by McIver (1972) in terms of type SP logs. The relative proportion of lithologies was thus determined mainly with reference to permeability. Though important from an exploration point of view, the potential for non-recognition of shaly and relatively permeable sandstones
Fig. 3.1. Gamma-ray, sonic and electrical log curves for a portion of the Mic Mac Formation type section. The gamma-ray log indicates a greater proportion of non-argillaceous lithologies than what might be discerned from the SP log. Only a portion of this difference can be explained by the presence of limestone interbeds.
Fig. 3.2. Gamma-ray, sonic and electrical log traces in a portion of the Mic Mac and Lower Missisaua Formations in the East Sable Island area (Mobil et al. Venture H-22). Comparison with the Mic Mac Formation succession in Figure 3.1 indicates increasing shaliness basinward.
has important implications in terms of lithofacies reconstructions. An accurate account of the proportion of sandstone and other lithologies can be readily extracted from the gamma-ray log.

Figures 3.1 and 3.2 compares gamma-ray, spontaneous potential, sonic and resistivity responses for representative intervals in the type section of the Mic Mac Formation and in the Mobil et al. Venture H-22 well. Sandstone and shale base lines have been superimposed on the gamma-ray and spontaneous potential logs. An arbitrary line corresponding to a maximum of 15% shale by volume has been drawn on the gamma-ray curve.

Comparisons of the SP and gamma-ray curves from the Mic Mac type well indicates that a significant quantity of non-argillaceous lithologies are not expressed on the spontaneous potential curve. The limestones are essentially non-porous and recognized by their high resistivity and acoustic velocity. Ambiguous log responses caused by lithologies, such as calcareous sandstone or porous carbonates, can usually be resolved by detailed log analysis. The gamma-ray curve indicates that the Mic Mac type well consists of 45% non-shale lithologies (<15% shale), whereas the SP log reveals that approximately 20% of the section shows appreciable permeability. Log analysis reveals that approximately 10% of the interval is limestone. Consequently, at least 15% of the sandstone in this interval is not expressed on the SP log curve. The relatively flat and serrated SP response is attributed to the thinly bedded nature of the sandstone and the rather common carbonate cementation of very fine- and fine-grained sandstones in the Mic Mac Formation type section. Mic Mac equivalent sediments in the Venture area have an average composition of 30% sandstone, 7% limestone and 69% shale. Though lithologically similar, the petrophysical log expression of the Mic Mac Formation in the type well and in the East Sable Island area are significantly different owing to the
basinward thickening of sandstone bodies that form distinct coarsening-upward or massive units. Also, higher porosities and permeabilities are encountered in the Venture field area.

The Lower Missisauga unit was originally informally designated by Given (1977). She utilized the 'O' Marker to divide the Missisauga Formation into an upper and lower division. A number of wells drilled in the Sable Subbasin have encountered a relatively thick shale prone interval within the lowermost portion of the Missisauga Formation (Section E-E'). This unit has been informally designated the Shale Member of the Missisauga Formation (Schedule of Wells, 1985). Stratigraphic correlations have confirmed that the Shale Member is a mappable unit in the subsurface. Within the context of this thesis, the top of the Lower Missisauga unit is designated to coincide with the top of the Shale Member and its lateral equivalents.

The Baccaro Member of the Abenaki Formation formed a prominent carbonate bank complex that developed along the edge of the LaHave Platform during the Late Jurassic. This carbonate bank was flanked to the east by an area of marine shelf and deltaic sedimentation which prograded to the south. These siliciclastics comprise the Mic Mac Formation. In the central shelf area, carbonate deposition occurred periodically in response to arrestation of siliciclastic input into the basin under transgressive conditions. The resulting stratigraphic sequence is one of prominent carbonate units in a dominantly siliciclastic succession (See Section A-A'). This study has confirmed the correlation potential of these lithologically distinct units. These limestones form locally prominent seismic markers and are referred to by the petroleum industry under a variety of names in well history reports. The limestone markers were included in the context of subunits in the overall lithostratigraphic framework.
The Mic Mac and Abenaki Formations pass into shales basinward to the south. In the basal sandy portions of the Mic Mac Formation, intervening mudstones become more common and thicken basinward. This complicates correlations in the lower portion of the formation. Biostratigraphic data normally cannot be sufficiently resolved to confirm lateral time equivalence in mudstone-dominated portions of the basin. Definition of the base of the unit is therefore somewhat arbitrary.

3.2 Lithostratigraphy - General

This section of the study identifies the various stratigraphic units, discusses their distribution, describes the lithotypes and interprets the broad depositional environment. Five stratigraphic cross-sections are utilized to illustrate the correlation of the main units and subunits between wells. Because of sparse local well control and the quality of data, the defined units and their distribution should be considered only partially delimited. Well control dictates that the units are best defined in the area immediately east and north of Sable Island.

The Mic Mac Formation has been subdivided into five stratigraphic units. A sixth unit, the Lower Mississauga overlies the Mic Mac Formation. A seventh unit overlying the Lower Mississauga unit has been tentatively identified. These units have been labelled sequentially, the lower most unit 'A' and the top 'G' (Sections A to E). It must be emphasized that each of the units are defined on the basis of their widespread recognition. Within the context of the large units, a number of subunits are recognized. However, they are not widely correlative owing to abrupt facies variations.

As discussed above, several limestone markers within a dominantly siliciclastic sequence have been used for correlation. These regionally
significant limestone markers represent overall transgressive pulses within
the basin. The initiation of the regressive phase is indicated by the abrupt
termination of limestone deposition by prograding siliciclastics. Erosional
and gradational contact relationships reflect the regressive nature of the
correlation surfaces. This can complicate correlations and result in
anomalous unit thickness. Local progradation of 'delta' lobes under
otherwise transgressing seas add further uncertainty. The basal sandstones
of some units display thick, cylindrical or bell-shaped log curve traces and
are typically coarse-grained, pebbly and incorporate coalified material
suggesting a probable fluvial origin. These contacts are invariably
erosional where the fluvial sandstone has cut down into the underlying unit.
This can result in significant unit thickness differences between relatively
closely spaced wells. Also, complex facies relationships in dominantly
alluvial depositional settings on the upper platform make recognition of
individual units difficult.

The seven main stratigraphic units are wedge-shaped, thicken basinward
and eventually shale out toward the south (Sections A to E). The amount of
basinward thickening decreases upward as the basin was gradually filled. The
thickening was most dramatic during regressive phases.

The initiation of a transgression is commonly indicated by the
appearance of limestone interbeds. In rare cases, a basal transgressive
quartzose sandstone or calcarenite with nodular bodies or abundant skeletal
debris and glauconite can be inferred from cuttings. As the transgression
proceeded, the frequency and thickness of limestone units generally
increased. This suggests the transgression is oscillatory. The younger
stratigraphic units commonly have less well developed transgressive limestone
intervals and a more prominent siliciclastic component (Section A-A').
Fig. 3.3. Schematic stratigraphic section (not to scale) illustrating lithostratigraphy in the Mic Mac and the Lower Mississauga Formations.
Fig. 3.4. Reference sections (partially schematic) for lithostratigraphic units in the Mic Mac Formation.
Ultimately, the nature of the sedimentation varies as a consequence of the energy in the environment of deposition and proximity to a terrigenous source of supply. The increasing proportion of coarse siliciclastic material in successively younger units reflects the overall progradational nature of Late Jurassic–Early Cretaceous sedimentation.

A schematic stratigraphic section is illustrated in Figure 3.3. Reference sections for units A to E in the Mic Mac Formation are graphically displayed in Figure 3.4.

3.3 Unit A

The lowermost lithostratigraphic unit of the Mic Mac Formation consists of shale and siltstone with subordinate interbeds of sandstone and minor limestone. Unit A has been penetrated in only four wells within the study area. Two wells are located on the Canso Ridge (Shell Eire D-26; Shell Wyandot E-53) and the other two in the Abenaki Subbasin (Shell Mic Mac H-86; Petro–Canada et al. West Esperanto B-78). Unit A abruptly overlies the Mississih Member or if absent the Scatarie Member of the Abenaki Formation. Where the Mississih Member is present, the lower surface is selected at the base of the first sandstone unit. The top was chosen at the first sharp-based, massive, thickly-bedded, coarse-grained sandstone unit. The upper bounding surface commonly shows a close association with limestone interbeds.

The shale and siltstone in Unit A are dominantly gray or brownish-gray in colour, fissile, silty, locally sandy and incorporate various amounts of mica, pyrite and mollusc shell debris. Relatively common light green shales and minor amounts of reddish shale and abundant dispersed finely comminuted carbonaceous and coal material are reported in cuttings from the Shell Eire D-26 and Shell Wyandot E-53 wells. In the Petro–Canada et al. West Esperanto
Fig. 3.5. Isopach map of Unit A.
Fig. 3.6. Graphic log of shallow marine sandstone and mudstone overlying the Scatarie member cored in the Shell Eire D-26 well (2242.1-2251.25 m).
B-78 and Shell Mic Mac H-86 wells, carbonaceous material only occurs sporadically. Sandstones are for the most part thinly bedded, very fine- and fine-grained, locally medium-grained, silty, argillaceous, moderate- to well-sorted calcareous, well indurated, and incorporate common mica flakes, mollusc shell fragments and scattered glauconite. Sandstone beds are less common and become more argillaceous with depth. In the Shell Mic Mac H-86 well, a 56 m zone between 4008 and 4066 m includes minor siliceous coarse- and medium-grained sandstone. Gamma-ray log traces indicate most sandstones form thin (2-4 m) coarsening-upward units, and attain a maximum thickness of 18 m. Limestones are rare and occur as thin (<3 m) sandy beds containing scattered oolites, pellets or shell debris.

In the study area, Unit A attains a maximum, known thickness of 676 m in the Petro-Canada et al. West Esperanto B-78 well (Fig. 3.5). The unit thins across the Canso Ridge and has a known minimum thickness of 149.4 m in the Shell Eire D-26 well. Isopach trends indicate a general southward thickening across the Canso Ridge into the Abenaki Subbasin. The thickening is more abrupt toward the southeast.

A core from the Shell Eire D-26 well (2242.1 - 2251.25 m) has been recovered from the basal beds of Unit A above the Scatarie Member (Fig. 3.6). The upper 5 m consists of interbedded medium- to dark-gray silty shale and increasingly common light-gray to light greenish-gray siltstone. The interval displays common lenticular and wavy-bedding with ripple-laminations. Quartz grains with calcite and siderite coatings (pseudo-oolids/ Oncolites) and fine gastropod and pelecypod shell debris occur commonly as lag deposits in ripple troughs and on bedding surfaces. The lower section of the core grades from sporadically burrowed argillaceous siltstone (as above) into strongly burrowed and bioturbated, silty, argillaceous, very fine- to fine-grained
sandstone. The sandstone incorporates minor carbonaceous material, shell debris, superficially carbonate-coated grains and glauconite. A few wavy, undulose laminae occur locally and are relatively undisturbed by biogenic activity.

Sedimentology

The limited well control and core material from Unit A precludes a detailed sedimentological analysis. The predominance of shale and siltstone enveloping well sorted, very fine- and fine-grained sandstone and sandy limestone containing glauconite, and scattered marine shell debris indicate a mostly marine origin. Generally there are insufficient data to be definitive about depositional environments, but the general setting is probably one of a low-energy, periodically high-energy, inner-shelf to nearshore marine environment. The proximity to a shoreline and periodic marginal-marine conditions near the Shell Eire D-26 and Shell Wyandot E-53 wells are indicated by the presence of local greenish-gray and reddish shales containing relatively abundant carbonaceous matter. The coarse-grained sandstones in the Shell Mic Mac H-86 well represent periodic incursions of coarser material into the nearshore environment. The well-sorted nature of these sandstones suggest probable reworking by marine processes. However, the possibility of non-marine episodes cannot be discounted.

The sandstone units are commonly expressed as thin coarsening-upward units. Though coarsening-upward units are indigenous to both marine and non-marine environments, the close association of biogenic activity with wavy- and lenticular-bedding favours a marine or marginal-marine origin. These thin coarsening-upward units suggest the existence of submarine bars. Such lithologic and sedimentary structure associations have also been described in
tidal-flat sediments (Reineck and Singh, 1973; Weiver et al., 1982) and lagoonal deposits (Coleman and Pryor, 1982; Reinson, 1984). However, log traces characteristic for fining-upward sequences are more typical of tidal-flat settings.

Age

The limited biostratigraphic data available from the four wells penetrating Unit A has required the consideration of the relative stratigraphic position of the succession in relation to the Missaine Member. These data suggest a dominantly Late Callovian age for Unit A. The biostratigraphic data do not permit greater resolution, particularly for the unit boundaries. The biostratigraphic data also support the lateral equivalency of Unit A and portions of the Missaine and Baccaro Members of the Abenaki Formation.

3.4° Unit B

Unit B has been penetrated by a total of eight wells within the study area, although only four wells encountered the base. Both the lower and upper contacts are lithologically abrupt and sharp in their well log responses. In the central-basin area, the contact occurs at the top of a thick carbonate unit overlain by fine- to coarse-grained siliciclastics. Updip in the basin and on the nearshore ridge, a sharp based, relatively thick, coarse-grained sandstone unit overlying a dominantly shale and subordinate limestone sequence defines the upper contact (Section B-B'). Unit B has been divided into two subunits, the lower and upper. In the central-basin area, only the upper subunit is observed. Investigation of the
upper limestone and associated siliciclastics indicate an overall deepening-
upward cycle. The uppermost limestone forms a thick (100-150 m) unit that
grades updip into interbedded shale and limestone with subordinate sandstone.
The lower subunit is sandstone-dominant and incorporates subordinate shale
and minor limestone. Overall, the upper subunit constitutes about one-third
of Unit B. The contact between the two subunits is abrupt and reflects a
distinct change in the dominant lithology and texture of sandstone bodies.

Massive Baccaro Member carbonate flanks the central-basin area. Well
log correlation of the limestone tongues observed north of Sable Island with
the massive limestone in the west has proven difficult (Section C-C'). It
may be possible to correlate these units if deepening-upward cycles can be
recognised on well logs. This would also require a detailed study of the
vertical variation in limestone composition. However, such detailed
correlations are not imperative to this study.

Limited well control has precluded any detailed discussion of isopach
trends in Fig. 3.7: A general thickening of units toward the south-southeast
is apparent. The isopach contours become increasingly closely spaced toward
the southwest, where the laterally equivalent, Baccaro Member limestone
becomes restricted to the leading edge of the southwest trending LaHave
Platform. Unit B attains an incomplete known thickness of more than 397 m in
the Shell Petro-Canada et al. Uniacke G-72 well. In the Shell Elire D-26
well, Unit B is only 111.25 m thick.

Unit B – Lower Subunit

The lower subunit consists of dominantly sandstone and shale. Owing to
facies variations in relation to basinal position, the nature of the
sandstone bodies and how they are arranged varies considerably. There are no
wells deep enough to have penetrated the lower subunit in the central-basin area. Updip, on the north edge of the Abenaki Subbasin, coarse- and medium-grained sandstone bodies occur in units 12-24 m thick and are separated by 21-67 m of thinly interbedded very fine- to fine-grained sandstone, shale and limestone. The coarser-grained units are commonly associated with abundant carbonaceous matter and form what have been interpreted to be composite coarsening-upward and fining-upward sandstone bodies. The lower sediments of one coarsening-upward sequence in the Shell Mic Mac H-86 well consists of gray shale and siltstone incorporating abundant carbonaceous matter, thin coal stringers and traces of red shale. Intervening lithologies include thin coarsening-upward units of calcareous and dolomitic, very fine- to fine-grained sandstone. The sandstones are well sorted, locally glauconitic or fossiliferous and interbedded with dark- to light-gray shale/siltstone and thin sandy, oolitic and bioclastic packstone, wackestone and minor grainstone.

Medium- to very coarse-grained, pebbly sandstones in thick, massive units are typical of the lower subunit in the Canso Ridge area (e.g. Shell Eire D-26, Shell Wyandot E-53). The sandstone units incorporate common feldspar and coal fragments. Minor interbeds of coal and silty, micaceous, carbonaceous, mottled gray, green and red shales are reported in cuttings. A cylindrical or blocky log trace is characteristic of the lower subunit in this area.
Unit B - Upper Subunit

The upper subunit is a shale-dominant succession resting abruptly on sandstone. The upper subunit incorporates variable amounts of sandstone which show a general basinward diminution in thickness and average grain size.

In the central-basin, the upper subunit is dominantly limestone with a relatively thin siliciclastic basal section. The lower siliciclastic interval consists of interbedded dark-gray, fissile, calcareous, silty, locally carbonaceous shale, very light-gray, calcareous, very fine- to medium-grained sandstone and gray, argillaceous, cryptocrystalline limestone. The capping limestone unit which defines the top of the upper subunit in the central-basin area consists of interbedded light brown to buff marlstone or claystone and light medium gray, variably argillaceous crypto- to microcrystalline limestone. The marlstone is silty in part and exhibits scarce laminations in cuttings.

A core from the limestone succession in the upper subunit is described in the well history report from the Shell Petro-Canada Penobscot L-30 (4049-4058 m) well. The core comprises dense microcrystalline, in part very fine, sandy limestone, thinly interbedded with dark-gray, calcareous shale. Several shale beds are 50-75 cm in thickness.

North of the central-basin area, the upper subunit typically consists of interbedded shale, sandstone and minor limestone in which there is generally more than 50% shale. The shales are mostly medium- to dark-gray, silty and include minor amounts of fossil debris, carbonaceous matter and mica flakes. Minor quantities of red and varicoloured shales are reported in cuttings from the lower section of the upper subunit in the Shell Eire D-26 and Shell Wyandot E-53 wells. Local, greenish-gray, sandy, carbonaceous shale is
described from the Shell Mic Mac J-77 well. Siltstones are common and typically medium- to light-gray, sandy, argillaceous, micaceous, incorporating common scattered glauconite, rare carbonaceous matter and possible locally scattered phosphatic debris. Sandstones are relatively thinly bedded and constitute approximately 10 to 40% of the upper subunit. Characteristically, the sandstones are very fine- to fine-grained, slightly argillaceous, medium- to well-sorted, calcareous and dolomitic and may incorporate scattered glauconite, shell debris, oolites and siderite. Limestone bodies include sandy, peloidal wackestones, oolitic, bioclastic packstones and rare grainstones.

Sedimentology

Both the upper and lower subunits contain siliciclastic sediments in their lower parts and grade upwards into massive limestone in the central-basin area. Updip on the nearshore ridge and near the north margin of the Abenaki subbasin the sandstone-dominant lower subunit grades upward into the shale-rich upper subunit. An overall deepening of the depositional environment across the basin is indicated. The succession has been interpreted as representing a deepening-upward cycle with the upper subunit indicating a greater degree of deepening. The presence of interbedded fine-grained lithologies in the lower part of the subunit in the Shell Petro-Canada et al. Uniacke G-72 well probably indicates deposition on a shallow marine shelf. The overlying marlstone and claystone represent calm-water deposition.

The benthic foraminifera and ostracoda microfaunal assemblages in the core taken from the Shell Petro-Canada Penobscot L-30 well indicate neritic conditions (Ascoli, pers. comm., 1979). Biostratigraphic data indicate,
laterally equivalent successions approximately 15 km to the south in the lower parts of the Mobil et al. Venture B-43 and Olympia A-12 wells. The cuttings consist of very dark-gray to black, dolomitic/calcareous shales and siltstone. Paleoeocological data from these wells confirm outer neritic to epibathyal water depths in the central-basin area (Ascoli, pers. comm., 1983).

The thickly-bedded, coarse-grained, pebbly sandstone units of the lower subunit in wells on the nearshore ridge likely represent alluvial deposits. The associated interbedded varicoloured shales and thin coal beds are characteristic of floodplain sediments.

Basinward, the lower subunit consists of several relatively thick, medium- to coarse-grained, composite coarsening-upward, fining-upward sandstone units separated by interbedded shale, glauconitic or fossiliferous, fine-grained sandstone and limestone. The composite sandstone units are interpreted as representing prograding distributary bar and channel deposits. The presence of minor red shale and thin coal stringers indicate some lower delta-plain sedimentation. The intervening fine-grained siliciclastics and limestone sediments indicate shallow marine and marginal marine deposition adjacent to and basinward of the main distributary system.

The predominance of shale, fine-grained glauconitic sandstone and limestone indicate a mostly marine environment for the upper subunit. Marginal marine episodes are suggested by the periodic occurrence of varicoloured shales in close association with common carbonaceous matter, glauconitic sandstone and peletoid wackestone.
A detailed biostratigraphic analysis of Unit B is available from four wells. There is very good agreement between biostratigraphic data determined from palynomorphs (Baras et al., 1979), foraminifera and ostracoda (Ascoli pers. comm., 1975, 1979) and well history reports. The biostratigraphic data support an exclusively Early Kimmeridgian-Oxfordian age. Ascoli (pers. comm., 1979) has conducted a detailed study of the microfaunal assemblage in core 2 cut in the Petro-Canada Shell Penobscot L-30 well. The interbedded shale units yielded abundant and exceptionally diversified foraminifera and ostracod assemblages. The cored interval 4049.3-4058.4 m has been unequivocally dated as Early Oxfordian.

3.5 Unit C

Unit C is known to exceed 700 m in the Shell Petro-Canada et al. Uniacke G-72 well, but regional isopach trends suggest continued thickening basinward to the south, where the succession shales out into Verrill Canyon shales (Fig. 3.8). Thickening is most prominent in the Sable Subbasin in the vicinity of Sable Island. Strata thin to the north and west. Unit C is possibly more than 100 m thick in the Shell Erie D-26 well, located on the Canso Ridge. Unit C also thins toward the southeast where the dominantly siliciclastic sequence is laterally equivalent to massive carbonate of the Baccaro Member. Correlation of the siliciclastic-dominant succession into the Baccaro Member penetrated in the Mobil TETCO PEX 'C' Cohasset L-97 well suggest that massive carbonate sediments equivalent to Unit C are approximately 320 m thick (Section C-C').
Both the upper and lower bounding surfaces of Unit C in the central-basin area are defined by prominent limestone units. The lower boundary lies abruptly upon limestone of the underlying Unit B. Similarly, the upper boundary is sharply defined by the top of a limestone unit. The lower and upper contacts in the Abenaki Subbasin and nearshore ridge are overlain by relatively thick, abrupt-based coarse-grained sandstone units displaying a blocky or cylindrical SP/GR log trace. The upper contact in the Shell Elie D-26 well has not been identified due to complex facies relationships resulting in a non-distinctive vertical succession.

The boundaries of the laterally equivalent massive limestone in the Mobil TETCO PEX 'C' Cohasset L-97 well were selected on the basis of the occurrence of siliciclastic material in the limestone. In this well, the lower contact (3643 m) is overlain by approximately 50 m of interbedded porous bioclastic limestone, very argillaceous cryptocrystalline limestone and silty, calcareous mudstone. The upper contact (3320 m) is selected at the top of the massive carbonate. The upper bounding surface is overlain by 135 m of interbedded increasingly argillaceous, bioclastic and peloidal limestone, fine-grained, calcareous sandstone and gray silty shale.

Limestone in the Mobil TETCO PEX 'C' Cohasset L-97 well is cored between 3407-3425 m and described in the well history. The limestone is light to medium gray, crypto- to very finely-crystalline and in part dolomitie, argillaceous and pseudo-brecciated. The interval contains rare to abundant fossil fragments including stromatoporoids and less common intraclasts.

In the central-basin area as represented by the Shell Petro-Canada et al. Uniacke G-72 well, sandstones occur as a series of stacked coarsening-upward sequences. The coarsening-upward units rarely exceed 10 m in thickness. Each cycle is normally abruptly overlain by 10 to 30 m of shale
and siltstone. The sandstones are mostly very fine- to fine-grained, moderately well sorted, slightly argillaceous with local traces of carbonaceous material and glauconite. Intervening lithologies are predominantly shale and argillaceous siltstone with rare thin limestone beds.

The overlying limestone consists of interbedded light- to medium-gray, argillaceous micro- to crypto-crystalline limestone and light-gray brown to buff marlstone. The limestone locally displays a chalky texture and cuttings reveal rare laminations. An upward reduction in the proportion of skeletal debris in the limestone unit indicates a gradually deepening environment.

The lower third of the succession in wells drilled in the Abenaki Subbasin contain relatively thickly bedded units displaying blocky SP/GR log traces or less commonly apparent composite coarsening-upward and fining-upward units. These sandstones are predominantly fine- to coarse-grained, locally pebbly, with common feldspar and associated slightly to moderately carbonaceous shale and siltstone.

Approximately 50% of the succession in the Shell Petro-Canada Mic Mac D-89 well is comprised of sandstone. The sandstones occur predominantly as relatively thick, blocky or fining-upward units. The sandstones are mostly medium-grained, moderately well sorted with rare fossil debris, common feldspar and no glauconite. The sandstone units in the Shell Mic Mac J-77 and H-86 wells only 4 km and 6.6 km respectively to the south are less common, thinly bedded and finer-grained. The lithologic variation displayed between these closely spaced wells indicate locally rapid change in depositional facies.

In the Shell Eire D-26 well, the succession is dominated by massive, medium- to very coarse-grained pebbly sandstone units incorporating common feldspar, pyritized wood, coal, shale intraclasts and pyrite nodules. A core
Fig. 3.9. Graphic logs of core interpreted as fluvial channel deposits with related floodplain, crevasse splay or levee sediments in the Shell Erie D-26 (Mic Mac Formation), Mic Mac J-77 (Missisauga Formation) and Mobil TETCO Esperanto K-78 (Missisauga Formation) wells. See Figure 3.4 for explanation of symbols. The schematic GR log on the right illustrates the typical log trace in stacked fluvial channel sequences.
from the Shell Eire D-26 well (1955-1961 m) displays structureless intervals and low- to high-angle planar and minor festoon cross-bedding (Fig. 3.9). Arcuate scour-and-fill structures with lag pebbles are also observed. These features are most typical of channel deposits (Walker and Cant, 1984; Cant, 1982). Cuttings suggest the sandstones contain minor interbeds of green and reddish, carbonaceous, silty shale, probably of floodplain origin. This coarse-grained succession is overlain and in part interbedded with fine- to medium-grained, moderately sorted, glauconitic sandstone associated with dark gray shale incorporating minor coal stringers. These complex interdigitating marine and non-marine facies have hampered any attempts to define the upper boundary of Unit C in the Shell Eire D-26 well.

The shales and siltstones of Unit C are mostly brownish and grayish hues, silty, micaceous, in part carbonaceous and calcareous or dolomitic. Scattered fossil debris, glauconite and pyrite form common accessories. Minor gray, green and red mottled shale is commonly interbedded with coarse-grained sandstone on the nearshore ridge. Traces of red-brown shale are also recorded in cuttings from the Shell Tuscarora D-61 well (3870 m). In the Abenaki Subbasin, minor green-gray shale is commonly, but not exclusively associated with limestone or calcareous, glauconitic, sandstone units.

Limestones in the Abenaki Subbasin are typically thinly bedded, sandy, silty with common skeletal material and oolites. Argillaceous, silty, pelleted limestone with minor bioclastic material is increasingly common basinward. Oolitic limestones appear to be more common in the lower portion of Unit C, which reflects an upward increase in the proportion of bioclastic material. The limestone beds normally occur in grouped sets interbedded with siliciclastics.
Sedimentology

In the nearshore ridge area and northeast margin of the Abenaki Subbasin, alluvial deposits dominate the lowermost sediments of Unit C. These sediments display a blocky log trace and consist of fine- to coarse-grained pebbly sandstone. A core from the Shell Eire D-26 well penetrating this facies has been discussed previously. Similar thick-bedded units characterize the lower two-thirds of Unit C in the Pétro-Canada et al. West Esperanto B-78 well, however the vertical succession demonstrates complex interdigitation of marginal marine and marine glauconitic fine-grained sandstone, shale and limestone with non-marine sediments.

Overlying and interbedded with the alluvial deposits are apparent composite coarsening-upward and fining-upward units. These units become less common in a basinward direction. The fining-upward unit is generally thin relative to the upward-coarsening unit. The gamma-ray log displays frequent deflections in response to the interbedded character of the depositional units. The overlying fining-upward sequences are locally glauconitic and normally better sorted, indicating a possible local transgressive sandstone unit. The failure to recognize common delta-plain sediments can be attributed to erosion and reworking of the uppermost beds preceding the deposition of a transgressive unit.

Marine shelf sediments are characterized by the predominance of shale and siltstone containing marine fossils and local glauconite. The thin coarsening-upward units represent periodic progradation of coarse siliciclastics into wave and current agitated marine environments. The presence of interbedded limestone confirms the marine interpretation. Local nearshore and inner-shelf depositional realms are suggested by abundant
sandstone incorporating minor coal debris and finely comminuted carbonaceous material, reflecting proximity to a shoreline.

A marine carbonate shelf persisted laterally, equivalent to the major siliciclastic wedge of sediments occupying the upper shelf and central-basin areas. The texture and allochemical composition of the limestones support a middle to outer neritic environment. Consequently, Unit C records a deepening-upward cycle, similar to that observed in Unit B.

Thick, massive limestone units equivalent to Unit C occur in a number of wells. Usually it is not possible to correlate with confidence the siliciclastic-dominant succession into these wells. Biostratigraphic data provides some assistance in establishing lateral equivalency. The limestone in the Shell Abenaki J-56 well consists dominantly of medium- to coarse-grained oolitic grainstone and wackestone incorporating minor bioclastic debris. Trace fine- to coarse-grained, fossiliferous, calcareous, sandstone is also present. The bioclastic debris is dominated by pelecypods, stromatoporoids, corals, bryozoans and echinoids. Pisolites occur locally.

Bioclastic wackestones dominate the limestone succession penetrated in the Mobil TETCO Cohasset D-42 well. Minor thin pelleted limestones, gray-green shales and local chalky textures are evident. The cryptocrystalline limestone and wackestone in the Shell Demascota G-32 well incorporates stromatoporoids, foraminifera, bryozoans, corals and algal structures. Several thin bioclastic or peletoïd grainstones are observed. In the Mobil TETCO Dauntless D-35 well the limestones are cryptocrystalline and incorporate minor scattered fossil debris dominated by small pelecypods and ostracods. Local, chalky textures are reported in cuttings. Minor, thin pelleted limestones and interbedded glauconitic very fine- to fine-grained sandstone and gray shale occur in the upper part of the interval.
The carbonates from the Shell Abenaki J-56 well represent a dominantly littoral and shallow sublittoral platform environment. The other limestones described above define an open marine carbonate shelf of dominantly middle- to outer-neritic depths.

Age.

Dating of Unit C has been based entirely on microfossils, particularly palynomorphs and foraminifera/ostracoda (Barss et al., 1979; Ascoli, pers. comm., 1974, 1975, 1979, 1981). The biostratigraphic data are generally readily correlated within the lithostratigraphic framework and no major age discrepancies exist. Unit C has been dated Early Kimmeridgian. The good agreement between biostratigraphic data derived from a number of sources is attributed to the widespread occurrence of marine sediments allowing for less reworking and a higher preservation potential for the fossils.

3.6 Unit D

The vertical succession in Unit D is similar to that of Units B and C which define transgressive episodes. Dominantly siliciclastic sediments in the lower part give way to carbonate at the top in the central-basin area. The upper carbonate forms a prominent marker unit in the central-basin area. The lower contact in the central-basin is abrupt where siliciclastics overlap massive carbonate of the underlying Unit C. The upper contact is equally abrupt where siliciclastics terminate carbonate deposition.

The base of Unit D in the Mobil TETCO PEX 'C' Cohasset L-97 well was picked at the top of the massive limestone in the upper part of the Baccaro Member (Section C-C'). The base is overlain by interbedded limestone and
mudstone with subordinate sandstone. The top has been selected somewhat arbitrarily at the base of a 7 m fine-grained sandstone unit which temporarily disrupts carbonate deposition.

Unit D in the Abenaki Subbasin consists of dominantly fine-grained siliciclastics. Here, the upper contact is generally abrupt and defined at the base of a relatively thick (10 m+) sharp-based, fining-upward, coarse- to fine-grained sandstone body overlying interbedded mudstone and siltstone. The base is gradational and commonly occurs in the lower part of a 15 to 30 m thick fine- to coarse-grained coarsening-upward unit. Locally, the sandstone may display a cylindrical gamma-ray log trace. The base is picked where the log trace begins to deflect continuously to the left. In the nearshore ridge area, the boundaries of Unit D are not defined. A distinctive vertical succession was not discerned.

The maximum known thickness of Unit D occurs in the Mobil et al. Arcadia J-16 well. Here, Unit D is more than 725 m thick (Fig. 3.10; Section A-A'). Correlations and seismic data indicate continued thickening basinward toward the south. Unit D thins dramatically toward the northwest from Sable Island across the LaHave Platform. Depositional thinning is more gradual in the Abenaki Subbasin.

The character of the limestones defining the upper part of Unit D gives important clues to the depositional environment. The upper Unit D limestone in the Mobil et al. Arcadia J-16 well is comprised of interbedded argillaceous micro- to crypto-crystalline limestone with trace to locally abundant skeletal debris and locally chalky marlstone to claystone. The marlstone/claystone is typically laminated in cuttings (well history report). Approximately 100 m of siliciclastics underlie the limestone. These consist of calcareous medium- to dark-gray to black, silty shale with minor claystone
and several thin silty very fine- to fine-grained sandstone beds with siliceous cement. The lower half of the Unit D limestone in the Mobil TETCO 
Texaco Citnalta I-59 and Mobil et al. Arcadia J-16 wells is comprised of interbedded slightly silty, cryptocrystalline limestone, gray, calcareous 
shale and marlstone. The interval contains rare pellets and bioclastic debris. Shoaling is indicated in the upper half of the Citnalta limestone. 
The upper limestone consists of interbedded very fine- to coarse-grained, oolitic and bioclastic grainstone, packstone and fossiliferous wackestone. 
Bioclastic fragments are dominated by bryozoans, stromatoporoids, corals and encrusting algae.

Unit D limestones developed to the north (Shell Petro-Canada Penobscot 
L-30, B-41, Shell Abenaki J-56) also consist of high-energy bioclastic, oolitic and pelleted grainstones and packstones. Fossil debris includes 
corals, echinoids, crinoids and brachiopods.

The Unit D succession in the Abenaki Subbasin is shale/mudstone- and siltstone-dominant with subordinate sandstone and limestone. Shales and mudstones are typically silty, medium- to dark-gray and brown and locally carbonaceous. Minor calcareous, locally fossiliferous green-gray shale is observed to be associated with thin limestone bodies. As discussed above, the basal part of Unit D normally comprises relatively thick coarsening-
upward units which define funnel-shape or cylindrical log traces. The other sandstones in Unit D are typically thinly bedded (<3 m), very fine- to fine-
grained, calcareous and incorporate common glauconite and shell fragments. Both fining- and coarsening-upward units are represented. The sandstone bodies in the Shell Petro-Canada et al. Unjace G-72 well are for the most part texturally similar, but thicker relative to the sandstone units observed in wells drilled to the north. The limestone units form relatively thin
bodies consisting of sandy, locally argillaceous, oolitic, pelleted and bioclastic packstone and less common wackestone. Pelocypod and brachiopod fragments are the most frequently reported fossil debris.

Unit D in the Petro-Canada et al. West Esperanto B-78 and Mobil TEICO Esperanto K-78 wells are dominantly composed of coarse-grained sandstone bodies normally displaying a cylindrical log trace. The interval also includes rare thin interbeds of siltstone, mudstone and glauconitic very fine- and fine-grained sandstone. The introduction of massive coarse-grained sandstone records a strong progradation of siliciclastics from the northeast.

Sedimentology

The total lack of cored material from Unit D precludes a detailed sedimentological analysis: The predominance of shale and mudstone enveloping glauconitic sandstone with marine fossils and limestone support a marine-shelf depositional setting. The local abundance of sandstone and high-energy grainstone and packstone in the Abenaki Subbasin suggest periodic or local nearshore and inner-shelf sedimentation. The thin fining- and coarsening-upward sandstone and oolitic limestone bodies possibly represent submarine shoals. The common association of green shale and limestone may indicate local restriction of water circulation, creating reducing conditions in the lee of oolitic shoals. The sandstone bodies defining the basal part of Unit D represent a transitional environment, possibly deltaic. The coarse-grained siliciclastics prograding into the Abenaki Subbasin from the northeast indicate dominantly non-marine and rare nearshore marine deposition as indicated by the local presence of glauconite in sandstone.

The texture and composition of limestones and siliciclastics basinward of the Abenaki Subbasin are important for understanding marine shelf
morphology and bathymetry. The proximity to sources of siliciclastic input are also important. Marlstone, claystone and cryptocrystalline limestone is characteristic of Unit D in the central-basin area (Mobil et al. Arcadia J-16, lower limestone in the Mobil TETCO Texaco Citnalta I-59 well). A middle-to outer-neritic depositional environment is indicated. This relatively deep water facies appears to extend toward the southwest (for example Mobil TETCO PEX 'C' Cohasset L-97, Mobil TETCO Cohasset D-42, Shell Demascota G-32).

Presumably, the edge of the LaHave Platform played an important role in basin sedimentation. The high-energy, bioclastic and oolitic grainstones and packstones that characterize limestones on the edge of the platform defined the Jurassic shelf margin in the southwest. Frequently, these limestones indicate deposition and reworking in a littoral environment, which suggests the shelf margin was rimmed with deeper water behind it. The upper limestone unit in the Mobil TETCO Texaco Citnalta I-59 well suggests carbonate shelf facies prograded seaward toward the south. The limestone in this well grades from interbedded marlstone, claystone and cryptocrystalline limestone into dominantly bioclastic and oolitic grainstone and packstone. The upper part of the Citnalta limestone may actually belong within the overlying Unit E since regression is clearly evident. However, in order to maintain consistency, the top of Unit D has been placed where limestone deposition is terminated by an influx of siliciclastics.

The correlation of strata between the Mobil TETCO PEX 'C' Cohasset L-97 and Petro-Canada Shell Penobsot L-30 wells in Section C-C' records the progressive termination of carbonate deposition toward the southwest. Siliciclastics derived from the north continually prograded southward throughout the Late Jurassic. Consequently, the top of the Baccaro limestone is significantly diachronous toward the southwest outside the study area.
The diachronism is less pronounced within the study area since carbonate deposition yielded rather abruptly to siliciclastic sedimentation.

Age

Unit D has been dated dominantly Late Kimmeridgian (Baras et al., 1979; Ascoli, pers. comm., 1975, 1979; Bujak, pers. comm., 1975; Fensome, pers. comm., 1985). Minor Early Kimmeridgian sediments are evident in the lower portion of wells in the Abenaki Subbasin. This would suggest Unit D is mainly early Late Kimmeridgian.

3.7 Unit E

The upper bounding surface of Unit E defines the top of the Mic Mac Formation. Unit E consists of interbedded shale, sandstone and limestone, commonly arranged as coarsening-upward units. The proportion of each rock type varies between wells, with a tendency to be shallier basinward. Siliciclastics of the basal portion of Unit E rests abruptly on the limestone of the underlying unit in the central-basin area. The top of a prominent limestone defines the top of the unit and hence, the top of the Mic Mac Formation in the Sable Subbasin. The upper and lower contacts of Unit E in the Abenaki Subbasin are defined at a sharp-based, relatively thick, medium- to coarse-grained sandstone body frequently exhibiting bell-shaped and cylindrical log traces (Section A-A'). The base of the upper sandstone overlies thinly interbedded shale, siltstone and limestone of Unit E. The top of the Mic Mac Formation has not been recognized in a number of wells north-northwest of Sable Island (Shell Abenaki J-56, Shell Petro-Canada Penobscot B-41 and L-30). The equivalent strata is particularly sandstone-
rich which hampers recognition of the upper contact. The top of the Mic Mac Formation is recognized in the Shell Eire D-26 and Shell Wyandot E-53 wells over the nearshore ridge. However, the base of Unit E is not evident owing to complex facies relationships.

Unit E can be divided into an upper and lower division in the East Sable Island area on the basis of the presence of two prominent limestone tongues (Section E-E'). The upper limestone defines the top of the Mic Mac Formation. These limestone units range from less than 20 m to more than 90 m thick. The lower limestone unit is not widely correlatable and not recognized north of the Arcadia fault block (Section A-A'). The limited areal extent of the lower limestone attests to the oscillatory and progradational nature of the sedimentation in this part of the basin.

Unit E consists of dominantly shale and mudstone. These lithologies are light to dark gray and brown, normally silty and variably micaceous. Incorporated sand and sandstone stringers are locally common, particularly toward the north. Finely comminuted carbonaceous matter, shell debris and chlorite flakes form common accessories. Shales and mudstones tend to have darker hues toward the north in the Abenaki Subbasin, reflecting increasing proportions of organic detritus. In the Venture field area, finer-grained lithologies are typically calcareous or dolomitic. Shales are rarely calcareous to the north of the Arcadia well.

Multicoloured shales are the dominant fine-grained lithology encountered in the upper parts of Unit E in wells over the Canso Ridge and north margin of the Abenaki Subbasin (Shell Eire D-26, Shell Wyandot E-53, Shell Mic Mac J-77, Shell Chippewa G-67, Mobil TECO Esperanto K-78). Green-gray, red and gray mottled shale exhibit close associations with abundant carbonaceous matter, thin coal stringers, fine shell debris (gastropods, pelecypods) and
 siderite. Siderite occurs bedded, as pellets or as nodular bodies either at the base or more frequently at the top of Unit E. Siderite pellets are reported in cuttings from the Shell Chippewa G-67 (3277 m) and Shell Mic Mac J-77 (3008 m) wells. Common siderite stringers occur in the Shell Mississauga H-54 well between 3788.5-3801 m.

Sandstones normally comprise less than 35% of Unit E. In the central-basin area the sandstones are very fine- to fine-grained, medium- to well-sorted, slightly argillaceous or silty and variably calcareous or dolomitic. Scattered glauconite and shell debris are frequently observed in cuttings. The sandstone bodies are typically arranged in a number of 5-15 m thick, coarsening-upward cycles or non-distinctive units. Sandstone bodies exhibit a tendency to become less frequent, thinner and finer-grained basinward in the succession.

Local sandstone-rich successions occur in some wells, reflecting their proximity to major sources of siliciclastic sediment. Thickly-bedded, coarse-grained, pebbly sandstone bodies characterize the lower part of Unit E in the Petro-Canada et al. West Esperanto B-78, Mobil TETCO Esperanto K-78, Shell Chippewa G-67, Shell Eire D-26 and Shell Wyandot E-52 wells. Traces of fine- and medium-grained, glauconitic sandstone occur locally and frequently in the upper part. Thin coal beds are reported in cuttings from the Petro-Canada et al. West Esperanto B-78 well. The basal 450 m in the Mobil TETCO Petro-Canada Migrant N-20 well (3900-4350 m) consists of thickly-bedded, fine- to very coarse-grained pebbly sandstone interbedded with subordinate shale and siltstone. The upper 250 m (3647-3900 m) display stacked, very fine- to medium-grained, coarsening-upward units 10-20 m thick.

The sandstone bodies in the Mobil Texaco PEX Venture B-43 well (5132-5872 m) are relatively thick-bedded (30-50 m) with local coarse-grained,
pebbly sandstone intervals incorporated in apparent composite coarsening- and
fining-upward sequences (Section E-E'). Equivalent strata located several
kilometres basinward in the Mobil et al. Venture 3-52 (5137.5960 m) and H-22
(5100-5944 m) wells comprise this coarsening-upward units of very fine- to
fine-grained sandstone (Section E-E'). Rapid facies changes are anticipated.
Similar composite sandstone bodies are observed toward the north and
northeast in the Mobil et al. Bluenose 2G-47, and Mobil et al. Arcadia J-16
wells (Section A-A' and D-D').

The limestone units in the central-basin area are typically
argillaceous, fossiliferous, cryptocrystalline, limestones and wackestones.
The most common types of shelly debris reported are bryozoans, echinoids,
corals, bivalves and rare stromatoporoids. To the north, the limestone beds
are normally thin (<3 m) and dominantly mud-supported. Minor sandy, oolitic
grainstone and packstone occurs in trace amounts at the base or less
frequently at the top of the limestone units. Basinward, marlstone may be
locally common. Individual limestone units can rarely be correlated between
wells except within the context of a field. Limestones grade laterally into
oolite-bearing or fossiliferous, very calcareous sandstone. The upper
limestone defining the top of the Mic Mac Formation indicates overall
shoaling. Argillaceous, fossiliferous wackestone grades up to sandy, coarse-
grained oolitic, bioclastic packstone and minor grainstone.

A maximum (but incomplete) thickness for Unit E of over 1000 m is
observed in the Mobil Texaco PEX Olympia A-12 well (Fig. 3.11). Seismic data
and isopach trends indicate that the maximum thickness occurs further south,
where it may be approximately 1250 m (J. Wade, pers. comm.). Unit E is less
than 100 m in the Shell Petro-Canada Mic Mac D-89 well. The unit thins
toward the northwest across the LaHave Platform and also north into the Abenaki Subbasin.

Sedimentology

Unit E strata in the central-basin area contains significant reserves of gas-condensate. Consequently, these rocks have been cored relatively extensively. Only the overlying Unit F has been cored to a greater degree. Most of the cores are from the Venture gas field and adjacent wells. When the core data are integrated with the other lithologic data, a fairly comprehensive sedimentological analysis is possible.

Three main depositional realms can be recognized in Unit E on the basis of variation in lithology, texture, and geophysical well-log expression. These three facies occur in a consistent vertical succession relative to basinal position. The three facies recognised are: 1) alluvial upper-delta plain sediments, 2) distributary channel and delta-marine fringe deposits and, 3) nearshore-marine shelf sediments. The alluvial deposits are the oldest and primarily restricted to the north margin of the Abenaki Subbasin and the lower part of the succession in the Mobil TECO Petro-Canada Migrant N-20 well. These sediments are laterally equivalent to, and in part overlain by, transitional coastal deposits which are in turn interbedded and overlain by marine shelf sediments.

Alluvial sediments consist of three main types of deposits: fluvial channel fill, crevasse splay, and overbank or floodplain. These sediments typically have a blocky, cylindrical or thick bell-shaped gamma-ray or SP log character. Floodplain deposits typically display a serrated log trace. Alluvial sediments have not been cored in Unit E. Interpreted alluvial sediments have been cored in several wells (Shell Eire D-26, Shell Mic Mac J-
Mobil TETCO Esperanto K-78) and exhibit similar log character and
lithology as those observed in Unit E (See Fig. 3.9) These sediments
typically consist of coarse-grained, pebbly, fluvial channel sandstone
at the base, gradationally overlain by finer-grained floodplain deposits. The
course sandstone is typically structureless or cross-bedded and may
incorporate rare pyritized, coalified wood and shale intraclasts. Floodplain
deposits comprise fine- to very fine-grained sandstone and micaceous silty
mudstone incorporating local organic rich lithologies, coal and mollusc shell
debris. Mudstones and shales are typically multicoloured, gray, black, red-
brown and gray-green.

Alluvial deposits comprise over three-quarters of the succession in the
Mobil TETCO Esperanto K-78 and Petro-Canada et al. West Esperanto B-78 wells.
Traces of marginal marine sediments are evident as intercalated finer-grained
glaucicnic sandstones in the upper parts of the main sandstone bodies. The
basal half of Unit E in the Mobil TETCO Petro-Canada Migrant N-20 and Shell
Chippewa G-67 wells and the basal sandstone body in the Mic Mac wells and the
Shell Tuscarora D-61 well are also comprised of dominantly alluvial deposits.
Scattered coarse-grained black chert grains have been identified in cuttings
from alluvial deposits in the Mobil TETCO Petro-Canada Migrant N-20 well
(3822–4306 m) and the Petro-Canada et al. West Esperanto K-78 well (between
3400–3445 m). Very trace amounts have also been reported in non-alluvial
deposits in the Shell Petro-Canada Penobscot B-41 well (at 3276.6 m) and the
Mobil et al. South Venture 0-59 well (3930 and 4260 m). No other reference
to black chert has been made in cuttings, side-wall cores and core
descriptions contained in well history reports or Canadian Stratigraphic
Services logs. The black chert appears to be primarily limited to Unit E.
The restricted distribution of black chert in only two wells over 170 km
apart representing different alluvial systems indicates a common provenance
during the deposition of Unit E.

Overlying and laterally equivalent to the alluvial deposits are
distributary-channel and delta-marine fringe sediments. These deposits are
particularly well developed in the central-basin area in the vicinity of the
Mobil et al. Arcadia J-16 and Mobil et al. Bluenose 2G-47 well. The
distributary channel deposits tend to occur north of these wells and
typically exhibit funnel and cylindrical log traces. The units are normally
30 to 40 m thick and complexly interbedded with marine sediments. The delta-
marine fringe deposits are expressed as stacked multi-storied coarsening-
upward units or composite coarsening-upward and fining-upward units typically
capped by limestone. Basinward, these coarsening-upward units are thicker,
and comprise correspondingly less of the total succession. The upper part of
the coarsening-upward sequences typically have a cylindrical or blocky
funnel-shaped log trace. Sandstone is increasingly common up-section,
suggesting the delta continued prograding throughout Unit E time.

The lower part of two of these coarsening-upward units are cored in the
Mobil et al. Arcadia J-16 well (4885-4897.13 m) and the Mobil et al. Bluenose
2G-47 well (5112.4-5129.2 m) and described in the well histories. The basal
5 m of core from the Mobil et al. Arcadia J-16 well consists of medium- to
dark-gray, micaceous, lenticular-bedded shale incorporating thin,
argillaceous, very fine-grained sandstone beds. The sandstones are slightly
carbonaceous, calcareous, laminated and burrowed. The overlying 4 m is
comprised of very fine- to fine-grained sandstone with numerous carbonaceous
plane- and ripple-laminations and scattered coal fragments or mudstone
intraclasts. The upper 4 m of sandstone is very fine- to medium-grained with
trace scattered coarse grain incorporating mostly irregular carbonaceous
mudstone partings and thin coal stringers. Minor soft sediment deformation structures are evident at the top. The top part of the coarsening-upward sequence was not cored, however cuttings indicate medium- to coarse-grained sandstone. The overall sequence is a composite unit. The overlying fining-upward part of the sequence consists of interbedded calcareous, well sorted, fine- to medium-grained sandstone and gray shale. The fining-upward unit is capped by 5 m of dense microcrystalline, argillaceous and in part sandy limestone. This upper unit represents a local transgressive sandstone body which illustrates the oscillatory nature of the sedimentation as facies shifted laterally. The coarsening-upward unit grades from prodelta sediments up to inner delta-marine fringe deposits. The exact nature of the upper sandstone cannot be discerned from this data. Distributary-mouth-bar sandstones, accretionary beach deposits or tidal channel/bar sediments are all certainly possible (Miall, 1984).

A core from the Mobil et al. Bluenose 2G-47 well (5112.4-5129.2 m) consists of light gray mudstone at the base, grading upward into dark gray to black shale exhibiting minor wavy- and lenticular-bedding. The increasingly darkish colour imparted to the shales reflects a higher proportion of disseminated, finely particulate carbonaceous material. The overlying sandstones are texturally similar and display the same sedimentary structures as those in the core from the Mobil et al. Arcadia J-16 well (4885-4897 m), but include rare interbeds (5-17 cm) of lenticular- and wavy-bedded, black, micaceous, carbonaceous, shale. All of the shale cuttings from Unit E in the Mobil et al. Bluenose 2G-47 well are typically medium- to dark-gray and carbonaceous with relatively common thin coal stringers. The preponderance of carbonaceous material in the sediments indicate their close proximity to a major distributary system located to the northeast. The presence of coal,
glaucocnite and siderite bearing siliciclastics interbedded with limestone in
the Shell Missisagua H-54 well (3758-4020 m) further illustrate the complex
interdigitation of non-marine, marginal marine and open marine facies.

Marine shelf deposits are characterized by the dominance of shale and
mudstone, presence of marine fossils, glauconite and the abundance of
bioturbated rocks. The marine sandstones cannot always be separated from
delta-marinfringe deposits. A marine interpretation is favoured for
sediments which are typically slightly or non-carbonaceous, and calcareous.
The sandstones are usually very fine- to fine-grained and form relatively
thin coarsening-upward units that are difficult to correlate, suggesting they
form isolated sandstone bodies enveloped by marine mudrocks.

The nearshore-marine shelf facies is represented in 6 cores from wells
in the central-basin area. One core is described in the well history from
the Mobil et al. Arcadia J-16 well (5158.1-5176.4 m). The other 5 cores are
from the Venture gas field. In all the cores, marginal-marine facies are
comprised of dominantly brown to gray mudstone with thin interbeds of
variably argillaceous siltstone to fine-grained sandstone. These sediments
are typically either structureless or extensively bioturbated and may locally
contain plane or undulose laminae. The mudstone is for the most part
slightly to moderately calcareous with traces of carbonaceous material. The
siltstone and sandstone beds may incorporate minor shale intraclasts. The
upper 7 m of core from the Mobil et al. Arcadia J-16 well consists of
interbedded structureless fine- to medium-grained sandstone and burrowed,
leucoclastic-bedded mudstone. The sandstone units are calcareous with rare
irregular carbonaceous laminae that are more common toward the base. The
cored interval grades up into interbedded medium-grained sandstone, with
minor coarse grains, and sandy mudstone. The presence of shoreface deposits is possible, but cannot be confirmed from cuttings.

A core from the Mobil et al. Venture B-52 well (5537.9-5555.4 m) exhibits strongly bioturbated offshore mudstones incorporating increasingly frequent and thick very fine- to fine-grained sandstone layers (Fig. 3.12). The sandstone bodies have abrupt, locally load-deformed bases, burrowed gradational tops and display ripple- and inclined plane-laminations. Shale-intraclast rich layers locally occur at the base and along bedding planes. The basal part of the core incorporates two thin (2 cm) micritic beds. The texture and sedimentary structures displayed by these deposits indicate an open marine shelf environment, periodically subject to current agitation as a result of high-energy storm surges. Several metres of laminated sandy cryptocrystalline limestone occurs approximately 10 m above the cored interval.

Core 6 from the Mobil et al. Venture B-52 well (5175.8-5190.3 m) is interpreted as offshore mudstones grading up to possible lower shoreface deposits (Fig. 3.13). The change from offshore to lower shoreface is transitional and consists of interbedded sandstone and mudstone. Mudstone units are bioturbated with a few remnant patches of laminated sand and silt. The sandstone beds have abrupt bases and gradational tops. Palynomorph assemblages have been extracted from these deposits at 5181 m and 5165 m (unadjusted core depths). These transitional to lower shoreface sediments contained dominantly corroded terrestrial elements with poorly preserved marine forms (R. Fensome, pers. comm., 1985). Exclusively terrestrial elements were recovered from the offshore shale/mudstone (R. Fensome, pers. comm., 1985). Despite this, a marine interpretation is still favoured. The relative paucity of marine elements and the corroded texture of all
Fig. 3.12. Graphic log of core from the Mobil et al. Venture B-52 well (5537.9–5555.4 m). See Figure 3.4 for explanation of symbols. Cored interval represents offshore and transitional shoreface (?) marine sandstones and mudstones. The core does not contain any distinctive features to permit depth correction. The core has been adjusted down by approximately 14.5 m.
Fig. 3.13. Graphic log of core from the Mobil et al. Venture B-52 well (5175.8-5190.3). See Figure 3.4 for explanation of symbols. The sediments in the cored interval are interpreted as shallow marine sandstones and mudstones.
palynomorphs indicate reworking and proximity to a shoreline and terrestrial source. These offshore sediments are underlain by a thin fining-upward unit comprising well sorted, very fine- to fine-grained, sandstone grading up to interbedded mudstone and siltstone. This unit is interpreted as a local transgressive sandstone body.

Offshore and submarine shoal deposits characterize the basal 7.8 m of core 9 (5397.15-5414.50 m) cut in the Mobil et al. Venture H-22 well (Fig. 3.14). This basal section is overlain by 5.5 m of low- to medium-angle cross-bedded, calcareous fine-grained sandstone. The cross-stratification occurs in truncated sets and coasts with thin ripple-laminated layers, very rare tubular burrows, glauconite and mudstone intraclasts. These sediments are interpreted as middle to upper shoreface deposits or shallow marine bars. Possible foreshore-beach deposits are represented by overlying structureless to indistinctly inclined plane-laminated fine-grained sandstone. The upper 3 m of core consists of very argillaceous, strongly bioturbated very fine- to fine-grained sandstone grading upwards to sandy siltstone incorporating scattered coarse grains, thin coaly partings and inclined plane-laminations. There is insufficient data to make a definitive interpretation of the upper portion of the core. However, evidence suggests possible back-barrier/lagoonal or intersubmarine bar deposits. Thin argillaceous, oolitic limestone beds occur approximately 10 m above the cored interval.

Tidally influenced shallow marine sandstone has been cored in core 8 (5237.0-5254.8 m) from the Mobil et al. Venture H-22 well (Fig. 3.15). A coarse-grained sandstone, approximately 75 cm thick, abruptly overlies shallow marine sandstone with a scoured pebbly base. The unit is fining-upward overall, dominantly pebbly fine-grained sandstone. It is overlain by a 10 cm conglomeratic layer capped by a 1 cm coaly shale bed which grades
Fig. 3.14. Graphic log of offshore and submarine shoal deposits cored in the Mobil et al. Venture H-22 well (5397.15-5414.5 m). See Figure 3.4 for explanation of symbols.
into bioturbated and current rippled fine-grained sandstone incorporating
minor coal partings. These are overlain by 7 m of bioturbated siltstone with
scattered coal fragments, shell debris and possibly glauconite. An offshore
marine interpretation is preferred for this interval because of pervasive
bioturbation, inferring well-circulated bottom conditions and the presence of
glaucocnite. Several metres of glauconitic lower-shoreface sandstones and
mudstones overlie this siltstone succession.

A core was cut in the Mobil et al. Venture B-52 well (5266.6-5279.5 m)
from lateral equivalent strata immediately above that cored in the Mobil et
al. Venture H-22 well (5237.0-5254.8 m, Fig. 3.13). Shallow marine sandstone
and minor thin graded storm deposits are well represented.

The nearshore-marine facies is dominantly offshore marine
mudstone/siltstone and sandstone but incorporates increasingly common upward,
possible barrier-shoreline complexes basinward of the delta-marine fringe
deposits identified in the Mobil et al. Arcadia J-16, Mobil et al. Bluenose
2G-47 and Mobil Texaco PEX Venture B-43 wells. Correlations indicate that
these shoreline sequences are not laterally extensive and were probably
locally interrupted by tidal channel/delta deposits. Coeval marine
carbonates were periodically deposited where siliciclastic supply was
limited.

Age

Biostratigraphic data available from 15 wells indicate Unit E is
exclusively Late Kimmeridgian (Barss et al., 1979; Fensome, pers. comm., 1985;
Ascoli, pers. comm., 1975, 1979, 1981, 1983). Data from three wells indicate
that part of Unit E may be Tithonian. However, correlation with adjacent
wells would suggest the top of the Kimmeridgian is further upsection. For
Fig. 3.15. Graphic log of possible tidally-influenced shallow marine sandstone deposits in a core from the Mobil et al. Venture H-22 well (5237.0-5254.8 m). A core was also cut in the Mobil et al. Venture B-52 well (5266.6-5279.5 m) from partially lateral equivalent strata. Refer to Figure 4.29 for the graphic log of this core. The sonic log trace was utilized in selecting the datum. See Figure 3.4 for explanation of symbols.
example, the Tithonian in the Mobil TETCO Texaco Cimalta I-59 well is over 400 m thick, which is clearly anomalous for this area (Ascoli, pers. comm., 1979). Using foraminifera and ostracods, Ascoli (pers. comm., 1979) outlined an age that would indicate the upper one-third of Unit E is Tithonian in the Mobil TETCO Cohasset D-42 well. Recent investigation of the palynomorphs in this well suggest a Late Kimmeridgian age (Fensome, pers. comm., 1985). A Tithonian age is proposed by Ascoli (pers. comm., 1975) for Unit E in the Shell Wyandot E-53 well. This may indicate errors in either the stratigraphic pick or biostratigraphy.

Unit F

The Lower Mississauga unit from the top of the Shale Member to the top of the Mic Mac Formation is a largely regressive sequence. The succession is dominantly made up of sandstone and shaly sandstone which pass into shale and mudstone basinward. The top of the Lower Mississauga unit cannot be readily recognized north of the Shell Abenaki J-56 well, though equivalent strata probably exists in the Shell Mississauga H-54 well. In the central-basin area the top of the Lower Mississauga unit is selected at the base of a coarsening-upward unit gradationally overlying a prominent shale interval (Section A-A'). The contact is chosen at a level where the gamma-ray log begins to deflect continuously to the left, indicating a dominantly sandstone content. Toward the north, the upper boundary occurs at the base of a sandstone unit with an abrupt-based cylindrical log trace. The sandstone is typically coarse-grained, pebbly and poorly-sorted. The upper shale unit is largely absent because of the erosional nature of the boundary. Nodular siderite and pyrite display a common association with the top of the Lower Mississauga unit in the Mobil Sable Island C-67 well (4281-4287 m), the Mobil et al. Venture
H-22 well (4415 m) and the Mobil TETCO PEX 'C' Cohasset L-97 well (3075 m). The base overlies limestone defining the top of the Mic Mac Formation in the central-basin area. Landward, the lower contact is selected at the base of a relatively thick sandstone unit exhibiting a cylindrical log trace.

The Lower Missisauga unit incorporates a number of limestone units which can be correlated locally, and in one case, widely within the central basin area. The most prominent of these limestone markers is referred to as the #3 Limestone (4689 m in Mobil et al. Venture B-52) by Mobil Canada Resources Limited and partners. The marker may be recognized as far north as the Shell Petro-Canada et al. Uniacke G-72 well and occurs south of the Mobil et al. South Venture O-59 well, representing a regional dip parallel distance of more than 30 km (J. Wade, pers. comm.). The top of the #3 Limestone is a convenient horizon to separate the Lower Missisauga unit into an upper and lower division in the East Sable Island area.

The maximum known thickness of the Lower Missisauga unit occurs in the Mobil et al. South Venture O-59 well (1293 m), but isopach and structural trends (Fig. 3.16 and 3.17) indicate that the unit thickens basinward. The unit thins toward the northwest over the LaHave Platform. The succession thins dramatically toward the Canso Ridge and north margin of the Abenaki Subbasin. The strongly progradational nature of the sediments suggest the proximal updip margin of the siliciclastic wedge may be eroded.

The Lower Missisauga unit consists of interbedded sandstone and mudstone/shale with subordinate limestone in which there is generally more than 60% sandstone. In the Venture field area the sandstone bodies are arranged as a series of stacked coarsening-upward and composite units (Section E-E'). Cylindrical and funnel-shaped log traces averaging 10-20 m thick are most common. There are also a number of intervals where no
Fig. 3.17. Structure contour map of the top of Lower Missisauga Formation.
diagnostic log shapes are discernible and correlation of individual sandstone bodies is difficult. Sandstone units typically show minor thickness variations and increased shaliness basinward. In the upper division, the main sandstone bodies are replaced basinward by relatively thin sandstone tongues. Several prominent sandstone bodies exhibit basinward thickening between the Venture field and the Mobil et al. South Venture O-59 well, but are accompanied by an overall increase in the proportion of shale in the succession (Section A-A'). Coarsening-upward units are much less common north of the Venture field area. Here sandstone units typically display cylindrical and irregular, non-diagnostic log traces. Several prominent fining-upward (with bell-shaped log traces) sandstone bodies occur in the Shell Missisauga H-54 well (Section B-B'). These units are probably laterally equivalent to at least a portion of the Lower Missisauga unit in the central-basin area.

Sandstones are very fine- to coarse-grained and locally pebbly. Pebbles tend to occur in the relatively poorly sorted top portion of the main coarsening-upward units or the middle of composite sandstone bodies. Relatively thin coarsening-upward sandstone bodies are typically very fine- to medium-grained, well sorted and locally incorporate minor glauconite. The shales and mudstones of the Lower Missisauga unit are commonly darkish gray and brown, rarely black in colour, silty, micaceous, carbonaceous often with scattered chlorite flakes and occasional thin coal partings. Traces of red shale are reported in cuttings from the Mobil Sable Island C-67 well (4303 m). Green-gray shale occurs in cuttings, most commonly in association with limestone and concentrations of carbonaceous matter. Distinct coal beds interbedded with shale are described in the Mobil Texaco PEX Venture D-23 well (4570 m), the Mobil Texaco PEX Olympia A-12 well (4435 m), the Mobil et
al. Bluenose 2G-47 well (4655 m and 4854 m), the Shell Missisauga H-54 well (3576 m and 3708 m), and the Shell Abenaki J-56 well (3133 m).

Carbonates comprise a relatively minor component (<5%) of the Lower Missisauga unit. From the cross-sections (Section E-E') it is apparent that limestone deposition persisted in close proximity to the main centre of deposition in the Venture field area (See Mobil Texaco PEX Olympia A-12 in particular). The limestones are dominantly high-energy, fine- to coarse-grained, sandy, oolitic and bioclastic packstones and grainstones. Rare marlstone, lime mudstone and wackestone where present, usually occurs at the top of a limestone body. Identifiable fossil fragments incorporated in limestone units in the central-basin area include echinoids, corals, and trace stromatoporoids in the Mobil Texaco PEX Olympia A-12 well; crinoids, bryozoans and ostracods in the Mobil et al. Venture B-52 well; corals, bryozoans and gastropods in the Mobil et al. Venture H-22 well. Rare siderite nodules are associated with some limestone units (See Mobil Texaco PEX Venture B-13; 4927 m).

Sedimentology

Lower Missisauga strata contain significant reserves of gas-condensate in the Venture field and adjacent wells. Consequently, these rocks have been extensively cored. All of the cores, including some of the best reservoir facies are from the Venture field. Cores have been selectively taken in 4 wells and represent only a fraction of the total succession. The correlative sandstone reservoirs and limestone markers have been numbered sequentially down the wells. Mobil's terminology had been adhered to in this study. A fairly comprehensive sedimentological analysis is possible in the immediate Venture field area. However, the lack of core material elsewhere in the
Lower Missisauga unit precludes a detailed discussion of the regional sedimentology.

The Lower Missisauga unit represents a dominantly regressive sequence, consisting of distributary-channel and delta-marine fringe complexes. Deposits from a number of subenvironments can be recognized including distributary-channel-fill, distributary-mouth-bar, barrier-beach, tidal channel/delta, lagoonal and shoreline complexes. The upper shale unit is indicative of a transgressive event within the overall sequence, but its absence in some nearby wells suggests siliciclastics continued to prograde at least locally into the East Sable Island area.

Facies have been distinguished on the basis of major vertical lithologic variations in texture and sedimentary structure. The core study indicates many of the sandstone bodies form complex composite units, particularly in the upper part of coarsening-upward sequences. In several instances, the upper part of the sandstone bodies are not cored which hampers interpretation of the depositional environment. Because of these limitations, it is difficult and potentially hazardous to assign diagnostic log responses to paleoenvironmental interpretations. The dipmeter log has proven useful in defining the nature of the various coarsening-upward units.

Core studies and log analysis indicate local marine transgressive shale units are distinctive lithologically and in their mechanical log response. One such shale has been cored in the Mobil et al. Venture H-22 well (4998 - 5007.5 m). The shale is medium- to dark-gray, hard, micromicaceous and mostly structureless. Increasingly common, silt and very fine-grained sand lenticles and laminations occur toward the base. The unit incorporates rare scattered molluscan debris and calcareous silt- and sand-filled burrows in the siltier sections. Several laminations rich in shell fragments occur near
the base. These shale units typically overlie limestone or calcareous fine-grained sandstone containing shell fragments and/or glauconite. Normally, these transgressive shale units exhibit relatively high resistivity and usually can be used to define the shale baseline on the SP or gamma-ray log.

The rocks between the #6 (5001 m in B-52) and the #9 (5137 m in B-52) limestones have been extensively cored in the Venture field. In the H-22 well the #6 to the #8 sandstone has been continuously cored for over 117 m between 4962.5 - 5080.15 m. The #6 sandstone is overall the best represented. The #6 sandstone has also been cored in the Mobil Texaco PEX Venture B-13 well (4952.75 - 4970.85 m), the B-43 well (4954.95 - 4972.65 m) and the Mobil et al. Venture B-52 well (5018.6 - 5024.5 m and 5033.0 - 5049.2 m). Parts of the #7B and #7C sandstones are cored in the B-52 well (5111.4 - 5130.2 m).

The #8 sandstone (5054.5-5090 m) is cored in the H-22 well only. The log trace is a highly serrated funnel-shape with a gradational top. The top 5 m (5054.5-5059.5 m) consists of burrowed, glauconitic very fine-grained sandstone capped by a 55 cm fining-upward, pebbly coarse- to medium-grained transgressive sandstone unit incorporating common fossil debris (crinoid oscicles, coral, mollusca) shale clasts and coal fragments. The equivalent sandstones in the B-13 and B-43 wells are not glauconitic. The balance of the unit represents a prograding shallow marine glauconitic sandstone or barrier-bar sequence (Fig. 3.18). Possible shoreface sediments are present. Coarse-grained sandstone occurs rarely within the cored sequence and is also reported in cuttings from the B-13 (5057-5060 m) and B-43 (5084-5087 m) wells. These coarse-grained units occur at the top of the coarsening-upward unit corresponding to the furthest leftward deflection of the gamma-ray log trace. There is insufficient evidence to ascertain the precise nature of
Fig. 3.18: Graphic log of core from the #8 sandstone (5052.0-5080.0 ft) in the Mobil et al. Venture H-22 well. See Figure 3.4 for explanation of symbols. The coarsening-upward sequence has offshore mudstone and siltstone at the base grading vertically into shoreface and finally foreshore deposits.
these coarse-grained sandstones, though their position in the sequence would suggest the strong possibility of a barrier-beach or tidal-channel origin.

The #7B and C sandstones are cored in the H-22 and B-52 wells. The log signature of these two units varies considerably between wells. In the B-52 well, two distinct stacked sandstone bodies exhibiting a cylindrical log trace are separated by a shale unit. Toward the wells to the east, the two units coalesce becoming less distinct and take on a funnel-shaped log trace.

Only the upper few metres of the #7C sandstone is cored in B-52. The core consists of fine-grained sandstone with slightly inclined planar-laminae and several tubular burrows. There is insufficient core to make a definite interpretation, but a marine origin, possibly upper shoreface is favoured.

A sandstone-dominant, shallow marine shelf interpretation is made for the #7C sandstone cored in the H-22 well. The succession comprises interbedded fine-grained sandstone and subordinate siltstone. The sandstones are glauconitic and exhibit abundant plane- and ripple cross-laminations with common burrowing. The top 3 m are cross-bedded with minor shell debris, coal fragments and rare burrowing. This may indicate upper/middle shoreface deposits at the top.

In the H-22 well, the top metre of the #7B sandstone represents a transgressive unit. The transgressive sandstone forms a fining-upward unit comprised of medium- to fine-grained sandstone with a pebbly base. The unit is moderately burrowed with scattered shell debris, glauconite and coal fragments. It is overlain by bioturbated, argillaceous siltstone (5018-5020 m) with trace glauconite at the base of the #7A sandstone indicating a probable marine origin. The equivalent shaly unit in the B-52 well (5111-5113 m) consists of dark gray shale with floating medium- to coarse-grained sand with rare ripple-laminations, coal partings and poorly sorted fine- to
coarse-grained laminae. Palynological data indicates an exclusively terrestrial assemblage in this interval (R. Fensome, pers. comm., 1985). This shale deposit in B–52 represents a lagoonal environment which is in contrast to the open marine siltstone observed in the H–22 well.

The #7B sandstone in the B–52 well (51113–5123 m) is 7–8 m thick and is comprised of fine- to medium-grained sandstone displaying low-angle cross-bedding or no sedimentary structure. The top 1.5 m is a fining-upward unit with distinct laminae which incorporates common pebbles, dark gray shale clasts and thin irregular coal laminae at the base. Common wispy coal partings are observed at the base. No biogenic structures are evident in the core.

The equivalent #7B sandstone in the H–22 well is approximately 17 m thick (5020–5037 m) of which the top metre is a transgressive sandstone as described previously. The next 2.5 m make up a composite coarsening-upward unit overlain by a fining-upward unit, though the division between the two is indistinct. The coarsening-upward unit is plane-laminated and fine-grained at the base grading up through to structureless coarse-grained sandstone. The overlying fining-upward unit is structureless and grades to fine- to medium-grained sandstone. All of the sandstone incorporates rare pebbles, coal fragments and large tubular burrows. The base of the coarsening-upward unit contains scattered fossil debris and glauconite. Minor indistinct concave-up laminae and discontinuous plane-laminae are evident in the medium-grained sandstone. The underlying 9 m of sandstone is medium- to fine-grained, burrowed, glauconitic with rare indistinct, discontinuous, argillaceous laminae and shell debris.

The vertical succession exhibited by the #7B sandstone in the B–52 well is interpreted as a prograding barrier-island complex. Tidal channel and
lagoonal deposits are subordinate to the underlying foreshore sediments. The basal sandstone is probably wash-over and back-barrier sandstones that overlie lagoonal deposits. These lower lagoonal sediments consist of dark gray shale interbedded with thin units of plane- and ripple-laminated fine-grained sandstone incorporating shale fragments, coal fragments and partings. The presence of abundant biogenic structures and glauconite in the #7B sandstone in H-22 indicates a mostly marine environment. The upper composite sandstone possibly represents barrier and tidal channel deposits. These barrier-complex sediments are relatively minor compared to those in the B-52 well. No lagoonal deposits are present either at the top or base of the core in the H-22 well. The majority of the #7B sandstone in the H-22 well is shallow marine, glauconitic sandstone and overlies marine sandstone of the #7C unit.

The #7A sandstone (5008–5018 m) has been cored in the H-22 well only (Fig. 3.19). The unit is comprised of interbedded bioturbated argillaceous very fine-grained sandstone/siltstone and subordinate slightly burrowed, plane- and ripple cross-laminated, fine-grained sandstone. No distinctive vertical succession can be discerned. Shell debris and glauconite form common accessories throughout the unit. The less argillaceous sandstone bodies are typically calcareous.

The argillaceous nature of the rocks and the abundance of bioturbated rocks observed in the core all suggest a marine origin for the #7A sandstone. The abundance of sandstone in the succession suggest a nearshore to inner shelf depositional setting. Cuttings from the B-52 and B-43 wells indicate the presence of a medium- to coarse-grained sandstone body at the base of the #7A sandstone which is apparently absent from the B-13 and H-22 wells.
Fig. 3.19. Graphic log of core from the #7 sandstone in the Venture field area. See Figure 3.4 for explanation of symbols.
An upper, middle and lower unit is recognized within the #6 sandstone in the B-52, B-43, and D-23 wells (Fig. 3.20). The middle sandstone is not well developed or possibly absent in the B-13 and H-22 well. The gamma-ray log trace indicates stacked sandstone bodies each exhibiting a cylindrical log trace and separated by relatively impermeable strata. Detailed correlations tied into cores indicate a general basinward diminution in grain size between laterally equivalent sandstone units, particularly in H-22. The nature of intervening permeable strata also varies between wells. All of the above suggest complex lateral and vertical facies relationships between sandstone bodies in the Venture area.

The top half of the #6U sandstone in all the Venture wells is medium- to coarse-grained, structureless to faintly cross-bedded in truncated sets often with pebbles, shale and coal fragment lags at the base of laminae. Most of the sandstone in the H-22 well is fine- to medium-grained. Several incorporated fining-upward sequences and scour-and-fill structures are evident. Minor interbeds of plane-laminated, finer-grained sandstone with burrows and shell debris occur irregularly. The coarse-grained unit grades down into increasingly well stratified fine- to medium-grained sandstone with plane- and low-angle cross-laminations and tubular burrows. The lower finer-grained section is largely absent in the B-43 and B-52 wells. These sediments are interpreted as distributary-mouth-bar and channel deposits. The dipmeter log displays well developed foreset cross-bedding patterns for these sandstone units.

Medium-grained, cross-bedded sandstone erosionally overlies dense, dark gray shale in the B-43 well (4965.5-4969 m) and the B-52 well (5048-5049 m) (Fig. 3.20). The shale grades downwards into bioturbated and burrowed bedded shaly sandstone. In the B-43 and B-52 wells, it is clear the shale
Fig. 3.20. Graphic log of core from the #6 sandstone in the Venture field area. The cored interval in the M-22 well is illustrated on the following page. See Figure 3.4 for explanation of symbols.
represents increasing restriction upward. The fact the shale is directly 
overlain by channel or crevasse deposits indicate a lagoonal or 
interdistributary bay environment. Equivalent strata in the B-13 and H-22 
wells consist of interbedded, bioturbated, argillaceous siltstone and ripple-
and cross-laminated, very fine-grained sandstone, indicating a less 
restricted environment.

The top of the 6U sandstone and the section above it has been cored in 
the B-52 well (Fig. 3.20). The lithologic associations indicate a marine 
transgressive unit overlies the 6U sandstone. The basal unit is a fining-
upward calcareous sandstone with a pebble lag at the base overlain by 
burrowed very fine- to fine-grained sandstone incorporating minor shell 
debris. The succession eventually grades up into the 6 limestone.

The top several metres of the 6M sandstone is marine and consists of 
fine- to medium-grained sandstone with common burrows and a few discontinuous 
carbonaceous laminae evident. The underlying sequence is very much like that 
described for the 6U sandstone. Lagoonal/interdistributary bay shale 
separates the 6M sandstone from the 6L sandstone in the B-52 well. The 6L 
sandstone is only cored in the H-22 well. The lithologic succession is 
similar to the units above, but includes more frequent burrowed and 
stratified finer-grained sandstone beds indicating more open marine 
influences.

Cores from the Mobil et al. Venture B-52 well (4944.0 - 4959.45 m) and 
the Mobil Texaco PEX Venture B-43 well (4875.5 - 4879.2 m) were recovered 
from the uppermost beds of the 5 sandstone in the Lower Missisauga unit. 
Figure 3.21 illustrates the vertical succession. The 5 sandstone forms a 
prominent coarsening-upward sequence which includes an overlying 10-15 m 
thick fining-upward sandstone body in the B-52, B-43, and D-23 wells. This
upper sandstone unit is absent in the B-13 and H-22 wells. The uncored lower part of the coarsening-upward units grades from siltstone to medium- and coarse-grained sandstone and is capped by a limy interval. The overlying cored interval are interpreted as barrier-island deposits represented in the cores by dominantly back-barrier tidal and lagoonal sediments.

The basal 2.5 m of core in the B-52 well contains at least four coarsening-upward cycles, each consisting of a basal part that is plane-laminated and less commonly ripple cross-laminated with numerous mudstone intercalations grading upwards into a slightly coarser-grained faintly cross-bedded sandstone. The plane-laminated units are slightly burrowed and calcareous. The upper cycle is the most prominent (80 cm) and contains minor coal fragments. These coarsening-upward units are interpreted as stacked offshore sand bars deposited in the upper to middle shoreface.

Foreshore deposits have not been recognized in the core owing to the fact that the upper part of the barrier-island sequence is represented by tidal-delta deposits. The tidal delta deposits are very distinct, forming cross-bedded fining-upward units with erosional bases (4949-4953 m). The sandstones are typically fine-to coarse-grained with small shale intraclasts, wispy coal fragments and pebbles near the base. Mudstone intercalations become more frequent and distinct upward and may incorporate rare burrows. The dipmeter log exhibits an upward-decreasing dip pattern characteristic of channel-fill deposits (Gilreath, 1978). The tidal channel-deposits are interbedded with mudstone/shale layers usually containing local ripple- and plane-laminated sand and silt, and frequently floating fine-to coarse-grained sand. Burrow structures are locally evident but not very common in the mudstone/shale. The presence of mudstone beds separating the channel deposits laterally and vertically suggests the channel sandstones
were not deposited in the tidal inlet where mud would likely be removed, but as tidal-delta deposits. The close association with lagoonal sediments tends to favour a flood tidal-delta interpretation. The presence of fossiliferous dark green-gray shale (4954.8 - 4955.1 m), micaceous, dark gray mudstones and floating sand grains in mud indicate local restriction in a lagoonal setting. There is no evidence to suggest the floating sand grains were deposited by current activity or are the product of biogenic reworking. The sand was probably introduced into the lagoon by wind or alternatively by rafting (e.g. logs). No root zones or coal stringers were observed to indicate periodic subaerial exposure of the flood tidal-delta.

The top 4.5 m of core in the B-52 well is predominantly calcareous, slightly burrowed, very fine- to fine-grained sandstone incorporating mudstone as planar-inclined laminations grading up to discontinuous and indistinct intercalations with local flaser-bedding and shale rip-up clasts. These deposits represent tidal bar and sandy tidal flat sediments developed in a somewhat less restricted open-marine regime. The uncored sediments above consist of glauconitic very fine-grained sandstone and siltstone overlain by shale. This may indicate rather rapid drowning of the barrier island and a return to offshore marine conditions in this area.

The basal 1.6 m of core from the B-43 well consists of at least three fining-upward (medium- to fine-grained) cycles. The sandstone in the lower part of the cycle is structureless or contains irregular, discontinuous laminae becoming ripple cross-laminated at the top. The top cycle contains a marked increase in coal fragments, shale clasts and trace glauconite and is overlain by lagoonal deposits which are strongly burrowed, silty argillaceous, very fine-grained sandstone. These fining-upward units are interpreted as either lagoonal tidal-flat or channel-margin sand-flat
deposits. The top 55 cm of the core comprises interlaminated medium- to very fine-grained sandstone, siltstone and carbonaceous mudstone/shale. These features are indicative of a tidal flat environment.

The approximately 18 m of core recovered from immediately below the #5a sandstone in Mobil et al. Venture H-22 (4899.05 - 4917.1 m) represents prodelta slope and distal delta-front platform sediments. The core is from the lower portion of a 30 m coarsening-upward unit. The deposits are dominantly micaceous, dark gray argillaceous siltstone and silty mudstone/shale. The most common sedimentary structures are small-scale lenticular laminations, graded planar silt laminations, small-scale current ripples, rare tubular burrows and rare steeply dipping sand-silt laminations. The shale incorporates decimetre-scale, argillaceous very fine- to fine-grained sandstone bodies displaying common burrowing, abrupt load-deformed bases, gradational tops and include rare shell fragments and glauconite (Fig. 3.22). Several graded coarse- to very fine-grained sandstone units (<20 cm thick) with pebbly bases occur in the lower and upper part of the core. Normal microfaults and soft sediment deformation structures occur sporadically in the deposits underlying the graded units.

The top 2 m of the #5b sandstone is represented in the base of the core and comprises common 15-30 cm beds of very coarse- to fine-grained sandstone in normally and inversely graded or plane-laminated units incorporating rip-up clasts, siderite nodules and rare burrows. Distal distributary-mouth-bar sediments occur in the upper 5 m and are represented by an increase in the proportion of sandstone arranged in irregular graded or plane-laminated units with coal partings, flow rolls, and shell debris including gastropods, pelecypods and brachiopods.
Fig. 3.21. Graphic log of core from the upper part of the #5 sandstone in the Mobil et al. Venture B-52 (4944.0-4959.45 m) and the B-43 wells (4875.5-4879.2 m). The cored sequence illustrates offshore deposits grading vertically into a barrier complex. Barrier-beach deposits are not recognised in the core. The upper part of the barrier island complex is represented by tidal delta and lagoonal sediments. See Figure 3.4 for explanation of symbols.
Fig. 3.22. Graphic log of prodelta and distal delta-front sediments cored in the Mobil et al. Venture H-22 well (4899.05-4917.7 m). See Figure 3.4 for explanation of symbols.
The textures and sedimentary structures of the prodelta sequence indicate alternating periods of sedimentation from suspension and from unidirectional current activity. The presence of flow rolls, steeply inclined laminations, microfaults and minor contorted bedding are evidence of deposition on an inclined surface and slumping (Fig. 3.23). These features are characteristic of prodelta deposits (Coleman and Prior, 1982; Miall, 1984).

The barrier-island sandstone comprising the upper part of the #5a sandstone unit is observed only in the B-52, B-43 and D-23 wells and is underlain by interpreted distributary-mouth-bar sediments. Apparently the barrier-island deposits are limited to the west edge of the Venture field and developed locally during an inactive phase of delta progradation.

The prodelta sediments overlying the #5b sandstone in the H-22 well indicates proximity to a distributary system. Limited data from the B-52 and B-43 wells suggests the laterally equivalent barrier-island complex to the west was drowned and is overlain by open marine mudstones rather than prodelta sediments.

Cores have been cut in four wells (all wells except D-23) within the #3A sandstone and #3 limestone units in the Venture Field. Detailed correlations indicate the cores can be stacked such that an almost complete continuous vertical section is available. The mechanical log character is not diagnostic in interpreting the depositional environment. The gamma-ray log displays a serrated cylindrical log trace, whereas the SP log exhibits an irregular bell-shaped curve because of the overlying carbonate and cemented sandstone. There is a general tendency for the sandstone to become finer-grained basinward. Coarse-grained sandstone is observed in the D-23 well (4645-4666 m), the B-13 well (4692.0 - 4734.9 m) and the B-43 well (4669.2 -
Fig. 3.23. Deformation structures observed in a prodelta and distal delta-front sequence cored in the Mobil et al. Venture H-22 well (4899.05-4917.1 m). The sedimentary structures displayed include graded plane-laminations, steeply dipping laminations, contorted bedding, flow rolls and microfaults.
4674.7 m) but is largely absent from the B-52 well (4708.25 - 4714.55 m) and the H-22 well (4714.5 - 4733.05 m).

A similar vertical sequence is observed in each of the cored sections (Fig. 3.24). The succession grades from offshore bioturbated siltstones and littoral deposits into oolitic shoals. The offshore sediments are comprised of bioturbated argillaceous siltstone incorporating rare plane- and ripple-laminated, very fine-grained sandstone beds with rare escape burrows. The sandstone layers have load-deformed bases and gradational tops and are likely deposited by storm generated currents. In the B-13 well, the offshore sediments are overlain by approximately 9.5 m of decreasingly argillaceous very fine-grading to medium-grained sandstone. The succession exhibits regular alternation of structureless layers with plane- to cross-laminated and burrowed layers. Glaucnite occurs in the top several metres. Mudstone laminae are less frequent and relatively clay-poor in the equivalent section in the H-22 well, which also includes several large (>7.5 cm) vertical tubular burrows and minor shell debris.

A series of four increasingly thick, stacked, fining-upward cycles overlie the shallow marine and littoral sandstones described previously. Each cycle erosionally overlies the preceding unit. The dominant basal unit is fine- to medium-grained grading upwards in the top two cycles to medium- to coarse-grained. The sandstone is structureless to indistinctly cross-beded with rare pebbles, shale intraclasts and coal fragments in the upper two cycles. The basal section is abruptly overlain by ripple- and plane-laminated, fine-grained sandstone capped by a 5-15 cm siltstone bed. The upper siltstone bed contains minor ripple-laminations and burrows. In one instance, the siltstone is absent where the overlying unit has scoured down to the stratified fine-grained sandstone. Three similar but less prominent
Fig. 3.24. Graphic log of core from the $\#3A$ sandstone and $\#3$ limestone in the Venture field area. Note the change of scale in the B-13 well. See Figure 3.4 for explanation of symbols.
stacked fining-upward cycles are observed in the B-43 well except the lower coarse-grained sandstone contains rare large tubular burrows, and the fine-grained units have carbonaceous laminae. These cycles are interpreted as stacked tidal channel/delta deposits. These tidal deposits are enveloped by marine glauconitic sandstones. The tidal deposits are overlain in the B-13 well by 3 m of very fine- to fine-grained sandstone with glauconite, trace scattered ooids, and sporadic burrowing associated with grouped mudstone laminae.

A succession equivalent to the tidal channel/delta deposits in the B-13 well is cored in the H-22 well, only 2 km to the south. Here, the sandstones are very fine- to medium-grained, burrowed with rare inclined coarse-grained laminae incorporating shell debris and shale fragments. Plane- and trough-cross-laminations in truncated sets and coal fragments are observed locally. These sandstones represent a mostly sublittoral, distal tidal delta facies.

The tidal channel/delta sediments are overlain by transgressive interbedded marine glauconitic sandstone, oolitic limestone and argillaceous very fine-grained sandstone and siltstone. The oscillatory nature of the sedimentation is evident on the acoustic or resistivity log (Fig. 3.24). In the #3 limestone in all Venture wells there are at least three discrete limestone bodies which are separated by interbedded sandstone and subordinate siltstone. The limestone units are interpreted as sandy oolitic shoals developed on a shallow marine shelf. The ooids are medium- and coarse-grained with quartz or shell fragment nuclei and are occasionally observed with outer algal coatings indicating low-energy conditions perhaps marginal to or behind the shoal. The interbedded sandstone is fine-grained, burrowed exhibiting rare plane- and ripple cross-laminations and thin graded, oolitic, coarse-grained layers. The oolitic bodies incorporate various proportions of
fossil debris including corals, bryozoans and pelecypods. Limestone bodies are overlain by marine shale.

Only one core is available from the upper division of the Lower Mississauga unit (Mobil Texaco PEX Venture B-43, 4430.2 - 4442.45 m, #2 sandstone). The geophysical log expression of the #2 sandstone varies considerably in the wells in the Venture field. The 25-50 m thick sandstone unit forms a series of stacked coarsening-upward sequences that are best defined in the D-23 and B-13 wells. Sandstone is less common in the two seaward wells (B-52, H-22).

Three well-defined coarsening-upward units occur in the core from B-43 (Fig. 3.22). The basal 90 cm of core probably represents the upper part of a fourth sequence. The three coarsening-upward sequences are 2.5-3.75 m thick and tend to be thicker upwards. The basal 60-70 cm of each sequence is comprised of strongly bioturbated argillaceous, silty, very fine-grained sandstone and siltstone incorporating rare ripple-laminations near the top. It is abruptly overlain by fine-grained sandstone exhibiting inclined laminae and truncated sets of plane-laminae and scattered burrows associated with grouped mudstone partings. Minor ripple cross-laminations may be evident in the basal part. Shale fragments, shell debris and glauconite are common accessories. The top part typically consists of medium-grained sandstone with indistinct planar-laminae and glauconite. The upper most sequence incorporates two thin, graded, coarse-grained sandstone layers with minor pebbles and shell fragments.

The top coarsening-upward sequence grades into a 20 cm medium- to coarse-grained, pebbly unit overlying moderate to high angle, faintly cross-bedded sandstone. The top 1 metre of core consists of plane-laminated, medium-grained sandstone grading upward into indistinct, small-scale festoon
Fig. 3.25. Graphic log of core from the Mobil et al. Venture B-43 well (4430.2-4442.45 m). See Figure 3.4 for explanation of symbols. The three coarsening-upward sequences evident in the core are interpreted as stacked offshore submarine bars.
cross-bedded sandstone with rare pebbles, shale clasts and coal fragments. Several large tubular burrows occur within the plane-laminated section.

The three coarsening-upward sandstone bodies are interpreted as stacked offshore submarine bars. The occurrence of two thin graded beds in the upper cycle indicate periodic dispersal of sediment by storm-generated suspension currents (Simpson, 1984). The upper conglomeratic bed and the overlying festoon cross-bedded sandstone were deposited within the middle to upper shoreface. The coarsest sand in the shoreface zone is normally deposited just below the breaker zone (Reinson, 1984). The presence of festoon cross-bedding overlying the conglomeratic unit may indicate deposition by directed currents in the upper shoreface zone (Weimer et al., 1982).

The overall marine interpretation is supported by lithologies encountered in adjacent wells. In the D-23 well, the #2 sandstone is interbedded with thin, sandy cryptocrystalline limestone. The #2 sandstone is overlain by marine shale interbedded locally with peloidal limestone in all Venture wells.

Age

Reliable biostratigraphic data available on approximately 15 wells indicate the Lower Missisauga unit is Late Kimmeridgian-Berriasian in age (Barras et al., 1979; P. Ascoli, pers. comm. 1975, 1979, 1981, 1983, 1984; E. Davies, 1983; J. Bujak, 1980; R. Fensome, 1985) There are no Early Cretaceous sediments recognized as equivalent to the Lower Missisauga unit north of the Shell Missisauga H-54 well. The top of the Jurassic occurs in the upper division in the vicinity of the #3 limestone.

Biostratigraphic data for the Mobil TEICO Texaco Citnalta I-59 and Mobil et al. South Venture O-59 wells indicate there are no Early Cretaceous sediments in Unit F in these wells (P. Ascoli, pers. comm. 1979, 1984).
However, the top of the Jurassic occurs only 16 and 40 m below the top of the Lower Missisauga unit. Detailed lithostratigraphic correlations suggest the probable existence of Early Cretaceous sediments. Consequently, minor modifications are required to the biostratigraphic picks. The anomalously thick Tithonian in the Mobil TETCO Texaco Citnalta I-59 well has been discussed previously in the section on Unit E. The Jurassic pick in the Mobil et al. South Venture O-59 well is substantially higher in the succession than that recorded in several wells to the north in Venture field. This is clearly untenable owing to the downward stepwise basinward thickening of stratigraphic units (See Fig. 2.7).

Detailed correlations north and west of the East Sable Island area suggests the conventional top of Mic Mac Formation pick as recorded in the Offshore Schedule of Wells (1985) in the Shell Abenaki J-56, Petro-Canada Shell Penobscot L-30, Shell Petro-Canada Penobscot B-41, Mobil TETCO Cohasset D-42 and Mobil TETCO PEX 'C' Cohasset L-97 wells may in fact be the top of the Lower Missisauga unit. Biostratigraphic data indicate these tops are all Berriasian in age. However, the Mic Mac Formation has proven to be exclusively Jurassic in the study area.

Ascoli (pers. comm., 1974) on the basis of foraminifera determined the presence of a hiatal surface within possible Lower Missisauga equivalent strata in the Mobil TETCO Dauntless D-35 well. The fauna that normally characterize the lower part of the Berriasian-Valanginian interval on the Scotian Shelf was found to be mostly missing. The palynological zonation for this well does not indicate a hiatus in the Early Cretaceous (Barss et al., 1979).
3.9 Unit G

Unit G represents a thick overall fining-upward sequence above the Lower Mississauga unit. Unit G has been divided into two parts, an upper shale subunit and a lower arenaceous subunit. The shale subunit constitutes approximately one-half to one-third of Unit G. Shales, mudstones and subordinate sandstone and limestone of the shale subunit lie abruptly on sandstone of the arenaceous subunit and is reflected as a sharp deflection to the right on the gamma-ray log. The contact between the two subunits is generally conformable.

Ease of recognition of the top of Unit G varies according to basinal position, reflecting the influence of facies. Normally, coarse siliciclastic sediments of the Mississauga Formation abruptly overlay the uppermost shaly beds of Unit G in the central portion of the basin.

In the Sable Subbasin, the top commonly forms part of a thick coarsening-upward unit expressed as a funnel-shaped log trace. In the Mobil TETCO Texaco Citalta I-59 and Mobil et al. Arcadia J-16 wells the Unit G succession is particularly sandy and a shale member is not recognized (Section A-A'). Here, the top of Unit G has been correlated to a thin carbonate bed within an overall coarse siliciclastic sequence.

The basal contact is sharp both lithologically and in its gamma-ray log response. The base normally coincides with the top of the Lower Mississauga unit. Toward the south, the base is undefined as the unit shales out basinward into the Verrill Canyon Formation.

In the subsurface, where both upper and lower subunits are readily documented, Unit G attains a maximum thickness of slightly less than 300 m in the Mobil et al. South Venture 0-59 well (Fig. 3.26). Isopach trends indicate that the thickest accumulation is probably just southeast of Sable...
Island. These data support a north-northwesterly source for the coarse
siliciclastics deposited near Sable Island. Unit G thickens abruptly at the
seaward margin due to thickening of the shale subunit. The succession
eventually thins-out completely. This thinning out is more abrupt west of
Sable Island in the vicinity of the Mobil TETCO Cohasset D-42 well where the
westerly trending LaHave Platform swings toward the southwest.

Arenaceous (lower) Subunit

The arenaceous subunit of Unit G consists of interbedded sandstone,
siltstone, shale and minor limestone with sandstone dominant. The subunit
lies between the sandstone-rich Lower Missisauga unit below and the shale
subunit above. The proportion of each lithology varies between wells with a
tendency for depositional units to thicken and become shaly in the more
basinward wells. Sandstones generally display a tendency toward becoming
less coarse upwards in the succession. Three distinct lithologic
associations related to basinal position have been recognized. Normally, the
base of the arenaceous subunit is sharp, but in places occurs at the base of
a thick coarsening-upward unit where the underlying Lower Missisauga unit is
particularly shaly (e.g. Mobil et al. Venture H-22). The base is selected at
the point where there is a continuous leftward deflection of the gamma-ray
log trace.

The coarsening-upward and fining-upward sequences in the arenaceous
subunit can be readily correlated between wells in the East Sable Island area
for distances of up to tens of kilometres. Coarsening-upward sequences are
typically better developed and thicker than overlying fining-upward or blocky
units. Coarsening-upward units may be replaced laterally by blocky or
composite sandstone units. Also, additional coarsening-upward and fining-
upward sequences are developed locally at the top of the arenaceous subunit.
replacing the laterally equivalent overlying shale subunit. One conventional core has been recovered directly from the arenaceous subunit in the Mobil Sable Island C-67 well (Fig. 3.27; 4084.4 - 4093.3 m).

The core in the Mobil Sable Island C-67 well represents the lower 10 m of a 22 m coarsening-upward sequence. The basal 5.5 m is predominantly strongly bioturbated, carbonaceous, silty mudstone with rare lenses and laminae of argillaceous siltstone and very fine-grained sandstone incorporating increasingly common laminae and thin beds of structureless, plane- and ripple-laminated and burrowed siltstone and very fine- to fine-grained sandstone. The lower section grades up through to argillaceous fine-grained sandstone, slightly burrowed with common wavy-bedding, plane- and ripple-laminations. Siderite occurs locally as cement within sandstone lenses enveloped in shales. The upper-half of the core includes several cross-bedded and cross-laminated, fine-grained sandstone beds with sharp, planar or load-deformed bases. Cuttings from the overlying 10 m indicate medium-grained grading to coarse-grained, poorly sorted, pebbly sandstone. The upper 2 m are very calcareous and contain scattered shelly debris.

Shale (upper) Subunit

The shale subunit of Unit G rests abruptly upon the arenaceous subunit and consists of predominantly carbonaceous and micaceous silty shale and mudstone with variable amounts of thinly interbedded siltstone, sandstone-and sandy pelleted/oolithic limestone. Shales and mudstones display dominantly medium to dark greyish hues with brownish shades relatively common. Minor reddish-brown and greenish-gray shales are observed locally and generally occur together in close association with bedded and nodular ferruginous carbonate in the lowermost few metres above the arenaceous subunit or at the top of the shale subunit (e.g. Mobil Sable Island C-67, Mobil TETCO PEX 'C')
Fig. 3.27. Graphic log of core from the Mobil Sable Island C-67 well (4084.4-4093.3 m). See Figure 3.4 for explanation of symbols. The core comprises the lower part of a thick coarsening-upward sequence interpreted as a distributary mouth bar succession.
Cohasset L-97, Shell Mobil TETCO Eagle D-21). Generally, shale and mudstone rest directly on the arenaceous subunit, but locally there may be silty and sandy units at the base. Sandstone beds are normally concentrated toward the base or top of the shale member. Typically, coarse siliciclastic beds occur in thin (<5m) coarsening-upward sequences (Mobil et al. Venture B-13, B-52, Mobil TETCO Petro-Canada Migrant N-20, Shell Abesaki J-56) and less commonly in fining-upward sequences (Mobil Sable Island C-67, Mobil TETCO Texaco Citmalta I-59) which can be correlated locally for several kilometres. Sandstone beds in the coarsening-upward units are mostly very fine- to fine-grained and commonly contain scattered glauconite and shell debris.

The best developed shale subunit is observed in wells immediately southeast and east of Sable Island (e.g. Mobil et al. Venture H-22, Mobil TETCO Bluenose G-47, Shell Saik A-57). The shale subunit shows more or less basinward thickening toward the south accompanied by a concomitant proportional decrease in the thickness of the arenaceous subunit. The shale subunit is very thin or even absent in the area immediately northeast of Sable Island and in several wells in the Venture Field where Unit G is thickest. Presumably this area represented the depocentre during deposition of Unit G. Consequently, a thick prograding clastic wedge of sediments was deposited at the expense of the shale subunit. Upper portions of the shale subunit may also have been removed because of downcutting by overlying facies. Unit G has been correlated to several wells seaward of Sable Island with some reservations. A common feature of the succession in these wells is that of relatively thick (30 m+) shales occurring between thin, coarser-grained siliciclastic units. Generally, no distinctive feature permits definitive correlation between these wells. The correlations have been made
on the basis of relative stratigraphic position and the recognition of some general features common to Unit G and in adjacent wells.

No cores have been cut from the shale subunit. However, one core has been cut within a shaly facies of the Missisauga Formation in the Petro-Canada et al. Banquereau C-2l well (4473 - 4477.7 m) from an interval interpreted to be laterally equivalent to Unit G (Fig. 3.28). The core consists of interbedded pebbly to conglomeratic, very fine- to medium-grained, sandstone and dark gray, micromicaceous, blocky shale incorporating rare siltstone lenticles. The sandstone is calcareous, well indurated in beds 3-30 cm thick; shale beds are 6-14 cm thick. Bedding surfaces are sharp and irregular. Conglomeratic-pebbly beds display a crude fining-upward character, as evidenced by a decrease in the size and quantity of pebbles and granules. Clasts are dominantly ovoidal, elongate to subrounded shale, laminated siltstone, sideritic pebbles and minor shell debris. The irregular shape of some clasts indicate they were non-lithified when deposited. One particularly thick fining-upward bed (60 cm) is overlain by low-angle, inclined, planar beds incorporating traces of shell debris and glauconite. Two thin silty zones in a shale-dominant interval near the top of the core display a general fabric that dips up to 45° from the core axis.

The fining-upward and thin-bedded nature of the conglomeratic beds and their matrix-supported character point to an origin as density flows or turbidites. The gamma-ray log expression in this interval qualitatively supports this conclusion. The deformed shale at the top of the core possibly indicates deposition on an inclined surface or soft sediment deformation. No formal data is available to possibly help discern the bathymetry, though an outer shelf to upper slope environment is anticipated (Wade, pers. comm., 1986).
Fig. 3.28. Graphic log of core from a shaly facies of the Mississauga Formation laterally equivalent to Unit G in the Petro-Canada et al. Banquereau C-21 well (4473.0-4477.7 m). See Figure 3.4 for explanation of symbols. The textural features of the conglomeratic beds and their thin-bedded character suggest an origin as density flows.
Sedimentology

The paucity of core material from Unit G precludes a detailed discussion of the sedimentology. However, general conclusions are possible and provide models which can be tested as more core material becomes available.

The two subunits of Unit G are successional and in part laterally equivalent. A complex interdigititation of strata is suggested by the existence of abundant non-marine and marine sediments, particularly in the arenaceous member.

The core in the Mobil Sable Island C-67 well forms the basal part of a coarsening-upward sequence and indicates general shoaling on a marine shelf. This core is overlain by poorly sorted, coarse-grained pebbly sandstone. The coarsening-upward sequence and the carbonaceous nature of the sediments support a distributary bar sequence. Commonly, the coarsening-upward sequence is overlain by a fining-upward or blocky, poorly sorted, coarse-grained, pebbly sandstone of probable distributary channel origin. The top of the coarsening-upward sequence is normally very calcareous and incorporates scattered shell debris and calcareous or sideritic nodular bodies or rare oolites. At least four such sequences are evident in the Mobil Sable Island C-67 well (Section E-E'). Each sequence is overlain by dark gray to gray-green shale and siltstone with rare nodular siderite and thin fining-upward sandstone bodies. These have been interpreted as delta-plain/interdistributary sediments. Most of these cycles are present in the Mobil Texaco PEX Olympia A-12 well and in the Venture field over 25 km to the east. However, the sandstones are finer-grained, more argillaceous, better sorted, less carbonaceous and incorporate more common limestone beds capping coarsening-upward sequences. These features suggest a possible increase in marine influences and a more distal position relative to the main
distributary system. These coarsening-upward sequences could possibly represent barrier/strand plain sandstones deposited adjacent to the main delta (see Reinson, 1984; Elliot, 1978 for summaries of barrier island/strand plain deposition). However, the lack of a well-developed shale subunit in these wells confirms their proximity to the main area of deposition. Isopach trends (fig. 3.26) indicate this distributary system prograded from an area north-northwest of Sable Island. Presumably the depositional cyclicity is provided by the lateral migration of the distributary system. The progressive westward migration of the depositional system is documented between the Mobil et al. Venture H-22 and Mobil et al. South Venture O-59 wells in section A-A'. Here, sandstone occurs progressively higher in the section toward the Mobil et al. South Venture O-59 well in the west.

Two additional depositional regimes are recognized in the arenaceous subunit. However, they share some common features. The sandstones occur as thin coarsening-upward and fining-upward units that cannot be readily correlated and no preferred sequence patterns are discernable. The overall sequence is also more argillaceous.

The first of these lithogenetic units consists of interbedded sandstone, carbonaceous shale, siltstone and coal. The sandstones are very fine- to medium-grained, rarely coarse-grained, moderately sorted and incorporate rare pebbles, fossil debris, coal fragments and feldspar. These sediments are interpreted to have been deposited on a delta/coastal plain. A variety of subsidiary environments are anticipated, including small fluvial channels, floodplains, swamps/marshes, lagoons and tidal flats/channels. Periodic marine incursions are indicated by the presence of thin glauconitic sandstones, oolitic limestones and fossiliferous calcarenites.
The second lithogenetic unit is related to the first but represents dominantly marine sedimentation in a nearshore-marginal marine environment. Very fine- to fine-grained, well sorted, locally glauconitic or fossiliferous sandstone occurs in thin fining-upward and coarsening-upward sequences with rare oolitic limestones. The proximity to a terrigenous source of sediment is indicated by an increase in the carbonaceous content of enveloping shales, the presence of thin coal stringers and a slight increase in the average grain size of the sandstone.

In the shale subunit, the predominance of shale and mudstone containing a principally marine fauna indicate a general marine setting. Where the shale subunit overlies alluvial or distributary-channel sediments, probable lower delta-/coastal-plain sedimentation is initially evident. Very fine- to fine-grained, glauconitic sandstones forming thin coarsening-upward sequences within the shale subunit represent the period of aggradation of coarse siliciclastic material into wave and current agitated zones. These thin units are most likely deposited as offshore submarine bars.

Age

The age of Unit G has been established on the basis of consideration of microfossil biostratigraphic data from 16 wells. These data indicate a dominantly Berriasian age. At present, the biostratigraphic data cannot be sufficiently resolved to qualitatively separate in time the lower arenaceous subunit from the upper shale subunit. The bounding surface between the Lower Missisauga unit and the overlying Unit G is a facies boundary. Consequently, the boundaries are somewhat diachronous. Basinward, upper portions of the shale subunit may be Early Valanginian. A probable Early Valanginian age is indicated for the Mobil Texaco PEX Venture D-23 well (Davies, pers. comm., 1982) and the Shell Eagle D-21 well (well history report).
Foraminiferal and palynological age determinations in six closely spaced wells in the East Sable Island area have revealed highly variable ages.

Dates derived from foraminifera in the Mobil et al. Venture B-43 and B-13 wells indicate Unit G is principally Late Valanginian (Ascoli, pers. comm., 1981, 1983). More appropriate ages are suggested in nearby wells by Ascoli (pers. comm., 1983) in the Mobil Texaco PEX Olympia A-12 well; Barsa et al. (1979) in the Mobil Sable Island C-67 well; Ascoli (pers. comm., 1982, 1984) in the Mobil Texaco PEX Venture D-23 and Mobil et al. South Venture O-59 wells. These discrepancies remain to be resolved.

3.10 Geological History andPaleogeography

In order to discuss the geological history, it must be presented within a known time framework. This can be accomplished by arbitrarily selecting time reference points or by utilizing real basin-wide events that have demonstrably regional geological significance. The units outlined in previous sections are not formations or members in the conventional lithostratigraphic sense, but rather, define depositional episodes. The boundaries of these units provide meaningful reference points from which the geological history can be discussed. This method of basin analysis has been proven to have merit and provides a more realistic approach than discussing the geological history using the present formal stratigraphic framework, or poorly defined time-stratigraphic units. The method employing depositional episodes is basically that advocated by Frazier (1974) and subsequently utilized by Dixon (1982) in the subsurface of the Mackenzie Delta-Tuktoyaktuk Peninsula, N.W.T.

Frazier (1974) identified a number of discrete genetically related depositional complexes bounded by hiatus surfaces in the Quaternary deposits of the Gulf Coast. These depositional complexes are composites of local
depositional units or facies-sequences (Dixon, 1982). A depositional complex forms during a depositional episode and a facies-sequence during a depositional event (Dixon, 1982). The hiatal surfaces bounding a depositional complex are basin-wide and related to 'hiatal' conditions imposed by marine transgressions (Frazier, 1974). Much of the clastic sediment supply is temporarily trapped in alluvial and coastal environments allowing marine shale or carbonate facies to penetrate far into a sedimentary sequence dominated by alluvial and marginal marine siliciclastics (Matthews, 1984). With time, marginal marine environments again advance seaward. The final phase of a depositional episode is represented by a transgression. Commonly, the hiatal surface rests upon transgressive (deepening-upward) facies (Dixon, 1982). Dixon (1982) typically defined his hiatal surfaces at the base of distinct, low velocity shale zones, or high velocity and resistive concretionary-rich shaly beds.

Within the Jurassic-Early Cretaceous succession comprising the Mic Mac, Lower Missisauga Formations and their lateral equivalents, at least seven depositional episodes have been recognised (Sections A to E, See Figs. 3.3 and 3.4). Because of the unique, lithologic associations in the Scotian Basin, the boundaries of the depositional complexes are not defined in the sense of Frazier (1974) or Dixon (1982). The presence of carbonate bank and shelf sediments complicate consistent use of stratigraphic subdivisions, but provide some indication of basin-wide changes in depositional setting. The limestone units are valuable markers for correlation, however by tracing their relationship to transgressive events, their significance in time-stratigraphic correlation can be established. The utility of using prominent carbonate tongues in defining an upper transgressive unit has been demonstrated in previous discussions. The upper boundary of the depositional
complex is not necessarily defined at a hiatal surface but is defined by the termination of carbonate deposition. The boundary is generally considered conformable, or possibly slightly diachronous. The diachrony is undoubtedly below the resolution of any biostratigraphic data. Concretion-rich lithologies periodically define the top of a depositional complex in wells in the Abenaki Subbasin or Canso ridge area.

Various tectonic and structural elements have influenced the thickness trends of the depositional complexes. There is abrupt thinning towards and over the Canso Ridge and LaHave platform. How much of this thinning can be attributed to depositional or erosional processes is difficult to assess. The seaward margin of these stable structural elements provided conditions allowing for the development of a carbonate-bank complex toward the southwest. Faulting along the hinge-line defining the north margin of the Abenaki Subbasin was particularly prevalent during early depositional episodes as evidenced by dramatic thickening of the sedimentary succession. Growth faulting also occurred along the shelf margin during later depositional episodes. The growth faults were particularly active during progradational phases of sedimentation.

Depositional episodes B to D are discussed together because they contain prominent prograding shelf and platform-edge carbonates that have a common basinal setting and similar sedimentological characteristics. The succeeding depositional units (E to G) mark strong progradation of coarse siliciclastics into the central-basin. Each has a distinct, but related, depositional character and are here discussed together.
3.10.1 Depositional Episode A

Depositional episode A represents the lowermost depositional unit of the Mic Mac Formation and was deposited during Late Callovian time. Earlier depositional episodes are represented by the Middle Jurassic Mohican Formation and the Scatarie and Missaine Members of the Abenaki Formation. The deposition of sheet-like oolitic facies comprising the Scatarie Member marks the beginning of this late Middle Jurassic transgression. The Scatarie limestone exhibits several cycles consisting of oolitic packstones and grainstones grading upward to lime mudstones (Eliuk, 1978). The maximum transgression occurred in the lower part of the Missaine Member (Given, 1977). The low numbers and diversity of foraminifera in the upper part of the Missaine Member suggests rejuvenation of terrigenous deposition as large quantities of mud were transported into the basin (Jansa and Wade, 1975). The Missaine Member is interpreted to represent a middle to outer neritic environment in the Shell Mohican I-100 well (Given, 1977).

The marginal marine, nearshore and shallow marine siliciclastics comprising Unit A are in part equivalent and successional to the Missaine Member. Part of Unit A is also laterally equivalent to the basal limestone sediments of the Baccaro Member of the Abenaki Formation. Unit A does not clearly define a depositional complex in the sense of Frazier (1974). A basinwide transgressive event cannot be easily recognised in the upper part of the succession. The upper boundary is instead defined at the base of the first coarse-grained fining-upward or massive sandstone unit indicating significant terrigenous sedimentation. This marks the transition to well-defined progradational, regressive deposition in the overlying depositional complex.
The depositional complex exhibits a distal southerly shale-out trend consistent with a northerly source area, though it has not been recognized in the subsurface. An indicator of proximity to a shoreline is the abundance of carbonaceous matter and multicoloured shales. Marine shelf sediments vary between fine- and coarse-grained siliciclastics as a function of variable sediment supply. The sandstone bodies originate as well-washed and well sorted shoals of sand that were periodically moved by currents into areas of carbonate deposition. Many of these thick marine sandstones may also be composites of several offlapping sandstone bodies formed as shoreline-nearshore deposits. Sand-oolite couplets are formed and are laterally equivalent to seaward oolitic and skeletal wackstones (Eliuk, 1978). The oncoids may form in the protected back-shoal area or in slightly deeper water in front of the oolitic bars.

The configuration of the basin is apparent from sediment thickness trends and the distribution of the lithofacies. Across the zone line into the Abenaki Subbasin the rate of thickening increases. The subbasin subsided toward the southeast and received more sediment than the LaHave Platform. The Mississauga Member and Unit A are dramatically thickened toward the southeast. The infilling of siliciclastics resulted in a gentle slope or ramp profile without a well-developed basinward flexure (Eliuk, 1978). To the southwest, a shelf-edge flexure is well defined as early as Scatarie time (Eliuk, 1978). The flexure became more prominent through time and formed a shallow water rimmed or platform shelf margin. The platform margin extended to the east beyond Shell Mississauga H-54 where the Mississauga shale seismic event is observed to turn sharply downward (Given, 1977).

The morphology and trend of the basin margin strongly influenced the development of the carbonate platform and shelf. The ramp profile in the
southeast resulted in relatively wide facies belts, including the deposition of low-energy carbonate facies locally at the paleoshelf edge (J. Wade, pers. comm.). Thick, prograding siliciclastics sequences are intermixed with the carbonates. The abrupt break in the shelf-edge slope on the rimmed platform margin in the southwest produced narrow facies belts. High-energy oolitic facies are concentrated on this rimmed margin. Thin mixed carbonate and siliciclastic sediments occur behind the platform margin.

3.10.2 Depositional Episodes B-D

Depositional episodes B, C, and D were laid down in Oxfordian to Late Kimmeridgian time. The Middle Jurassic deepening-upward carbonate ramp facies comprising the Scatarie and Missaine Members gave way to mixed Upper Jurassic fluvial/deltoid and shelf carbonate and bank deposits. The Abenaki Subbasin formed the major clastic depocentre in Middle to Late Jurassic time. In the central-basin area, each of the depositional episodes represents deepening-upward cycles. Regressive siliciclastic tongues grade vertically into open marine shelf and bank carbonate facies. These three cycles are best illustrated in the Shell Petro-Canada et al. Uniacke G-72 well (Section A-A'). Limited data indicates these cycles can be correlated to Eliuk's (1978) deepening-upward cycles recognized in wells with thick, massive Baccaro Member carbonate such as the Mobil TETCO PEX 'C' Cohasset L-97 well. On the north margin of the basin and nearshore ridge, the deepening-upward or transgressive units are recognized where dominantly non-marine, coarse-grained terrigenous sediments at the base grade laterally and vertically into interbedded marginal marine siliciclastics and subtidal carbonates. As the transgression developed, the sediment supply declined and finer-grained siliciclastics and carbonates became more prevalent.
The development of carbonate sediments in the central-basin area represents a fundamental change in the depositional milieu under transgressing seas. During transgressions, carbonate sediments penetrated into areas of the basin normally receiving siliciclastic sediments. The decrease of siliciclastic material transported into the basin permits chemical sedimentation, particularly finely crystalline carbonate. Overall the carbonate sequences exhibit significant vertical and lateral facies changes. Depending on basinal position, the carbonate facies either expanded, shrank, moved basinward or landward depending on the relative stand of sea-level and proximity to sources of siliciclastic input. Variations in the morphology of the preceding depositional surface may have grossly affected the distribution of facies during the next transgression.

Three types of carbonate units are represented in this sequence. In the southwest, the platform- and prograding-type margin are recognized. A prograding ramp-style margin without high-energy shelf-edge facies characterize the carbonate sequence in the Abenaki Subbasin east-northeast of Sable Island (Eliuk, 1978). Quiet-water pelleted lime mudstones occur in the Mobil TEICO Dauntless D-35 well. Carbonate deposition became increasingly restricted to the outer shelf in the southwest during the Late Jurassic, creating a narrow, but extensive carbonate bank with a seaward slope of 20–30° into the basin (Jansa, 1981). The upper limestone in Unit D is clearly progradational as high-energy, shelf carbonates overlie deeper-water carbonates and siliciclastics (Citnlata Limestone). During this late phase, local conditions near the shelf-margin were favourable for the growth of coral-stromatoporoid bioherms and perhaps reefs (Eliuk, 1978). The Unit D limestone also marks the break-up of the carbonate bank and its retreat toward the southwest. The massive Baccaro limestone in the Shell Abenaki J-
well and the Cohasset wells gives way to intercalated carbonate and
siliciclastics and eventually, shelf-edge carbonate deposition was
terminated in the area.

The lower part of a carbonate shelf-edge or shelf cycle is composed of
oolitic and algal oncitic grainstone interbedded with skeletal grainstone
to wackestone. These normally grade upwards into biomicrites, argillaceous
crystalline limestones and lime mudstones incorporating a dominantly pelagic
biota. The high-energy facies are deposited in the littoral and shallow
sublittoral zones and the upper low-energy facies in middle- to outer-neritic
environments.

The subtidal interior platform was the site of extensive siliciclastic
deposition. Carbonate deposition is separated by periods of siliciclastic
deposition characterized by alternating argillaceous carbonates and shales or
sandstones. Carbonate bodies became increasingly common toward the top of a
depositional complex as the sea transgressed over the shelf. Interbedded
carbonates and sandstones indicate deposition in the inner to middle neritic
zones (Conybeare, 1979). Undoubtedly, the relatively shallow platform
promoted the widespread dispersal of siliciclastics. Sand derived from
beaches and bars was periodically swept into areas of carbonate deposition by
currents. Intercalated carbonates are dominantly skeletal, or pelleted,
incorporating a significant proportion of siliciclastics and lime mud.
Bryozoans are a common component of skeletal limestone with large amounts of
interbedded coarse siliciclastics (Eliuk, 1978). Minor high-energy
limestones are associated with marginal marine coarse-grained siliciclastics,
possibly as shallow subtidal shoals or tidal deltas. Frequently, upward-
coarsening bars alternate with oolitic bars. Both shoaling- and deepening-
upward sequences are capped by lagoonal/back-bar deposits (Eliuk, 1978).
Deepening-upward sequences formed during minor marine transgressive episodes and are represented by oncitic and pelleted beds overlain by open marine shale or skeletal wackestones. Light gray-green shales associated with limestone bodies are commonly observed in intertidal and shallow, subtidal environments (Weimer, et al., 1982).

Prograding terrigenous and marginal-marine siliciclastics were important in infilling the subbasins, constructing coastal and delta marine-fringe complexes basinward and displacing carbonate shelf facies and banks seaward. The local development of carbonate and siliciclastic sediments resulted in a very complicated facies mosaic. Facies reconstructions identify a large, thick clastic wedge in the Abenaki Subbasin adjacent to areas of carbonate facies (Fig. 3.29). Depositional thinning occurs toward the north and northwest over the nearshore ridge and platform. Seismic reflectors located behind the carbonate bank are truncated in some cases. This suggests the carbonate bank-edge subsided more slowly than the platform interior in Late Jurassic time (Schlee and Jansa, 1981). Consequently, depositional thinning also occurs across the carbonate platform-edge. The succession penetrated by the Petro-Canada et al. West Esperanto B-78 well records the progradation of a thick clastic wedge from a source area northeast of the well. The sequence consists of cyclical, thick, channel sandstones fining-upward into relatively thin deposits of shallow marine glauconitic siliciclastics and minor limestone. The thickness and frequency of the channel deposits increases upsection. These sediments are considered to be deposited in a delta- or coastal-plain and marine-fringe environment.

A second source area north-northwest of Sable Island is evident during the late stages of depositional episode D in early Late Kimmeridgian time. A strong progradational phase occurs in the overlying depositional complex E.
A thick clastic-wedge was deposited in the Abenaki Subbasin peripheral to the carbonate facies. Two main distributary lobes are recognised to the northwest of Sable Island and to the northeast. The northwest lobe developed later and is first evident in the study area during early Late Kimmeridgian time.

Fig. 3.29. Lithofacies map for Kimmeridgian time.
and is represented in the Mobil TETCO Petro-Canada Migrant N-20 well. The
influx of siliciclastics into this part of the basin created local conditions
unfavorable for limestone deposition, and ultimately caused the seaward
retreat of the carbonate platform toward the southwest. The thick intervals
of shale between the carbonate tongues in the Petro-Canada Shell Penobscot L-
30 well (Section C-C') suggest this well occupied a relatively distal, deep-
water setting through most of depositional episodes B to D but was subject to
periodic influxes of mud during clastic progradation. These two distinct
source areas became better defined through time as they continued to prograde
basinward. Given (1977) recognized these two source areas as developing more
or less at the same time. The limited data available (from Unit B) indicates
the northeast source prograded into the Abenaki Subbasin first in the Early
Oxfordian-Late Callovian time.

The lower member of Unit B in the Shell Mic Mac H-86 well contains a
succession similar to that observed in the Petro-Canada et al. West Esperanto
B-78 well (Section B-B'). This would suggest the initial regressive phase
recorded in the lower member of Unit B occurred over a broad front indicating
a coastal-plain environment. Above the lower member of Unit B in the Shell
Mic Mac H-86 well, the remainder of the Mic Mac Formation is comprised of
dominantly marine shale, marginal-marine sandstone and limestone. Two
distinct source areas were developed only following the transgression
defining the upper part of Unit B.

A possible analogue to the depositional episodes of the Mic Mac
Formation occur in the Jurassic-Lower Cretaceous strata of the Texas-
Louisiana Gulf Coast. These sediments formed on a broad shelf that was
characterized by the development of carbonate bank margin deposits along its
seaward edge. Like the depositional complexes outlined herein, the carbonate
margin expanded during transgressive phases causing carbonate deposition in areas of the basin normally receiving siliciclastic sediments (Matthews, 1984). This scenario is basically the one advocated in the discussion of the depositional episodes in the Mic Mac Formation. Eliuk (1978) presented an opposing model for the Baccaro Member and its lateral equivalents. He proposed that during low stands of sea-level, the platform interior most zone contracted with a concurrent expansion of the offshore bank and an increase in the influx of coarse siliciclastics into the offshore-bank zone. The platform-edge carbonates in the Scotian basin define deepening-upward cycles that are accompanied updip by finer-grained siliciclastics and limestone interbeds. Under transgressing seas, the high-energy platform-edge carbonates migrate shoreward and are eventually drowned. The carbonate bank and platform will expand upon significant arrestation of siliciclastic input into the basin, conditions best created during a transgression. During low stands of sea-level, the platform-edge carbonates will migrate seaward in response to prograding siliciclastics.

Successions similar to the designated type section of the Mic Mac Formation are not recognized in many wells other than those in the immediate vicinity of the type well (Shell Mic Mac H-86). The thinly bedded, non-distinctive sandstone units in the type well grade laterally and seaward into complex, basinward thickened, distinctive, fining- and coarsening-upward bodies with prominent intervening shale successions. Mic Mac Formation deposits in wells near the two main source areas are typically very sandstone-rich with common coarse-grained siliciclastics. The almost unique character of the Mic Mac Formation type section is attributed to its unusual position in the basin. The type well occurs in an area which lies in between two actively prograding lobes. Consequently, the sediments are dominantly
marginal marine siliciclastics and limestone. Minor non-marine strata were
deposited at the base of the depositional complexes during the initial
regressive pulse.

3.10.3 Depositional Episodes E–G

Depositional episodes E, F and G consist of the uppermost unit of the
Mic Mac Formation and two units of the lower part of the Missisauga
Formation. A Late Kimmeridgian to Valanginian age is indicated. These
depositional complexes formed in response to influxes of terrigenous material
and fluctuations in relative sea-level. The strongly progradational nature
of the sedimentation resulted in very asymmetric stratigraphic thickening of
units basinward, in part due to active growth faulting. The Sable Subbasin
became the major clastic depocentre as the mixed clastic–carbonate platforms
were covered by large prograding delta plains. The initiation of the
dominantly regressive, progradational phase is evident in the carbonate
sequence at the top of Unit D. This carbonate body defines the top of a
seaward retreating carbonate platform. Carbonate deposition became
increasingly restricted to the outer shelf during Late Jurassic time with
offshore banks and shoals developing adjacent to active delta lobes.

The initiation of this major regression is possibly related to the
The accompanying tectonism resulted in a regional change of the depositional
framework from dominantly carbonate-shelf to siliciclastic sedimentation
owing to a rejuvenation of source areas including the Avalon Uplift. The
regressive phase is indicated by an overall vertical increase in the
proportion of sandstone and a concomitant decrease in carbonate. The three
depositional episodes reflect a series of transgressive-regressive pulses.
within the broad regressive phase, depositing a widespread blanket of similar but slightly diachronous lithologies. These cycles are best developed in the central-basin area and are most difficult to recognise in the vicinity of the nearshore ridges and platform.

In the southwest, the Oxfordian-Kimmeridgian massive Baccaro carbonate platform graded vertically into alternating platformal and biothermal limestone, shale and sandstone during the Latest Kimmeridgian-Valanginian. Coral, stromatoporoid and sponge biostratomes were locally developed along the paleoshelf-edge during the transition from dominantly carbonate to dominantly siliciclastic deposition (Jansa, 1981; Eliuk, 1978). Seismic profiles indicate the shelf-edge break was more sharply defined by the end of massive Baccaro carbonate deposition (Eliuk, 1978). The overlying carbonate tongues appear on seismic as a series of prograding shingled reflectors that build progressively to the south-southeast. Abundant sandstone and shale spilled into the Sable Subbasin accompanied by active growth faulting. However, it is apparent that coarse siliciclastics entered the Sable Subbasin during Unit D time, as revealed by the succession in the Shell Petro-Canada et al. Uniacke G-72 well (Section A-A'). Growth faulting along the seaward margin is also in evidence as early as Unit D.

The Mic Mac Formation, observed in the Venture area, represents the distal elements of a thick, prograding wedge of sediments that is increasingly sandy updip. The sediments north of the Venture field are interpreted as distributary-channel and delta-marine fringe complexes. Alluvial and upper delta-plain sediments characterize the nearshore ridge area. Sandstone bodies display complex stepwise thickening with a minor decrease in grain size and age basinward. Depositional units in the East
Sable Island area exhibit a general westward thickening, reflecting the slow lateral migration of the main depocentre toward the southwest.

The two depositional systems recognized in the early Late Jurassic are still evident in Late Jurassic–Early Cretaceous time (Fig. 3.30). However, it appears the north-northwest distributary complex is prograding over a narrow area relative to the northeast complex. The dominantly marginal and nearshore marine sediments in the Shell Mississauga H-54 well indicate the two source areas were separated. The sandy nature of the upper carbonates in the Shell Abenaki J-56 well and other wells in the central-basin area attest to the proximity of the northwesterly source. By latest Kimmeridgian time, a delta-marine fringe complex was evident just north of Sable Island.

Percent limestone and coarse-grained sandstone maps have been constructed for the Mic Mac Formation (Units A to E) and are illustrated in Figures 3.31 and 3.32. These two parameters are used because they reflect broad variations in facies which can be related to the geological history. The proportion of limestone indirectly reflects the influence of marine depositional processes. Limestone occurs less frequently in the nearshore ridge and north part of the Abenaki Subbasin where proximity to source areas created conditions unfavorable for carbonate deposition. The Mic Mac Formation is relatively thin where it has prograded over the Baccaro carbonate, but is carbonate-rich since it represents the transition from carbonate to siliciclastic deposition. Basinward, no carbonate exists where Verrill Canyon Formation shales are laterally equivalent to the Mic Mac Formation. The central-basin area contains moderate proportions of limestone, since it defines the transitional environment between basinal shales and nearshore, marginal-marine siliciclastics. Alternating upward-coarsening oolitic bars and sandstone occur in the Shell Sauk A-57 well.
The lithofacies map reveals the continued progradation of two lobes into the Sable Subbasin and the seaward retreat of carbonate facies.

Fig. 3.30. Lithofacies map for Tithonian time.
The presence of coarse-grained sandstone (average grain-size > 0.5 mm) indicates certain minimum energy requirements in the environment of deposition. These sandstones are most typical of high-energy, alluvial channel and paralic-nearshore environments. The values used to construct Figure 3.32 were determined using an integrated approach. The study of conventional cores, cuttings, sidewall cores and descriptions in well history reports provide the initial indication of the presence of coarse-grained sandstone. In composite sandstone bodies, log analysis techniques were employed. The presence of shale or argillaceous intercalations can usually be discerned by means of micrologs or microlaterologs if available. The higher permeabilities encountered in coarse-grained units may also be revealed by the build-up of excess mudcake in the well-bore. Cross-plotting irreducible water saturation (Swirr) and porosity can indicate grain size. Irreducible water saturation is the point at which all water is absorbed on grains or held in the capillaries (Asquith, 1982). The amount of water a formation can hold by capillary pressure increases with decreasing grain size. The bulk water volume (Sw x Ø) also increases with decreasing grain size (Timmerman, 1982). This method provides an indirect means of determining grain size from logs by comparing known grain sizes and corresponding irreducible water saturations with log derived values.

Figure 3.32 defines two basinward prograding lobes in the Mic Mac Formation. One lobe occurs along a south trending line through the Shell Erie D-26, and Shell Mic Mac H-86 wells and into the Sable Island area. The axis of the northeast lobe trends south-southeast. These lobes likely define the two principal source areas during the deposition of the Mic Mac Formation. The lobe in the vicinity of the Mobil TETCO Petro-Canada Migrant N-20 well shown in Figure 3.29 is not evident since the Mic Mac Formation is
Fig. 3.32. Percent coarse-grained (>0.5 mm) sandstone map for the Mic Mac Formation (Units A to E). The Mic Mac Formation is relatively thin (<100 m) where it overlies the Baccaro Member in the southwest. However, this succession contains a large proportion of coarse-grained sandstone indicating rather abrupt progradation of siliciclastics into the area.
very thin where it overlies the Baccaro Member. However, the relatively high proportion of coarse-grained sand indicates the abrupt initiation of regressive sedimentation in this area. The western lobe only became well defined in the Latest Kimmeridgian. The quantity of coarse-grained sandstone decreases appreciably across the nearshore ridges into the Abenaki Subbasin. Minor coarse-grained sandstone also occurs within turbidite deposits in the Petro-Canada Banquereau C-21 well (See Fig. 3.28).

Shortly before the end of Jurassic time, the sea retreated from the paleoshelf region in response to continental uplift and a rejuvenation of source areas causing a rapid increase in the detrital input. Clastics prograded southwest over and basinward of the massive Baccaro carbonates. Consequently, the resultant basin fill is younger toward the southwest. These sediments comprise the Lower Mississauga unit. Within this overall regressive wedge a series of minor, transgressive-regressive oscillations are recognized. The transgression is recognized by the presence of oolitic/bioclastic limestones, very calcareous sandstones with scattered superficially carbonate-coated grains and fossil debris or calcareous, glauconitic, fossiliferous sandstone perhaps with minor siderite. Each of these lithologies is overlain by relatively thick shale and siltstone in the Venture area. North of Venture, the limestones are thickened during transgressive events, but are almost directly overlain by sandstone indicating proximity to a source of siliciclastic detritus (Fig. 3.33). These broad sequences comprise a series of increasingly prominent, stacked, coarsening-upward units that take on a more blocky log trace upwards.

Overall deepening of the depositional environment in the central-basin area is suggested by the occurrence of thick shale units in basin areas. These shale units thin abruptly to the north. The transgressive pulse began
Fig. 3.33. Schematic correlation between the Mobil et al. Arcadia J-16 well and the Venture field area. Correlative oolitic limestone units in the Lower Mississauga Formation are thicker in the Mobil et al. Arcadia J-16 well relative to those in the Venture Field area, despite the general basinward thickening of stratigraphic units. However, the overlying transgressive shale is thicker basinward. During transgressive phases the Venture field area apparently occupied a relatively distal position on the shelf. Synsedimentary growth faulting must have been less active during transgressive episodes.
possibly as early as in Late Tithonian time and reached its maximum lateral extent by the Early Berriasian. In the cross-sections (Section E-E'), this shale unit is much better developed in the east and may be largely absent toward the west where siliciclastics continued to prograde basinward possibly in response to a general westerly lateral shift of the depocentre. The ramp paleoshelf profile was maintained in the east during post-Baccaro Member time. This possibly promoted major inundation in the eastern part of the basin, resulting in a better defined shale unit.

In the central-basin, prograding clastic sediments were deposited in lower delta-plain, delta-marine fringe and prodelta environments. The coarsening-upward sandstone bodies are dominated by deltaic foreset deposits comprising barrier-beach, river mouth bar, tidal and nearshore deposits. Alluvial topset deposits occur locally near the top of a transgressive sequence. In the East Sable Island region, the areas in between the distributary channels and river mouth bars were filled in by extensive development of barrier-beach, tidal and nearshore sandstone deposits which were redistributed by reworking of sediments on the coastline and by longshore transport. These sandstones prograded over the delta-front to form an almost continuous linear to arcuate body of beach, bar and tidal sandstone around the entire perimeter of the delta. These sandstones coalesce and form large complex, composite reservoirs. The stacked, multi-story nature of the sandstone bodies indicate that deposition kept pace with subsidence (North, 1985). The vertical and lateral distribution of sandstone bodies indicate the delta probably was wave-dominated and had an arcuate geometry much like that of the Tertiary Niger Delta (Poston, Berry and Molokwu, 1983; Allen, 1965). A mesotidal regime is also interpreted by inference.
Limestone beds are locally observed overlying distributary deposits. These local rapid rises in sea-level within broader transgressive-regressive cycles suggest the rate of movement on synsedimentary growth faults was variable or episodic. The rapid downward movement on these faults resulted in local drowned topography. This was accompanied by a raised base-level updip which caused an increase in detrital input and reworking of coastline deposits. True regional and possibly eustatic rises in sea-level resulted in the deposition of regional transgressive units, most commonly oolitic limestones. Local depocentres migrating laterally owing to compaction and shifts in the river system account for these local transgressions.

On a regional scale, the lateral migration of the principal depocentre toward the southwest is evident. Of particular interest is the fact that hydrocarbon productive trends typically follow the shifting path of a depocentre (Coneybeare, 1979). This trend may be applicable to the Nova Scotia Shelf. The Late Jurassic-Early Cretaceous depocentre in the Venture gas-condensate field area migrated slowly toward the southwest during the Early Cretaceous. Recent gas-condensate discoveries at the Shell Petro-Canada et al. Alma P-67 and Glenelg J-48 wells in sediments of Neocomian age may be related to the migration of the depocentre.

A lithofacies map has been constructed for the Lower Mississauga unit (Fig. 3.34). The percent limestone and coarse-grained sandstone in the Lower Mississauga unit is illustrated in Figures 3.35 and 3.36. These figures document the continued progradation of a thick clastic-wedge toward the southwest and the progressive termination of carbonate deposition. There is some evidence of two major prograding lobes, however the northeasterly lobe became less defined through Early Cretaceous time as broad coastal-plain sedimentation developed. Minor limestone occurs between the two lobes and

167
The lithofacies map documents the continued progradation of a thick clastic-wedge toward the southwest.

Fig. 3.34. Lithofacies map for the Lower Mississauga Formation (Late Kimmeridgian-Berriasian).
Fig. 3.36. Percent coarse-grained (>0.5 mm) sandstone map for the Lower Mississauga Formation. The map shows a large wedge of coarse clastics prograding from the north into the Sable Subbasin. The Lower Mississauga Formation thins toward the southwest above the Baccaro Member, but contains a relatively large proportion of coarse-grained sandstone.
toward the east adjacent to deltaic facies (Fig. 3.35). Pelagic carbonate sedimentation continued during Tithonian time on the outer shelf where biomicrites were deposited (Jansa et al., 1980). Carbonate deposition was terminated at the Shell Demascota G-32 well at the end of Jurassic time by Verrill Canyon Formation shale, but persisted toward the southwest. High-energy environments accompanying prograding siliciclastics eventually brought an end to carbonate deposition during the Late Berriasian-Hauterivian.
4.0 Characterization of Potential Reservoir Facies

4.1 Reservoir Heterogeneity and Sequence Elements

Sandstone reservoir bodies reflect primary depositional processes
modified by burial, compaction, diagenesis and structural deformation. The
resultant spatial distribution and magnitude of porosity and permeability
will significantly influence the migration and accumulation of subsurface
fluids and gases. The nature and distribution of porosity and permeability
is primarily a result of textural properties inherited from the depositional
environment. Textural heterogeneity is principally defined by bedding
variations reflected in grain size and sorting. Beard and Weyl (1973) and
Pryor (1973) have shown that initial porosity is dependent on sorting and
independent of grain size. Initial permeability is a function of both grain
size and sorting. Textural properties such as grain shape, orientation and
packing have only a minor influence on initial pore distributions (Sneider et
al., 1983).

Secondary porosity is often observed to be controlled by the
distribution of preserved primary porosity which depends on the distribution
of coarser sediments, and is thus indirectly controlled by depositional
facies (Cant, 1983). Sneider et al. (1983) found in a study of sandstones in
the Deep Basin of Western Canada, that grain size and sorting still exhibited
some control on porosity and permeability despite the rocks being well
cemented and compacted.

Primary depositional heterogeneities are ultimately amplified by
diagenesis. Homogeneity of texture facilitates ease of flow through
sandstone reservoirs. The quantity and distribution of thin discontinuities
can have a significant detrimental effect on lateral and vertical permeability.

Primary sedimentary structures, particularly the type and configuration of layering, provide important clues about permeability anisotropy in sandstone reservoir bodies (Pettijohn et al., 1973). Laterally persistent shale beds are the most obvious primary impediment to the vertical movement of fluids. The boundary conditions between sandstone beds and shale layers are important in determining the effectiveness of the inhomogeneity on fluid flow. Sets and coasts of cross-strata with preferred orientation may strongly influence horizontal permeability (Pettijohn et al., 1973).

Secondary reservoir heterogeneities such as well indurated concretionary bodies commonly constitute effective barriers to flow. The distribution of these structures is to some extent controlled by primary depositional texture. Presumably, original high-permeability zones permitted the transmission of large flow volumes of evolving subsurface fluids.

Documentation of the pattern and distribution of primary and secondary heterogeneities within reservoir facies takes on considerable significance for predicting porosity and permeability gradients, particularly into areas of limited data control.

The gradational lithologic relationships between the dominantly upward-coarsening units in the Mic Mac and Lower Missisauga Formation sandstones in the East Sable Island area present certain difficulties in their systematic description. These difficulties are overcome by utilizing conventional logging techniques augmented by the use of a scheme of sequence elements outlined in Table 4.1. The basic elements are erected on the basis of gross lithology and sedimentary structures. The scheme is particularly applicable in describing the monotonous sequence of bedded, bioturbated and variably
shaly sandstones and siltstones commonly observed in the lower portion of upward-coarsening sequences. The utility of this unique approach has been demonstrated for the entire marine Cretaceous succession of Saskatchewan (Simpson, 1971, 1975, 1979, 1980, 1982). The scheme places special emphasis on the quantity and continuity of shale layers. The degree to which primary heterogeneities are disrupted by biogenic activity is also an important consideration. A particular advantage in the use of this approach is that the scheme provides a ready framework for detailed reservoir studies.
Table 4.1
Sequence Elements in Lower Missisauaga and Mic Mac Formation Sandstones - Offshore Nova Scotia
(See Figures 4.1, 4.2, 4.3)

<table>
<thead>
<tr>
<th>Sequence Element</th>
<th>Sub-element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I Sandstone - Limestone Element</td>
<td>a) limestone interbedded with shaly sandstone/siltstone</td>
</tr>
<tr>
<td></td>
<td>b) limestone interbedded with well-washed sandstone</td>
</tr>
<tr>
<td>Type-II Well-Washed Sandstone Element</td>
<td>a) structureless sandstone</td>
</tr>
<tr>
<td></td>
<td>b) plane-laminated sandstone</td>
</tr>
<tr>
<td></td>
<td>c) sandstone with planar and trough cross-laminations</td>
</tr>
<tr>
<td></td>
<td>d) planar and trough cross-bedded sandstone</td>
</tr>
<tr>
<td>Type-III Bedded Shaly Sandstone-Siltstone Element</td>
<td>a) lenticular-beded siltstone/sandstone in mudstone</td>
</tr>
<tr>
<td></td>
<td>b) alternating mudstone and subordinate siltstone</td>
</tr>
<tr>
<td></td>
<td>c) wavy-beded sandstone/siltstone</td>
</tr>
<tr>
<td>Type-IV Bioturbated Element</td>
<td>a) well-washed sandstone</td>
</tr>
<tr>
<td></td>
<td>b) bedded shaly sandstone</td>
</tr>
<tr>
<td></td>
<td>c) siltstone</td>
</tr>
<tr>
<td>Type-V Mudstone Element</td>
<td>a) lenses of siltstone/sandstone as occasional layers</td>
</tr>
<tr>
<td></td>
<td>b) mudstone</td>
</tr>
</tbody>
</table>

The study of depositional environments and the reservoir facies contained therein provide a basis for predicting the character and lateral variation of reservoir anisotropy. Alpay (1972) proposed a hierarchical classification of reservoir heterogeneity based on variations in scale (Table 4.2).
Fig. 6.3. Core photographs of Type III sandstone. All core is presented in 75 mm wide.

1. Cross-beded, fine-grained sandstone with thin carbonaceous mudstone laminae occasionally overlain by medium-grained, structureless sandstone.

2. Structureless and cross-laminated sandstone. Irregular patches in lower part of photograph are probable burrows.

3. Subhorizontal, plane-laminated, fine-grained sandstone displaying an escape burrow in the lower part. Solif and pellets occur locally on bedding surfaces and in laminae.

4. Cross-laminated and cross-beded fine- to medium-grained sandstone with rare mudstone intrusions and carbonaceous laminations.

5. Low-angle, plane-laminated, fine-grained sandstone. Laminae are relatively clay-poor and bedding in core to the far right can only be recognised by inclined mudstone flakes, coal fragments and discontinuous vesicular streaks.

6. Cross-beded, fine- to medium-grained sandstone with moderately inclined coal stringer near the base and irregular patches of coarser sandstone.

7. Moderately high-angle, planar cross-laminated at the base to horizontal-laminated at the top.
Fig. 4.2. Core photographs of Type-III elements. All core in photographs is 7.6 cm wide. The photographs display common wavy- and lenticular-bedded sandstone/siltstone and mudstone with sporadic burrowing of sandstone layers and local carbonaceous streaks. Alternating beds of argillaceous, cross-laminated sandstone and mudstone are shown in the middle and upper right photograph. Burrowing is primarily restricted to muddy layers in this case.
Fig. 4.3. Core photographs of Type-IV elements. All core in photographs is 7.6 cm wide.

a-c) Bioturbated and burrowed sandstone displaying various degrees of disruption of primary layering. Different burrow sizes, shapes, linings, infillings and orientations are represented.

d) Churned shaly sandstone with few recognisable sand- and mud-filled burrows.

e) Well developed Chondrites burrows within a bedded shaly sandstone unit.

f) Burrowed bedded shaly sandstone/siltstone with only minor disruption of primary layering.
Table 4.2
Hierarchy of Reservoir Heterogeneities, Alpay (1972)

Microscopic (scale of individual pores)
  a) pore-size distribution  b) pore geometry
  b) pore occlusion  d) dead-end pore space

Macroscopic (lithologic variation between wells)
  a) stratification characteristics
  b) $\Omega-K$ characteristics

Megasscopic (lithologic variation on scale of field or regional, in extent)
  a) stratigraphic framework of reservoir
  b) structural framework of reservoir
  c) hyper-permeability oriented along natural fracture systems

The introduction of cement and the complexities of the size, shape, orientation, and continuity of pores in sandstones is obviously important in reservoir studies. Compaction, dissolution, clay mineralization and fracturing act to further alter initial pore space. In a stratigraphic framework, reservoir pinchouts, shale breaks and cementation barriers have an effect on reservoir size and performance. Accurate petrophysical correlations can aid in the delineation of these major permeability barriers. Regionally, tectonic activity, including penecontemporaneous growth faulting and diapirism causes an overall reduction in reservoir quality, particularly by a tendency to compartmentalize reservoirs.
4.2 Porosity and Permeability Relationships

Laboratory core analysis on four wells in the Venture field have been combined with well log interpretations to help determine the spatial variation of porosity and permeability within particular sequence elements. The integration of sedimentological data (sequence elements) and lab analyses has great potential for understanding reservoir behaviour. The total variability of all sedimentary parameters within a sequence sub-element is finite. Consequently, the relative magnitude of porosity and permeability should be well defined within the context of a single sub-element (Fig. 4.4). Post-depositional modification of the sediment and diagenetic processes can alter this simple relationship.

The problems of obtaining representative average values for porosity and permeability within a sedimentary unit is very substantial (Timmerman, 1982). The sedimentary rock sampled by cores and logs is a very small part of the total volume of the potential reservoir. The most important primary controls on permeability, and to a lesser extent porosity distribution in a sandstone body are bed thickness, types and abundances of sedimentary structures and frequency of shale intercalations. It is the arrangement of sand and shale much more than permeability and porosity variation from point to point within the sandstone that ultimately controls reservoir behaviour. Combining sequence elements with an adequate data base of laboratory core analyses alleviates problems of obtaining representative values for porosity and permeability.

Permeability is normally reduced by confining pressure. In low-permeability rocks, laboratory measured permeability to air and porosity in cores usually requires correction to allow for this change in confining pressure (Timmerman, 1982). These corrections have not been made for the
Fig. 4.4. Cumulative frequency plot of porosity values and their relationship to sequence elements.
<table>
<thead>
<tr>
<th>Depositional Environments</th>
<th>Alluvial</th>
<th>Distributary Channel</th>
<th>Coastal Marine</th>
<th>Marine Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence Element</td>
<td>Fracture Channel</td>
<td>Distributary Bar</td>
<td>Barlee, Tidal Delta/ Beach, Nearshore</td>
<td>Barlee, Shelfface</td>
</tr>
<tr>
<td>Type-I well developed, good quality, tectonically controlled</td>
<td>absent</td>
<td>absent</td>
<td>common; scattered gravel or thin layers within other elements</td>
<td>common; shallow sub-littoral area</td>
</tr>
<tr>
<td>Type-II well developed, good quality, tectonically controlled</td>
<td>common; variable quality; permeability 0.1 to 4.000 md, porosity 0.1-3.500; sheets and slabs, interbedded lithologies with Type-II and -Y elements</td>
<td>common; polychrome, sheets, and slabs; interbedded lithologies with Type-II and -Y elements</td>
<td>abundant; ribbons; excellent porosity and permeability when cemented, 2.0 to 3.500 md, porosity 3 to 250</td>
<td>abundant; planar foresets and interbedded sands give rise to highest permeabilities, 0.01 to 4.000 md, porosity 0.01 to 0.01; variability</td>
</tr>
<tr>
<td>Type-III reservoir quality fair to poor; with rare concretions (calcite, siderite) and numerous mudstone layers</td>
<td>scarce; accretion deposits and thin crevasse splay</td>
<td>scarce to absent; minor thin crevasse splay deposits</td>
<td>relatively common; associated with tidal flats and lagomorph deposits; extensively compartmentalized</td>
<td>scarce; occur near base of sequence</td>
</tr>
<tr>
<td>Type-IV reservoir quality poor to fair; continuous mudstone intercalations are common barriers</td>
<td>absent</td>
<td>scarce; at top of sequence during abandonment phase</td>
<td>relatively common; in lower part of sequence; permeability 0.1 to several thousand md, porosity 14-27</td>
<td>abundant; variable reservoir quality; permeability 0.1 to 5.0 md, porosity 0.01 to 1.0; common; high void content, increasing in frequency upward</td>
</tr>
<tr>
<td>Type-V reservoir heterogeneities, reservoir barrier</td>
<td>scarce; vertical accretion deposits and floodplains</td>
<td>scarce; lenses, flood-basalt deposits</td>
<td>relatively common; in lower part of sequence; permeability 0.1 to several thousand md, porosity 14-27</td>
<td>abundant; occur near top or base of succession and as intercalations</td>
</tr>
</tbody>
</table>

Note: The table provides a summary of sequence elements and depositional environments, highlighting the characteristics of various sequences and their implications for reservoir quality and permeability.
present study. The permeability to air and porosity measured in low permeability rocks recovered from deep depths should be considered maximum values.

The porosity and permeability relationships within the various sequence elements are discussed in the following sections (See Table 4.3). No data are available for the mudstone element since it is a barrier to subsurface flow. The bedded shaly sandstone elements have only limited porosity and permeability data. Normally, only the most sandstone-rich and relatively thicker bedded intervals have been analysed. Therefore, porosity and permeability values obtained are not necessarily representative of the whole bedded shaly sandstone element.

4.2.1 Sandstone - Limestone Element (Type-I)

The sandstone-limestone element commonly overlies shallowing-upward regressive sequences. The element has two modes of occurrence. The most common consists of interbedded laminated to structureless, well-washed sandstone and well sorted, medium- to coarse-grained, oolitic grainstone to packstone. The sandstone is calcareous and rarely fossiliferous. The lowermost oolitic layer initially overlies bioturbated sandstone. Less commonly, the sandstone-limestone element is comprised of a chaotic mixture of ooids, fossil shell debris, granules and pebbles interbedded with bioturbated shaly sandstone and siltstone. The shell debris and pebbles frequently form lags at the base of sandstone units.

The ubiquitous carbonate cementation throughout Type-I elements omits them from being considered as significant reservoir facies. Porosities range from 1% to less than 10%, but are most commonly 3-6% (Figs. 4.5 and 4.6). Permeability is very poor, usually less than 0.05 md (Fig. 4.5 and 4.6).
Fig. 4.5. Frequency and cumulative frequency plot of porosity and permeability for Type-I (sandstone/limestone) elements.
Fig. 4.6. Porosity-permeability scattergram for Type-I (sandstone/limestone) elements.
Fig. 4.7. $K_y/K_y$ plot for Type-1 (sandstone/limestone) elements.
Little data are available comparing the maximum horizontal permeability and vertical permeability. The Kh/Kv ratio was measured on several samples and ranged from 1.5 to 15 (Fig. 4.7).

4.2.2 Well-Washed Sandstone Element (Type-II)

Type-II elements form the best potential reservoir facies. However, considerable variation in reservoir quality is observed owing to the nature and quantity of primary and secondary heterogeneities and discontinuities (Fig. 4.1). Differences in texture and possibly fabric are also controlling factors. The definition and quantity of lamination is important.

Laminations are chiefly bipartite, clay-rich to clay-poor. Unipartite laminations defined by sand grain-size variations are also observed. Minor biogenic activity usually expressed as discrete tubular burrows occurs sporadically. These sandstones are not included in Type-IV elements since the burrowing is sparse, and does not disrupt primary layering or display specific lithologic associations.

The porosity and permeability relationships expressed in the sub-elements are summarized in Table 4.4 and illustrated in Figures 4.8 to 4.11. The presence of preferred directional properties impart a natural anisotropy to the sandstone. The permeability will tend to increase along the preferred orientation and decrease in the direction normal to it. Theoretically, permeability should increase with porosity, but this is not always displayed by sandstone units (Fryor, 1973; See Figures 4.12 to 4.15).

The structureless sandstone bodies comprising part of Type-II elements are very fine- to coarse-grained. The sandstones may incorporate scattered granules, pebbles, mudstone clasts, minor flasers near the top, and very rare
<table>
<thead>
<tr>
<th>Sub-Element</th>
<th>Porosity Permeability Trends</th>
<th>Porosity (θ) (percent) Mode Range</th>
<th>Max. Horizontal Permeability (millidarcies) Mode Range</th>
<th>Kh/Kv Mode Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structureless Sandstone</td>
<td>θ ∝ K</td>
<td>20.0 2-28</td>
<td>1.50 0.01-4250</td>
<td>2-3</td>
<td>1-25 Possible bimodal trends in θ-K and Kh/Kv</td>
</tr>
<tr>
<td>Plane-Laminated Sandstone</td>
<td>θ ∝ K</td>
<td>11.8 3-28</td>
<td>0.43 0.01-450</td>
<td>3-4</td>
<td>2-10</td>
</tr>
<tr>
<td>Cross-Laminated Sandstone</td>
<td>θ ∝ K</td>
<td>10.0 1-30</td>
<td>0.30 0.01-80</td>
<td>8-10</td>
<td>1.5-25</td>
</tr>
<tr>
<td>Cross-Bedded Sandstone</td>
<td>Variable</td>
<td>18.4 4-33</td>
<td>4.50 0.01-4970</td>
<td>2-3</td>
<td>1-17 Bimodal trends in θ-K and Kh/Kv</td>
</tr>
</tbody>
</table>
Fig. 4.8. Frequency and cumulative frequency plots of porosity and permeability for structureless sandstone.
Fig. 4.9. Frequency and cumulative frequency plots of porosity and permeability in cross-bedded sandstone.
Fig. 4.10. Frequency and cumulative frequency plots of porosity and permeability in cross-laminated sandstones.
Fig. 4.11. Frequency and cumulative frequency plots of porosity and permeability in plane-laminated sandstones.
Fig. 4.12. Porosity-permeability scattergram for structureless sandstone. The two trends reflect differences in average grain-size. The upper curve represents medium- and coarse-grained sandstones.
Fig. 4.13. Porosity-permeability scattergram for cross-bedded sandstone.
Fig. 4.14. Porosity-permeability scattergram for cross-laminated sandstone.
Fig. 4.15. Porosity-permeability scattergram for plane-laminated sandstone.
burrows. Core data indicate there may be a bimodal trend in porosity and permeability (Fig. 4.12). The bimodal trend may arise from selective development of secondary porosity. The development of secondary heterogeneties such as cementation barriers and minor concretionary bodies help to emphasize the bimodal trend. Local concentrations of argillaceous material may also reduce the reservoir quality of the sandstones.

In the absence of cement, some variations in porosity and permeability can be attributed to texture, particularly grain size and fabric. Fabric (packing and shape orientation of framework grains) tends to control permeability anisotropy in non-laminated sandstone bodies (Lindquist, 1983). Permeability is maximum parallel to mean grain-shape fabric. Grain orientation may be more important in poorly sorted sandstone (Dodge, et al., 1971). Thicker beds tend to be coarser-grained and thus more permeable, if cement is not a factor. For constant grain size, there is generally a greater disparity between horizontal and vertical permeability when the sandstone is thinly bedded. In weakly cemented or uncemented sedimentary rocks the ratio of maximum to minimum permeability is usually less than 5 to 1 (North, 1965). If cement controls the distribution of permeability, the ratio may exceed 100 to 1 or more (Fig. 4.16).

Horizontal to slightly inclined, plane-laminated sandstones are typically very fine- to medium-grained. Laminations are exclusively bipartite and dominantly clay-poor. The laminations occur as single laminae or as grouped sets. Evidence of biogenic activity is very rare. Escape burrows are the most common type of biogenic structure. Sandstone beds with clay-poor laminations commonly have granule and pebble layers near the base.

Porosity and permeability trends are controlled principally by the frequency and clay-richness of the mudstone intercalations (Fig. 4.11). As
Fig. 4.16. $X_1/Y_1$ plots for structureless and plane-laminated sandstone.
the laminations become more clayey, there is a decrease in the vertical permeability relative to the horizontal permeability (Fig. 4.16). In the upper part of coarsening-upward units, bipartite mudstone laminations are relatively scarce and the sandstones typically carbonate cemented.

Cross-laminated sandstones form the poorest reservoir facies of the well-washed sandstone elements. The range of porosity values are similar to those observed in horizontal laminated well-washed sandstones (Fig. 4.17). However, differences in the arrangement of the laminations has resulted in a large disparity in permeability. The frequent truncation of laminae and laminae with opposing dips seriously effect the horizontal permeability. In the cross-laminated sandstones, the laminations are typically more abundant and clay-rich. Ultimately, the porosity and the permeability will depend on the quantity, clay-richness and arrangement of the laminations. The maximum permeability normally parallels the laminations. These sandstones are typically very fine- to fine-grained, rarely medium-grained.

The low- to high-angle cross-bedded sandstone sub-element is dominantly medium- to coarse-grained. Laminations are mainly unipartite, defined by grain size variations. Less commonly, clay-poor, bipartite laminations are also observed. Porosity and permeability data indicate a possible bimodal distribution (Fig. 4.9). The bimodal character is probably a result of diagenetic processes including selective cementation and development of secondary porosity. The sandstones in this sub-element are too similar texturally to explain the bimodal character of porosity and permeability distribution.

Though not evident from the laboratory core analyses, intuitively the nature of the cross-stratification should have an effect on the overall permeability. The size and arrangement of cross-bed-sets and cosets can be
Fig. 4.17. Kh/Kv plots for cross-bedded and cross-laminated sandstones.
important (Dodge, et al., 1971). The inclination and dip direction will have an effect on permeability. The horizontal permeability will tend to parallel the direction of inclination and the trough axis of cross-beds (Pryor, 1973). If the angle of dip is large, laminae interfaces must be crossed. Flow will be impeded by shaly laminae and laminae defined by variable grain size. The larger the grain size contrast between laminae, the more it will reduce overall permeability (Linquist, 1983).

4.2.3 Bedded Shaly Sandstone Element (Type-III)

The bedded shaly sandstone element consists of regular alternations of argillaceous, silty, very fine- to fine-grained sandstone/siltstone and mudstone (See Fig. 4.2). The sandstones are structureless and plane- to ripple-laminated. There is commonly a vertical increase in the proportion and thickness of sandstone layers. Contacts are gradational or sharp with common soft sediment deformation and load structures at the base of sandstone units. Thicker sandstone units tend to have sharp undulatory to irregular basal contacts and gradational, frequently burrowed upper contacts.

The presence of abundant mudstone intercalations seriously hampers vertical permeability. Individual sandstone units will tend to behave as flow 'packets'. The size and lateral continuity of sandstone bodies, and the density of packing of mudstone layers are important considerations in the distribution of porosity and permeability (Fig. 4.18). Concretionary bodies can have a serious detrimental effect on the reservoir potential of a single sandstone layer because of the thinly-bedded nature of the lithologies. Ripple-laminated sandstones with shale intercalations normally constitute permeability barriers (Simpson, 1984). Maximum porosities of 14% have been measured in the bedded shaly sandstones (Figs. 4.19 and 4.20). The average
Fig. 4.18: Porosity-permeability scattergram for bedded shaly sandstone and siltstone.
Fig. 4.19. Frequency and cumulative frequency plots of porosity and permeability in wavy-bedded sandstone.
Fig. 4.20. Frequency and cumulative frequency plots of porosity and permeability in lenticular-bedded sandstone/siltstone and thinly bedded mudstone and sandstone/siltstone.
porosity is less than 8%. The average permeability is approximately 0.07 md. The highest maximum horizontal permeability measured is less than 1.0 md.

4.2.4 Bioturbated Element (Type-IV)

Biogenic activity serves to break the continuity of clayey partings and homogenize the sediment (See Fig. 4.3). The homogenization tends to improve the vertical permeability and give a more even distribution of porosity. However, the biogenic structures destroy the depositional fabric and bedding which causes an overall reduction in the maximum directional permeability (Dodge et al., 1971).

The distribution of porosity and permeability in bioturbated and burrowed units is related to the quantity of mudstone intercalations. The overall improved reservoir quality associated with biogenic activity may not be evident from laboratory derived porosity and permeability measurements performed on core plugs. The frequency of burrowing is obviously important. The improved vertical permeability associated with sporadic burrowing of clayey laminations is probably not reflected in laboratory core analyses.

The physical description of biogenic structures can give important clues to how the porosity and permeability is affected. Three aspects potentially affecting reservoir behaviour warrant special consideration:

1. Spatial relationships size, shape, orientation and arrangement (grouped or solitary) of burrows.

2. Degree and quality of disruption continuity and density of packing of mudstone and sandstone layers or pods.

3. Burrow infilling sand-or mud-filled and lined.
There is commonly an association between particular biogenic structures and primary sedimentary layering.

Bioturbated well-washed sandstones have two modes of occurrence. The most common association consists of moderate to strongly-burrowed, grouped or solitary, clay-rich, planar, horizontal to slightly inclined laminations in sandstone. Burrowing tends to increase with an increase in clay content. The second association shows sporadic burrowing of mostly solitary clay-rich and clay-poor laminations. The burrowing is in conjunction with a relative increase in mud content. The sandstones are dominantly very fine- to fine-grained. The bioturbated units are often terminated by sandstone layers containing occasional escape burrows.

The porosity and permeability data for well-washed bioturbated sandstones indicate two trends (Figs. 4.21 and 4.22). Primary textural features responsible for these trends include variations in grain size, the proportion and arrangement of mudstone partings and the degree of disruption of the mudstone. Diagenetic effects on the distribution of porosity and permeability are potentially important. A summary of the porosity-permeability trends in Type-IV elements can be found in Table 4.5.

Bioturbated bedded shaly sandstones typically consist of pods and lenses of sandstone with intervening continuous and discontinuous closely spaced mudstone partings. The continuity of the mudstone layers depends on the degree of churning. Beds display a general vertical increase in biogenic churning. The sandstone beds commonly have sharp, irregular bases which terminate biogenic structures. The churning has had a detrimental effect on overall permeability. There has been a reduction in average maximum horizontal permeability from 0.07 md in the bedded shaly units to 0.045 md in the bioturbated units (Figs. 4.23 and 4.24). This reduction is attributed to
Table 4.5
Porosity-Permeability Trends in Type-IV Elements

<table>
<thead>
<tr>
<th>Sub-Element</th>
<th>Porosity - Permeability Trends</th>
<th>Porosity (θ) Percent</th>
<th>Maximum Horizontal Permeability (K) Millidarcies</th>
<th>Kh/Kv</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioturbated Well-Washed Sandstone</td>
<td>0.000</td>
<td>14.3</td>
<td>2-27</td>
<td>0.45</td>
<td>0.01-300 3-4 1.5-100</td>
</tr>
<tr>
<td>Bioturbated Bedded Shaly Sandstone</td>
<td>Variable</td>
<td>7.5</td>
<td>1-14</td>
<td>0.045</td>
<td>0.01-0.40 2 &lt;1-40</td>
</tr>
<tr>
<td>Bioturbated Siltstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not Measured</td>
</tr>
</tbody>
</table>

207
Fig. 4.21. Frequency and cumulative frequency plots of porosity and permeability in well-washed burrowed sandstone.
Fig. 4.22. Porosity-permeability scattergram for well-washed burrowed sandstone.
$\phi_{50} = 7.5\%$

$K_{50} = 0.045\text{md}$

Fig. 4.23. Frequency and cumulative frequency plots of porosity and permeability in muddy bioturbated sandstones.
Fig. 4.24. Porosity-permeability scattergram for muddy bioturbated sandstone.
admixing of argillaceous material into the sandstone by biogenic processes. Bioturbation had very little effect on the porosity. Burrowing has locally enhanced vertical permeability, such that it exceeds the measured maximum horizontal permeability in a number of samples (Fig. 4.25).

4.2.5 Order of Occurrence

Sequence elements typically occur in a series of repetitive units which are important for understanding fluid dynamics within the overall reservoir. All elements are not necessarily present in any one core or reservoir sandstone body. Two types of alternating interbedded relationships are recognized (See Figs. 4.26, 4.27, and 4.28). Many sandstone bodies exhibit alternating layers of bioturbated well-washed and argillaceous sandstone interbedded with bedded shaly sandstone layers. The sandstone layers frequently have sharp bases and burrowed tops. The second association is comprised of well-washed structureless sandstone and sandstone with well developed primary sedimentary structures commonly alternating with subordinate layers of bedded and bioturbated shaly sandstone (See Fig. 4.29).

Many of the sandstone bodies exhibit coarsening-upward sequences with bedded shaly sandstone and mudstone at the base succeeded gradationally upward by bioturbated elements and capped by regularly bedded, well-washed sandstones. There is normally a vertical increase in grain size and a decrease in argillaceous material. The thickness and frequency of mudstone intercalations decreases upward. Secondary heterogeneities are rare and do not affect overall reservoir quality. Oolitic grainstone to packstone layers periodically form the top of coarsening-upward units. The oolitic layers alternate with well-washed sandstone. These successions are usually carbonate cemented and display no reservoir potential.
4) Oolitic layers initially overlying bioturbated sandstone grades vertically to massive sandstone interbeds.

3) Bioturbated sandstone-pods and lenses of sandstone with intervening mudstone partings that are either continuous or discontinuous.

2) Regularly laminated sandstone with discrete burrows.

1) Muddy siltstone/sandstone, regularly laminated and thinly bedded with common soft sediment deformation.

(overall upward increase in biogenic activity)

3) Bedded shaly sandstone interbedded with mudstone or siltstone.

2) a. Regularly laminated sandstone (clay-rich partings) with discrete burrows. Increasingly burrowed upward or as mud content increases.

b. Well-washed sandstone with discrete burrows (associated with increasing mud content).

--- Bioturbated units terminated by sandstone layers with occasional escape burrows.

3) Well-washed sandstone incorporating rare biogenic structures. Structureless or with horizontal and inclined plane-laminations; mainly biotite but relatively clay-poor. Occasional pebbly layer with mudstone clasts and shell debris near the base.

Fig. 4.26. Two repetitive series of sequence elements important in fluid dynamics are commonly observed in the Venture field area. Core photographs of these sequences are in Figures 4.27 and 4.28.
Fig. 4.27. Core photographs of sequence A. The unit incorporates bedded shaly sandstone/siltstone at the base grading vertically through regularly laminated and burrowed sandstone. The sequence may be capped by interbedded oolitic limestone and sandstone. The lower right photograph is a detail of the regularly laminated to burrowed sandstone transition. The lower right photograph shows biogenically disrupted sandstone overlain by a thin oolitic layer grading into regularly laminated sandstone.
Fig. 4.28. Core photograph of sequence B. The sequence has well-washed, regularly laminated or structureless sandstone at the base and displays an overall vertical increase in biogenic churning and mud content. Bedded shaly sandstone interbedded with mudstone occurs at the top. The photograph to the right shows a large escape burrow with well-developed spreite.
Fig. 4.29. Relationship between sequence elements, porosity, permeability and log derived clay volume in core #7 from Mobil et al. Venture B-52 (5266.6-5280.0 m). Type-II elements represent the best reservoir facies. Type-III and -IV elements are poor reservoir rocks owing to high clay content and local carbonate cement in sandstone bodies.
4.3 Petrography

Reservoir potential is ultimately a function of pore size distribution, pore geometry and the type and quantity of cements or pore-filling materials. Petrography allows one to determine the relative paragenetic sequence, documenting the appearance and removal of cementing materials and other authigenic minerals. The detrital and authigenic mineralogy from the main sequence elements discussed previously will be described and their spatial distribution outlined.

Thin sections from 5 wells were used to characterize the petrography. This study is not an exhaustive investigation of the diagenetic history of the Lower Mississauga and Mic Mac Formation sandstones in the East Sable Island area. Mineralogy and texture are readily determined using a petrographic microscope. Staining techniques have been employed where necessary to highlight particular cements. Clay mineralogy and morphology have not been studied. Clay mineralogy in sandstones of the Venture field have been studied by Meloche (1985) and Nogeura (pers. comm., 1986). The distribution of clay minerals relative to framework grains and pores is readily apparent in thin sections. Attention was largely focussed on the textural features of the sandstones in this part of the study.

The Late Jurassic-Early Cretaceous sandstones in the Venture field exhibit relatively consistent detrital mineralogy. The sandstones are dominantly variably indurated sublitharenites and subarkoses incorporating alkali and calcic feldspars, volcanic rock fragments and less common sedimentary rock fragments, chert, detrital clays, mica, (chlorite, muscovite, minor biotite), glauconite, carbonaceous matter, shell debris and pyrite. Plagioclase and alkali feldspars are typically turbid, slightly to moderately altered and locally corroded. Fossil fragments are dominantly
molluscs and echinoids composed of fibrous calcite and/or dolomite. The
detrital mineralogy is apparently independent of texture. The original
porosity has been significantly altered by carbonate and quartz cements and
the growth of authigenic clays, particularly chlorite (Meloche, 1985;
Nogeura, pers. comm.). Undulose extinction is occasionally shown by the
chlorite cement. The chlorite is typically an iron-rich, low to medium
magnesium variety (Nogeura, pers. comm.) Porosities estimated from thin
sections range from less than 3% to approximately 30%.

The interpreted paragenetic sequence appears to be relatively consistent
between different sandstones in overpressured and normally pressured
reservoirs. Textural relationships between detrital and authigenic minerals
are occasionally ambiguous and not well developed. This ambiguity has been
somewhat resolved by utilizing sequence elements. Variations in the types of
authigenic minerals and their relative proportion have been explained by
primary porosity and permeability relationships which controlled the
distribution of diagenetic cementing fluids.

The relative sequence of precipitation of authigenic minerals as
revealed by petrographic techniques was determined to be:

Chlorite-quartz-feldspar-ferroan calcite-ferroan dolomite
+- pyrite +- siderite +- kaolinite

The earliest deposited cements are better formed or more euhedral
(quartz) and are therefore typically attached to the pore walls or protrude
into pore space (Fig. 4.30). The relative timing of local pyrite, siderite
and probable kaolinite cement is uncertain from petrographic evidence.
Ferroan calcite and ferroan dolomite cements typically occur together. The
dolomite crystals typically display undulose extinction. The carbonate
Fig. 4.30. Photomicrograph of a medium-grained sandstone from 4958.25 m (core depth) in the Mobil et al. Venture B-43 well. The sandstone has patchy carbonate cement and an average laboratory measured porosity of 23%. The field of view in the photomicrograph is approximately 0.65 mm wide. A euhedral quartz (Q) overgrowth (thin arrow) on a detrital grain protrudes into a pore now occluded by carbonate (C) cement. The carbonate is observed replacing and corroding adjacent framework grains and even the overgrowth. Pore-lining chlorite (thick arrow) appears in the photomicrographs as dark, relatively thick, diffuse edges on framework grains. Normally, grain boundaries appear sharp. Note the absence of overgrowths where chlorite is present.
cement is occasionally observed partially replacing framework grains. Earlier and multiple stages of carbonate emplacement, dissolution or replacement are possible but not readily documentable from these data. Frosted and pitted quartzose framework grains in friable sandstones provide indirect evidence of carbonate dissolution. Remnant patchy carbonate cement was observed in a number of thin sections. Nogeura (pers. comm.) has also proposed late carbonate dissolution evidenced by corroded carbonate cement. Irregular and frambooidal aggregates of pyrite cement occlude pores locally and are most commonly, but not exclusively, associated with carbonaceous matter. Plagioclase feldspars occasionally exhibit overgrowths (Fig. 4.31).

Meloche (1985) recently completed a study of the authigenic minerals in Mic Mac Formation sandstones within the Venture field and observed the following assemblage:

Quartz-albite-chlorite-sphene-anatase-tourmaline-calcite-dolomite
(+/- barite +/- kaolinite, smectite, illite)

Anatase, tourmaline, sphene and barite were not observed in any thin sections in this study. Kaolinite, smectite and illite could not be distinguished petrographically. The paragenetic sequence outlined by Meloche (1985) differs from that observed in this study with regard to the relative timing of quartz emplacement.

Chlorite where present, occurs as drusy rims on virtually all framework grains. Quartz overgrowths were rarely observed when ubiquitous authigenic chlorite was present. The quartz overgrowths are easily recognized as syntaxial euhedral terminations or rare isopachous rims with thin lines of inclusions (Fig. 4.32). It seems probable that quartz overgrowths are controlled to some extent by earlier developed chlorite cement lining pores.
Fig. 4.31. Photomicrograph (X-N) of a fine-grained sandstone from 4726.35 m (core depth) in the Mobil et al. Venture B-13 well. The sandstone is slightly burrowed with minor indistinct plane- and ripple-laminations. The thin section contains a 3 mm thick micaceous, indurated, carbonate cemented, very fine-grained lamination. The sandstone body has an average laboratory measured porosity of 18%. The field of view of the photomicrograph is approximately 0.65 mm wide. Carbonate partially replaces a plagioclase or quartz framework grain exhibiting a relatively intact euhedral overgrowth. Remnant cleavage traces and twin planes indicate the host grain is probably plagioclase (P). Dark areas rimming framework grains are chlorite rims.
Fig. 4.32. Photomicrograph (PPL) of a fine- to medium-grained sandstone cored in the Mobil et al. Venture B-43 well (4965.7 m, core depth). Laboratory core analysis indicate an average porosity of 10.5%. The field of view of the photomicrograph is approximately 0.65 mm wide. The sandstone is moderately indurated with rare pore-filling carbonate cement. The thin section exhibits an interlocking mosaic of quartz overgrowths with syntaxial, euhedral terminations (arrow), discontinuous isopachous rims and thin lines of inclusions. Minor chloritized rock fragments (R) are also observed. Note the absence of grain-rimming chlorite. Detrital feldspar grains are locally replaced by carbonate elsewhere in the thin section.
The earlier chlorite cements cover potential quartz nucleation sites (Cecil and Heald, 1971; Friedman and Sanders, 1978). Quartz overgrowths in the presence of authigenic chlorite post-dates chlorite emplacement and the overgrowth sites are largely restricted to preserved primary porosity. The local presence of smectite clays reported by Meloche (1985) may have actually promoted the formation of quartz overgrowths. The conversion of smectite to illite liberates silica which is then available for the formation of quartz overgrowths (Dutton and Land, 1985).

Porosity in the sandstone units is primarily intergranular. Diagenesis has reduced the overall reservoir quality by intergranular cementation and clay mineralization, however dissolution porosity has been recognized (Fig. 4.33). Pore-throat morphology provides a clue to the nature of the porosity. Triangular and sub-equant pore apertures have been interpreted to be primary because of their shape and relative position. Irregular pore shapes, oversized, elongated or channel pores and floating grains and oversized pores result from partial or advanced dissolution of framework grains or cements. Chlorite rim ghosts have also been observed (Fig. 4.34). The chemical instability of certain minerals is important in the formation of secondary dissolution porosity. The excellent porosities encountered in the Venture field have been attributed to various degrees of dissolution of alumino-silicate framework grains, dominantly calcic plagioclase and volcanic rock fragments (Meloche, 1985). The development of secondary porosity may not affect permeability depending on interconnection of pores. The formation of kaolinite is closely associated with the dissolution of feldspars (Wilson and Pittman, 1977). Partially chloritized rock fragments and altered plagioclase were observed in all thin sections (Fig. 4.35). Carbonate, particularly dolomite is observed to partially replace non-quartzose framework grains.
Fig. 4.33. Photomicrograph (X-N) of a poorly indurated, fine-grained sandstone from the normal pressured succession of the upper Missisauga Formation in the Shell Petro-Canada Penobscot B-41 well (2655.9 m, core depth). The sandstone has minor patchy carbonate cement and good porosity. The field of view is approximately 0.65 mm wide. The thin section shows a detrital quartz grain with a syntaxial, euhedral overgrowth (upper right) protruding into an oversized-pore now occluded by carbonate cement. The carbonate cement incorporates a remnant chloritized rock fragment. The thick, dark boundaries around framework grains is a consequence of pore-lining chlorite cement. Quartz grain boundaries are commonly sutured or concavo-convex. The textural relationships indicate carbonate replaced the rock fragment. Consequently, the carbonate is not a late stage cement that occludes dissolution porosity. The presence of dissolution porosity in a sediment probably indicates a late stage carbonate dissolution event preceded by carbonate replacement of framework grains. The patchy carbonate cement in this sandstone is a remnant of a late stage carbonate dissolution event. This thin section also displays a comparable paragenetic sequence to that observed in normal and overpressured reservoirs in the Lower Missisauga and Mic Mac Formations in the Venture field area.
Fig. 3.34. Photomicrograph (X-N) of a well indurated, very fine- to fine-grained, glauconitic sandstone from the normal pressured succession in the Mobil et al., Verdère B-43 (4433.55, core depth) well. The sandstone is indistinctly plane- and cross-laminated with rare mollusc shell debris. The measured porosity is less than 10%. The field of view is approximately 0.65 mm wide. The thin section displays a chlorite rim ghost in an oversized pore now occluded by carbonate cement. Other chlorite ghosts in the thin section incorporate small inclusions of plagioclase feldspar and rock fragments. Rare quartz overgrowths are also observed. The preservation of a delicate chlorite rim indicates the pore-filling carbonate replaced the framework grain. It is possible a late phase of intergranular carbonate cementation post-dates carbonate replacement of the detrital grains. However, this is not readily documentable from this data.
Fig. 4.35. Photomicrograph (X-Y) of a glauconitic sandstone from the Mobil et al. Venture B-43 well (4963.95 m, core depth). The thin section is from a bedded shaly sandstone unit comprising alternating thinly-bedded mudstone, siltstone and very fine-grained sandstone with rare burrow structures. The field of view is approximately 0.65 mm wide. The photomicrograph displays a chloritized volcanic rock fragment (V) with two distinct laths of plagioclase feldspar and small opaque inclusions. The rock fragment is incorporated into an interlocking mosaic of anhedral, pore-filling quartz overgrowths on detrital grains.
Fig. 4.35. Photomicrograph (X-N) of a glauconitic sandstone from the Mobil et al. Venture B-43 well (4963.95 m, core depth). The thin section is from a bedded shaly sandstone unit comprising alternating thinly-beded mudstone, siltstone and very fine-grained sandstone with rare burrow structures. The field of view is approximately 0.65 mm wide. The photomicrograph displays a chloritized volcanic rock fragment (V) with two distinct laths of plagioclase feldspar and small opaque inclusions. The rock fragment is incorporated into an interlocking mosaic of anhedral, pore-filling quartz overgrowths on detrital grains.
The main authigenic minerals responsible for impairing reservoir quality and porosity occlusion are chlorite, quartz and carbonate cements. Though chlorite is probably one of the earliest cements, it is still well exposed to pore systems. All clay minerals have high surface area to volume ratios and tend to have electrically charged surfaces. The clays are then effective at binding water and can cause high irreducible water saturation (Hutchenson, 1983). Intergranular pores are typically lined with chlorite or euhedral quartz and possibly infilled by carbonate. The clay minerals have a patchy appearance owing to the absence of authigenic minerals at grain contacts. Carbonate cement occurs as: a) isolated, irregular drusy coatings on framework grains; b) patchy, fine to coarsely crystalline mosaics between grains and; c) local infillings of intergranular pores creating a poikilolitic texture. Locally, carbonate cement may partially replace framework grains, particularly feldspar and quartz as evidenced by corroded and embayed grains.

Other clay cements are locally voluminous particularly illitic clays (Meloche, 1985). Illite has a more detrimental effect on permeability than on porosity. Illite is microporous owing to its fibrous morphology (Lindquist, 1983). The microporosity is largely ineffective as it decreases the size of the pore aperture (Hutchenson, 1983). Some porosity reduction may be attributed to deformation of less competent framework grains such as micas, sedimentary rock fragments, glauconite pellets and pelitic metamorphic rock fragments.

Differences in the diagenetic history and hence, microscopic heterogeneities affecting reservoir quality are suspected of occurring in different sequence elements. This variation is a function of sedimentary composition, texture and the degree of lithologic variation which will
ultimately control the hydrodynamic gradient and chemical reaction rate (Hutcheon, 1983). In general, the overall effect of diagenesis has been to amplify the reservoir potential inherited from the depositional environment. However, the development of secondary porosity may not show a direct relationship with depositional environment.

Two types of sub-elements have been recognized within the limestone/sandstone sequence element. Textural features suggest the basis for this division is related to the energy level in the depositional environment. Eliuk (1978) has discussed the environmental significance of types of ooids in carbonates on the Scotian Shelf. He recognized both radial and concentric (tangential, annular) crystalline growth patterns. The radial growth pattern implies slow precipitation and weak agitation of grains (e.g. lagoons, subwave base). The concentrically ringed carbonate grains form in strongly agitated environments such as the crests of submarine bars and tidal-delta complexes. The oolites observed in the East Sable Island area indicate a composite history. Following the development of concentric ooid grains a period of relative quiescence is indicated by the growth of encrusting algae (Fig. 4.36). The algal growths usually contain inclusions of organic matter, silt or sand, and may bind several ooids together (grapestone). Normally several stages of growth are evident. When the grain is periodically disturbed, new growth commences at a different location on the grain. Carbonate cement is mainly microsparite and/or mosaic sparry calcite. Evidence suggests the type of cement may be a function of the proportion of incorporated siliciclastic material. Microspar cement becomes more abundant as the amount of siliciclastic material increases. Packing of framework grains also becomes tighter, with common irregular and broken carbonate grains displaying stylolitic grain boundaries (Fig. 4.37).
Fig. 4.36. Photomicrograph (X-X) of an oolitic unit interbedded with fine-grained sandstone in the Mobil et al. Venture B-13 well (4692.32 m, core depth). The field of view is approximately 1.5 mm wide. The oolitic/bioclastic packstone is comprised of oolites, pellets, shell debris and minor silt to fine-grained sand in a finely crystalline spar or matrix. The oolite grains indicate a composite history. The concentrically ringed part of the ooid has a shell fragment nucleus. The outer margin is covered with several algal growth structures incorporating inclusions of organic matter, silt and shell fragments. Algal coated sand grains and shell debris are also evident. These features indicate transport of oolites from a relatively high-energy environment to a low-energy, periodically agitated setting.
Fig. 4.37. Photomicrograph (PPL) of a oolitic/bioclastic grainstone in the Mobil et al. Venture B-13 well (4712.4 m, core depth). The field of view is approximately 1.5 mm wide. Oolites range from fine- to coarse-grained and commonly exhibit stylolitic grain boundaries, particularly when there is an increase in the quartzose sandstone component. Finely crystalline sparry calcite occupies the interstices. Algal coated grains are occasionally observed. Occluded oomoldic porosity is locally present.
In Type-II elements, the textural features imparted to sedimentary rocks by depositional processes are particularly important in the development of primary and secondary heterogeneities. The earliest cements typically occur in the most permeable layers. Chlorite rims around framework grains tend to be highly concentrated in the cleaner, less argillaceous parts. Later cements are also preferentially developed in the sediments with the highest original permeability and porosity, but tend to have an irregular distribution relative to earlier cements. The largest quantity of dissolution porosity occurs in the most permeable units. In coarse-grained, pebbly units much primary porosity is preserved presumably because the pores are so large that authigenic minerals could not completely fill them. Finer-grained unipartite laminae in cross-bedded sandstones typically exhibit less porosity. Vertical permeability can be seriously affected by finer-grained laminae possessing abundant sutured and curved grain contacts. Pore-bridging micas and locally concentrated detrital clays associated with sporadic biogenic activity are normally less detrimental to permeability.

Marine bedded shaly siltstone-sandstone bodies (Type-III elements) exhibit varying degrees of shaliness. Clays and other fines are very important in terms of reservoir quality in these low-porosity and low-permeability sediments. Where authigenic or detrital clay matrix, mica and carbonaceous matter is highly concentrated, no macroporosity exists. There is no evidence of secondary porosity in these sandstones. Cements, primarily carbonate, tend to be concentrated within the cleaner, less argillaceous sections. However, the cement displays an irregular distribution. Some sandstone layers can be strongly cemented and separated by a shale layer from adjacent, texturally similar non-cemented sandstone. The presence or absence of fossil debris may be important in this respect. The shell fragments may
have provided an internal source of carbonate which would be isolated from adjacent sandstone layers. However, no fossil molds or evidence of partial dissolution have been observed within these strongly carbonate-cemented sandstone layers.

Biogenic activity affects the distribution and continuity of reservoir microheterogeneities in Type-IV elements. It is difficult to evaluate the effect burrowing might have had on overall reservoir quality. Burrowing can create local large discontinuous coarser-grained areas with better porosity. Also, some burrowing organisms tend to create discontinuities and locally improve overall porosity by concentrating mud in burrow linings. However, the enhanced porosity is largely isolated and not likely to contribute significantly to overall reservoir quality. Ultimately, the effect of biogenic activity is one of disruption of primary discontinuities and homogenization of the sediment by redistributing detrital clays into pores. The resultant sediment is a homogeneous texture, but with only moderate porosity and permeability.

The possible role overpressuring has played in enhancing the porosity in the siliciclastic reservoirs in the Venture field is not clear. Meloche (1985) constructed porosity-depth plots for normally pressured sandstones from 34 wells on the Scotian shelf. A porosity-loss gradient of 7.5%/km was defined. However a reversal in trend was observed within the overpressured zone, showing a general increase in porosity with depth. Porosities can exceed 30% in the overpressured zone, normally encountered below approximately 4500 m in the Venture field area. The development of secondary porosity from the advanced dissolution of alumino-silicate framework grains is believed to have occurred at temperatures below 150°C under conditions of dynamic overpressuring and high salinities. (Meloche, 1985). Maturation data
suggest that the overpressuring is a recent phenomenon related to gas generation (Rodrigue et al., 1985; Nantais, 1984).

Petrographic thin sections from normal and overpressured sandstone reservoir bodies were studied. There is no petrographic evidence to suggest a different diagenetic history for normal and overpressured sandstone reservoirs. However, it is difficult to quantify degrees of partial dissolution of framework grains or cement. It is possible that dissolution porosity is more advanced under conditions of overpressuring and higher subsurface temperatures. There is also the possibility that the secondary porosity is indirectly related to gas generation (Meloche, 1985). Because the overpressured zone shows a complex diagenetic history, fluid movement must have occurred. Convective fluid movement is important within the confined volume of the overpressured zone. The convective hydrodynamic gradient can control differential dissolution and other diagenetic processes by imposing temperature changes in the system (Hutcheon, 1983).

4.4 Summary of Diagenetic Effects Controlling Reservoir Properties

A simplified sequence has been compiled from this study and those of Meloche (1985) and Nogeura (pers. comm.). The physical and chemical events and their qualitative effect on reservoir properties is summarized in Figure 4.38. The relative ordering of the sequence is based primarily on the petrographic study. Diagenetic events are mainly sequential, although earlier diagenetic events are more difficult to separate in time than later events. The earliest events in the paragenetic sequence probably overlap suggesting a continuum of diagenetic reactions.
Fig. 4.38. Factors affecting reservoir quality and the paragenetic history of Mac Mac and Lower Mississauga Formation sandstones in the East Sable Island area. Stars indicate the relative timing of events. Arrows indicate continued or episodic events.

2. Meloche (1985); principally from the breakdown of feldspars.
3.0 Concluding Remarks

The Lower Mississauga and Mic Mac Formations form a dominantly siliciclastic succession incorporating subordinate carbonate units. The overall stratigraphic sequence records the progradation of delta complexes which dispersed sediment across a marine shelf into basin and slope environments. A thick sequence of limestone accumulated seaward of the delta complexes in carbonate shelf and shelf-margin environments.

Six depositional complexes from 400 to 1300 m thick define broad deepening-upward cycles within the prograding clastic wedge. A poorly defined, initially regressive unit at the base of the Mic Mac Formation is also recognized. The presence of prominent limestone units in the central-basin area, representing transgressive phases imposed on the overall regressive sequences have been valuable for correlation of the basal 5 depositional complexes. Each sequence in the central basin area comprises dominantly regressive, shallow marine and paralic siliciclastics at the base, grading vertically into marine carbonate shelf facies. Landward, terrigenous clastics in the lower part prograded over the shelf as deltaic deposits and graded vertically into mixed inner shelf and nonmarine deposits with minor limestone intercalations. The change in the depositional milieu during a transgression resulted in the deposition of carbonate sediments in areas of the basin normally receiving siliciclastics. Continuing progradation of siliciclastics caused the carbonate facies to become increasingly restricted to the outer shelf during the Late Jurassic.

Late Jurassic tectonism gave rise to a regional change in the depositional framework from dominantly carbonate shelf to siliciclastic sedimentation, as a result of rejuvenation of source areas. Prominent shale
tongues in the Lower Mississauga define two minor transgressive phases imposed on an otherwise regressive sequence. These two depositional episodes are best developed in the central basin area. The succession is strongly progradational resulting in very asymmetric stratigraphic thickening basinward, in part due to active growth faulting.

Broad lithofacies reconstructions define two prograding lobes of siliciclastic material and the progressive lateral migration of the depocentre toward the southwest. The northeasterly lobe initially developed during the early Late Jurassic. The lobe to the northwest is first recognised in the study area during the Late Kimmeridgian.

Late Kimmeridgian–Early Valanginian reservoir facies studied in the East Sable Island area reveal complex depositional units. Sandstones of the Mic Mac Formation form dominantly coarsening-upward sequences enveloped in mudstone and siltstone and were deposited on a shallow marine shelf. The shelf-to-basin transition defines a general basinward diminution of grain-size. Prograding clastic sediments comprising the Lower Mississauga were deposited in lower delta-plain, delta-marine fringe complexes and prodelta environments. Coarsening-upward-sequences are dominated by deltaic foreset deposits comprising barrier-beach, river mouth bar, tidal delta/bar and nearshore marine sediments. Topset deposits occur irregularly. The sandstones prograded over the delta front to form an almost continuous linear to arcuate body of beach, bar and tidal deposits around the entire perimeter of the delta.

These various deltaic sandstone bodies coalesce and form large, stacked composite sandstone reservoirs. The best reservoirs occur in the upper part of coarsening-upward sequences in zones with the best original primary porosity, despite a complex paragenetic history. Porosity loss occurred
sequentially from compaction, pressure solution and finally growth of authigenic minerals including early pore-lining chlorite, quartz as overgrowths and intergranular carbonate. Porosity has been enhanced by the advanced alteration, replacement and dissolution of alumino-silicate framework grains and selective dissolution of carbonate cement. The porosity and permeability is ultimately a function of the effectiveness of carbonate cementation and replacement of framework grains followed by carbonate dissolution, irrespective of the presence of earlier-formed dissolution porosity. There is no petrographic evidence to indicate that overpressured sandstone reservoirs are different from normally pressured reservoirs. A similar paragenetic sequence is observed in both cases. However, it is difficult to quantitatively evaluate degrees of dissolution porosity development.
References


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Appendix I. Stratigraphic Tops

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1955.00-1959.45 m Sandstone. Pale yellowish brown (10 YR 6/2), medium- to coarse-grained, with rare pebbles, variably indurated, moderately sorted, with common quartz overgrowths and scattered feldspar, chert, lithic fragments, pyrite nodules, muscovite and carbonaceous grains. Massive to indistinctly defined planar and trough cross-stratification with minor scour-and-fill features. Basal 20 cm contain common pyritized, coalified wood fragments. Base is a sharp scour-and-fill structure with a 3 cm pebbly lag in the trough.

1959.45-1961.00 m Sandstone. Pale yellowish brown (10 YR 6/2), coarse-grained sandstone to granule size, moderately sorted, well rounded, poorly indurated with local pyrite nodules, minor feldspar, chert and lithic grains; coal fragments to 5 cm. Massive with rare scour-and-fill structures. Subtle grain size variation defines indistinct trough cross-bedding.

1961.00-1964.10 m No core recovered.

2242.10-2247.05 m Shale and Siltstone. Interbedded and laminated dark gray (N3) to medium dark gray (N4) fissile, silty, micromicaceous shale and increasingly common, light gray (N7) to light greenish gray (5 Y 8/1), slightly calcareous shaly siltstone. Siltstone in beds to 18 cm, averaging 2-4 cm; shale layers up to 70 cm thick, averaging < 10 cm. Common lenticular and wavy bedding with ripple laminations. Common superficially coated calcite/foeferite? grains (pseudoids, oncolites) and echinoderm/gastropod shelly debris as lags in ripple troughs and grain-thick layers on bedding surfaces. Gradational contact with

2247.05-2248.05 m Siltstone. Light olive gray (5 Y 6/1), argillaceous, incorporating subordinate very thin shale layers and partings and scattered shell debris; planar laminated with rare cross-lamination. Pyritic carbonaceous matter commonly concentrated on bedding surfaces. Rare tubular burrows associated with the more argillaceous layers. Gradational contact with

2248.05-2251.25 m Siltstone and Sandstone. Light olive gray (5 Y 6/1), quartzose, sandy siltstone grading to silty, very fine- to fine-grained sandstone, moderately calcareous, locally argillaceous with trace carbonaceous matter and siderite, particularly in the basal 30 cm. Strongly bioturbated
with a few wavy, discontinuous argillaceous laminae preserved. Lower 50 cm are micaceous with rare disseminated pyrite, siderite, scattered molluscan shell debris and superficially coated grains.

SHELL MC MAC J-77
(44°36'42.8"N; 59°26'10.9"W) Core 1
RT 25.9 m Missisauga Formation

2817.90-2819.15 m Sandstone. Grayish yellow green (5 GY 7/2) to light greenish gray (5 GY 8/1), medium- to coarse-grained, with minor granules and rare pebbles; siliceous, moderately to poorly sorted, angular, with minor feldspar, carbonaceous grains, pyrite nodules and greenish gray shale and fine sandstone pebbles. Trough cross-bedded, with common scour- and-fill displaying pebble and coal-fragment lags at bottoms of troughs. Gradational contact with

2819.15-2819.45 m Sandstone. Light gray (N7), very coarse to granule size, rare pebbles, moderately sorted, locally slightly silty with scattered grains of coal, detrital pyrite and feldspar; massive. Sharp contact with

2819.45-2820.55 m Sandstone. Main lithology as 2817.9-2819.15 m. Top 65 cm massive with indistinct low-angle inclined stratification defined by the orientation of elongate, tabular coal fragments. Basal 45 cm slightly silty and argillaceous with indistinct poorly developed, planar, inclined laminae.

2820.55-2821.45 m Sandstone. Main lithology as 2819.15-2819.45 m. Basal 20 cm display planar, inclined, very fine- to fine-grained sandstone intercalations; coal fragments to 1.5 cm. Sharp, scoured lower contact.

2821.45-2822.75 m Sandstone. Light olive gray (5 Y 6/1), very fine- to fine-grained, slightly silty and argillaceous, moderately well sorted, well indurated. Locally common inclined, planar parallel to discontinuous carbonaceous laminae, becoming wavy toward the base; scattered coal fragments to 4 cm. Small pebbles and granules embedded in base of core probably similar to 2819.15-2819.45 m.

2822.75-2827.10 m No core recovered.

SABLE ISLAND C-67
(43°56'4.9"N; 59°55'1.4"W) GL 4.0 m Core 3 Missisauga Formation
RT 8.2 m

3369.35-3375.65 m Shale. Dark gray (N5) to medium dark gray (N4), blocky to fissile, silty, locally sandy, micritic, carbonaceous, incorporating subordinate argillaceous, sideritic, laminated and burrowed very fine sandstone and
siltstone in layers 5 to 11 cm thick and scattered sideritic and pyritic nodules. The upper 1.35 m and basal 1.0 m display common, irregular medium light gray (N6) sand and silt laminae and lenses with carbonaceous matter prominent on bedding surfaces. Minor burrowing traces evident as solitary, mud-filled, tubular burrows and rare ripple cross-laminations displaying draped foreset laminae. Scattered bivalve and gastropod shelly debris and coarse quartz grains common in the basal 1 m. Base of sandy zones display disrupted load features. Three zones display normal microfaulting, reorienting laminae 25° to 70° to the core axis.

3375.65-3376.10 m Sandstone. Light gray (N7), very fine- to fine-grained slightly argillaceous, moderately well sorted, moderately calcareous, well indurated with scattered traces of muscovite, glauconite, disseminated siderite and small shale and coal fragments. Poorly developed parallel, horizontal laminae are defined by variable siderite and carbonate cementation and concentrations of argillaceous matter.

3376.10-3376.25 m Sandstone. Medium light (N6) to light gray (N7), with common light brown (5 YR 5/6) staining, due to disseminated siderite; fining up, coarse- and medium-grading to fine-grained, poorly sorted, moderately calcareous with minor glauconite, muscovite, feldspar, chert pebbles, and bivalve, gastropod shell debris and crinoid ossicles. Scattered sideritic siltstone fragments common near the base.

3376.25-3376.45 m Sandstone. Main lithology as in 3375.65-3376.1 m; sharp undolose basal contact.

3376.45-3376.70 m Sandstone. Light olive gray (5 Y 6/1) to pale yellowish brown (10 YR 6/2), fine- and medium-grained incorporating thin, low-angle, inclined planar pebbly sandstone beds, siliceous, well indurated with traces of muscovite and glauconite. Clasts consist of angular shale and coaly fragments with minor shell debris and granules of quartz.

3376.70-3377.70 m Sandstone. Main lithology as in 3375.65-3376.1 m, vary calcareous, glauconitic; cross-beded, displaying truncated, inclined, gently curved concave-up laminae.

3377.70-3378.45 m Sandstone. Light gray (N7), fine- to medium-grained, moderately sorted with patchy carbonate cement and traces of glauconite and mica. Cross-beded, gently inclined planar and concave-up laminae, locally indicating truncation of sets.
MOBIL SABLE C-67  RT 8.2 m  Missisauga Formation (Unit G)
(43°56'4.9"N; 59°55'1.4"W)  GL 4.0 m  Core 4

4084.40-4093.60 m Interbedded sandstone, siltstone and shale. Sandstone, light gray (N7), very fine- to fine-grained, argillaceous, silty, micaceous, trace carbonaceous, mostly calcareous in layers commonly 2-5 cm thick, to 20 cm with sharp load-deformed bases. Siltstone, medium (N5) to medium light gray (N6), argillaceous, very fine sandy, micaceous in layers several centimetres thick. Shale, dark gray (N3), silty, micromicaceous, slightly carbonaceous and pyritic. Common wavy-bedding minor current ripple-laminations and scarce lenticular and flaser bedding, numerous planar inclined laminae. The proportion of sandstone decreases from approximately 70% at the top to 20% near the base; lower sandstone bodies are not calcareous and slightly pyritic. Local traces of burrowing evident in the upper portion of sandstone layers in the top 3.5 m; sandstone and siltstone layers become moderately to strongly burrowed in the lower section. Burrows are dominantly tubular and flattened, horizontal and sub-horizontal mud-lined, and sand-filled.

PETRO-CANADA BANQUEREAU C-21  RT 27.0 m  Missisauga Formation
(44°10'7.5"N; 58°34'0.2"W)  Core 1

4473.00-4474.10 m Shale and Pebby Sandstone. Shale, dark gray (N3) to grayish black (N2), blocky, micromicaceous, slightly carbonaceous, incorporating a few discontinuous and lenticular siltstone layers. Sandstone in irregular 3-8 cm layers, light gray (N7), fine- and very fine-grained, moderately well indurated, siliceous with common angular, dark gray shale clasts (to 2 cm), siltstone clasts, rounded sideritic pebbles (to 4 cm) and very coarse quartz grains. Two zones within the shale indicate probable slumping, where the general fabric of the shale is dipping 60° to core axis.

4474.10-4474.50 m Sandstone. Very light gray (N8) light gray (N7) and medium light gray (N6), fine- and medium-grained, moderately sorted, overall fining up, well-indurated, calcareous, micaceous with trace carbonaceous matter and shell debris. Clasts are 0.5 to 7 cm, decreasing in size and proportion (50% to 20%) upward. Clasts consist of moderate yellow brown (10 YR 5/4) to dark yellowish brown (10 YR 4/2), rounded, oblate, sideritic siltstone (60%) confined to the lower 30 cm; medium dark gray (N4) angular, tabular, pyritic, silty shale (30%) most common in the upper 30 cm; light olive gray (5 Y 6/1) to yellowish gray (5 Y 8/1), angular, micaceous, carbonaceous, locally laminated siltstone (10%); and minor very fine- to fine-grained sandstone clasts. The
irregular shapes of the shale and laminated siltstone clasts suggest they were soft when ripped up.

4475.10-4475.90 m Conglomeratic, pebbly sandstone and shale. Shale as in 4473.0-4474.1 m, in beds 6 to 14 cm thick, commonly with scoured upper surfaces and rare sand-filled, horizontal tubular burrows near the top. Conglomeratic and pebbly units as in 4474.5-4475.1 m in beds 7.5 to 30 cm thick, tops are abrupt and irregular, proportion of clasts varies from 10 to 40%; each bed is dominated by one type of clast only.

SHELL ONONDAGA 0-95  
(43°44'48.1"N; 60°13'52.7"W)  Core 1  
RT 31.4 m  
Mississauga Formation

3267.45-3271.05 m Sandstone. Medium light gray (N6) to pale yellowish brown (10 YR 6/2), fine- and very fine-grained, moderately sorted, calcareous with traces of muscovite, chlorite and carbonaceous matter interbedded with light olive gray (5 Y 6/1) fine-grained, well sorted, very calcareous, locally slightly pyritic sandstone. Mostly massive with rare, grouped tubular burrows near the top of beds associated with irregular, inclined, micaceous shale laminae; burrow infilling is often sideritic. Beds are sharp-based and 15 to 65 cm thick. Three carbonate concretionary layers (3 to 7 cm) evident near the base. Gradational contact with

3271.05-3271.70 m Sandstone. Grayish orange (10 YR 7/4) grading to pale yellowish brown (10 YR 6/2), fine-grained grading down to very fine-grained, calcareous, well indurated with trace muscovite and carbonaceous matter. Minor poorly defined, planar, inclined bedding evident; one thin bioturbated, argillaceous layer near the base. Abrupt contact with

3271.70-3276.40 m Sandstone. Light olive gray (5 Y 6/1), very fine-grained locally grading to sandy siltstone, increasingly argillaceous toward the base, micaceous, non calcareous with scattered siderite nodules and shell debris. Strongly bioturbated with rare preserved discrete mud-lined, sand-filled tubular burrows and shale laminae. Incorporates two 15- and 30-cm massive, very fine- and fine-grained sandstone beds, calcareous with abrupt bases and gradational, slightly burrowed tops.
Sandstone. Very light gray (N8) and pale yellowish brown (10 YR 6/2), medium- and fine-grained, local trace silt and argillaceous matter, moderately sorted. Massive with rare, discontinuous argillaceous, carbonaceous, partings and laminae inclined 10-20º suggesting possible cross-stratification. Incorporates a 10 cm thick coarse sand unit at 2962.0 m with minor, slightly wavy, inclined micaceous, carbonaceous, pyritic mudstone partings with a flood of clasts of yellowish brown siltstone, greenish shale and coal; overlying 10 cm of well-indurated, cross-laminated fine-grained sandstone. Two 10 cm coalified wood fragments and small sideritic fragments occur at about 2961.9 m. Lower contact sharp and irregular with

Sandstone. Light olive gray (5 Y 6/1), coarse-grained, subrounded, moderately well sorted with rare, slightly inclined carbonaceous partings and scattered coal and shale fragments. Scoured contact with

Sandstone. Main lithology as 2960.5-2965.3 m, massive.

Sandstone. Pale yellowish brown (10 YR 6/2), coarse- and fine-grained as distinct layers indicating increasingly inclined (5-15º), planar cross-bedding. Incorporates locally common, rounded and oblate reddish brown, sideritic siltstone and coal clasts. Lower 10 cm is slightly calcareous. Gradational contact with

Sandstone. Very light gray (N8) to light gray (N7), coarse-grained, calcareous with common feldspar grains and rare coal, sideritic siltstone and gray-green shale clasts. Cross-stratification is indicated by variably dipping and intersecting, carbonaceous, argillaceous partings. Traces of soft, dark green peletoid grains (chlorite/glauconite?) evident in basal 40 cm. Abundant, multicoloured shale lenses and layers present as rubble in the lower 15 cm. Sharp contact with

Conglomerate. Light olive gray (5 Y 6/1), clasts of rounded and oblate sideritic siltstone in a poorly sorted, medium- to very fine-grained matrix; two layers of clast-supported conglomerate, grading to pebbly sand, are evident. Basal 5 cm is a dark gray (N3) subfissile shale bed which has a scoured contact with the above sandstone.

Sandstone. Light olive gray (5 Y 6/1), fine- to medium-grained, locally very fine-grained, slightly argillaceous, micaceous. Massive, top 25 cm contain abundant angular and wispy dark gray (N3) micaceous shale rip-up clasts.
Note: A number of sideritic clasts scattered throughout the core display burrowing traces and are locally laminated.

**Mobil Texaco Pex Venture B-13**

RT 33.8 m Lower Missisauga Unit

Cores 1-3

4692.00-4693.06 m

Sandstone. Dusky yellowish brown (10 YR 2/2), fine- to very fine-grained, slightly silty, well sorted, well indurated, very calcareous. Incorporates 10-15% ooids with quartz nuclei and trace indiscriminant shell debris, trace glauconite and pyrite. Local sparry calcite infills fossil clasts. A sulphurous, fetid odour is produced upon applying dilute HCl.

4693.06-4694.75 m

Sandstone. Dark gray (N3) to dusky yellowish brown (10 YR 2/2), very fine- to fine-grained, very argillaceous and silty, dolomitie becoming calcareous toward the base, locally pyritic. Contains trace scattered glauconite and shell debris. Minor scattered indistinct well-washed sandstone lenticles are present.

4694.75-4699.55 m

Interbedded sandstone and sandy oolitic/pelleted limestone. Sandstone is dusky yellowish brown (10 YR 2/2) fine- and very fine-grained, silty, slightly argillaceous as in 4692.0-4693.06 m with less than 10%, medium-grained oolites/pellets with a sand and silt matrix and minor shell debris. Sandstone beds are 10-60 cm thick; limestone beds 10-45 cm. The average thickness of beds increases upward. Several 1-2 cm, undulose dark gray, very argillaceous siltstone layers overlie oolitic layers in the lower 75 cm of the interval. Logged 3.8 m.

4699.55-4701.88 m

Limestone. Dusky yellowish brown (10 YR 2/2), oolitic, pelleted, very fine sandy. Ooids average 1 mm, with increasingly common pisoliths toward the base. Common bioclastic debris including molluscs, brachiopods and crinoid ossicles. Incorporates a few undulose, discontinuous, dark gray mudstone laminae and one 11 cm plane-laminated, fine-grained sandstone layer containing 1-2% ooids and trace glauconite.

4701.88-4702.90 m

Sandstone. Dark gray (N3), fine-grained grading to very fine-grained, argillaceous, silty, decreasingly calcareous downward with traces of mica, pyrite and ooids. Bioturbated with several plane cross-laminated sandstone layers discernible. Gradational contact with

4702.90-4706.75 m

Sandstone. Medium light gray (N6), fine-grained, slightly silty and argillaceous, moderately calcareous with trace pyrite, chlorite flakes and glauconite. Unit incorporates rare undulose and planar, dark gray, micaceous mudstone
laminae commonly disrupted by biogenic activity. Top 10 cm is moderately burrowed. Scoured basal contact with

4706.75-4708.00 m Silty shale and very argillaceous, micaceous, carbonaceous siltstone. Dark gray (N3), minor very fine-grained sand, moderate to heavily bioturbated and burrowed with rare discontinuous sandstone laminae evident.

4708.00-4711.75 m Sandstone. Light gray (N7) to light olive gray (5 Y 6/1), fine-grained, slightly argillaceous, silty calcareous. Incorporates thin, dark gray, micaceous, locally burrowed undulose shale laminae. Several thin cross-laminated and ripple-laminated layers evident. Includes several 2-8 cm layers containing coarse-grained sand and ooids in a siltstone to fine-grained sandstone matrix. The overlying sandstone contains numerous low-angle, plane-laminations. Ooids and coarse sand grains form lags within some ripple troughs. Logged 2.0 m. Abrupt contact with

4711.75-4712.10 m Limestone. Main lithology as 4699.55-4701.88 m. Crudely bedded appearance created by several thin fine-grained sandstone layers. Scoured basal contact with a 1 cm angular clast of the underlying unit incorporated in the lower 3 cm.

4712.10-4712.40 m Sandstone. Pale yellowish brown (10 YR 6/2), and light gray brown, very fine- to fine-grained, slightly silty, calcareous. Slightly burrowed with common wavy and ripple-laminae. Includes minor shelly debris and coarse-grained laminae near the base.

4712.40-4712.85 m Limestone and sandstone. Main lithology as 4711.75-4712.1. Includes several angular sandstone and black shale intraclasts. Several reactivation surfaces truncating shale laminae occur near the base. Irregular scoured base overlain by a 2.5 cm graded oolitic and coarse-grained sand layer.

4712.85-4713.30 m Sandstone. Yellowish gray (5 Y 8/1), fine-grained, silty, slightly micaceous and carbonaceous. Moderately burrowed incorporating rare planar mudstone laminae. Locally, well laminated layers may truncate burrowed layers. One 0.5 cm coarse-grained sand and oolitic layer occurs near the base.

4713.30-4713.65 m Limestone. Main lithology as 4711.75-4712.10 m. Basal-10 cm contains only 30% oolites and an increasing proportion of fossil debris. Scoured contact with

4713.65-4716.65 m Sandstone. Main lithology as in 4712.85-4713.3 m. Common clay-rich laminae between 4715.15-4715.45 m with a 4 cm very sandy, coarse-grained sandstone/oolitic layer at the
base. Basal 1.2 m incorporates common clay-poor inclined (5-7°) laminae. Partially dolomitic and calcareous.

4716.65-4716.85 m Interlaminated silty shale and shaly siltstone. Dark gray (N3) and black (N1), plane- and cross-laminated siltstone with rare burrowing; slightly carbonaceous with rare pyrite.

4716.85-4717.45 m Sandstone. Pale yellowish brown (10 YR 6/2) to light olive gray (5 Y 6/1), very fine- to fine-grained, silty, argillaceous, dolomitic, well sorted. Incorporates common plane-laminations, local ripple-laminations and rare tubular burrows. The basal 5 cm contains four 1-3 mm thick coarse-grained sandstone laminae.

4717.45-4719.65 m Sandstone. Grayish yellow green (5 GY 7/2) to light greenish gray (5 GY 8/1), coarse-grained grading to very coarse-grained, poorly-sorted, dolomitic with traces of chlorite, pyrite, carbonaceous matter, glauconite and carbonate and shale intraclasts. Planar variably dipping laminae defined by grain size variations indicate cross bedding. Quartzose framework grains are commonly frosted and pitted. Base is defined by a 3-4 cm black, siliceous mudstone layer.

4719.65-4720.60 m Sandstone. Greenish gray (5 GY 6/1 ) to light gray (N7), medium grained with minor fine and coarse sand, slightly argillaceous and carbonaceous. The top 40 cm displays clay-rich, carbonaceous, undulose laminae and plane cross-laminated layers with several 2-3 mm planar black shale stringers; includes very rare horizontal sand-filled tubular burrows. Basal 10 cm contains abundant plane to slightly inclined argillaceous, micaceous laminae. Slightly scoured basal contact with

4720.60-4720.85 m Sandstone. Medium (N5) to medium dark gray (N4), fine-grained, silty, argillaceous. Plane- and cross-laminated, variably inclined in truncated sets. Top 5 cm consists of lenticular-bedded black silty mudstone.

4720.85-4722.15 m Sandstone. Light olive gray (5 Y 6/1), medium- to coarse-grained incorporating subordinate fine-grained sandstone interbeds; slightly argillaceous, silty, dolomitic. Coarser grained units have very rare tubular burrows; finer-grained units contain common tubular burrows with several 3-4 cm plane-laminated layers. Gradational contact with

4722.15-4730.30 m Sandstone. Grayish yellow green (5 GY 7/2) grading to light greenish gray (5 GY 8/1) and light olive gray (5 Y 6/1), very fine- to fine-grained, increasingly argillaceous toward the base, glauconitic, micaceous, dolomitic with minor patchy carbonate cement. Top 3.4 m consists of interbedded plane-laminated layers and
argillaceous bioturbated layers 2-10 cm thick; incorporates an 12 cm medium- to coarse-grained sandstone layer as 4720.85-4722.15 m. Lower part of the interval consists of cross-laminated layers with rare tubular burrows and shale intraclasts to 1 cm; lamination are less common towards the base.

4730.30-4735.40 m Sandstone interbedded with decreasingly common mudstone. Sandstone, medium gray (N5), fine-grained, silty, calcareous, in layers 10-75 cm thick. Mudstone dark gray (N3) to grayish black (N2), micaceous, with irregular pods of silt; strongly bioturbated with rare cross-laminated siltstone lenses incorporating rare scattered mollusc shell debris. Sandstone beds typically have scoured bases and burrowed tops; and are cross-laminated

MOBIL TEXACO PEX VENTURE B-13  
RT 33.8 m  Lower Mississauga Unit  
(44°02'11.6"N; 59°32'3.5"W)  
Core 4

4952.60-4953.75 m Sandstone. Pale yellowish brown (10 YR 6/2) and light olive gray (5 Y 6/1), medium-grained, with minor fine- and coarse-grained sand, friable, dolomitic and glauconitic toward the base; trace pyrite and coal fragments. Dominantly structureless with several clay-poor, indistinct laminae inclined to 25°. Scoured basal contact with

4953.75-4955.50 m Sandstone. Light greenish gray (5 GY 8/1) and light gray (N7), very fine- to fine-grained, silty, slightly argillaceous, micaceous, carbonaceous, calcareous with traces of chlorite, glauconite, shell debris and coal fragments; incorporates subordinate very argillaceous, silty, micaceous, very fine-grained sandstone in layers 10-30 cm, strongly bioturbated with rare cross-laminated lenses. Sandstone is mostly plane-laminated with rare planar cross-laminated layers; incorporates one 5 cm poorly sorted, coarse-grained layer exhibiting high-angle planar laminations.

4955.50-4958.35 m Sandstone. Grayish orange pink (5 YR 7/2), medium- to coarse-grained, well sorted, friable, slightly calcareous; incorporates several 2-3 mm shale and coal fragments near the top. Structureless with rare, clay-poor, discontinuous laminae inclined 15° near the base. Logged 2.35 m. Gradational contact with

4958.35-4960.20 m Interbedded sandstone as 4955.50-4958.35 m in layers 15-55 cm and fine-grained sandstone, light olive gray (5 Y 6/1) well sorted, friable, argillaceous, micaceous, slightly calcareous in layers 5-30 cm. Coarser layers exhibit moderately distinct, slightly inclined argillaceous laminae; tops of beds are occasionally
cross-laminated and the bases scoured. Finer-grained beds have distinct argillaceous, carbonaceous cross-laminae in truncated sets with rare mud-filled tubular burrows. Two 1-2 cm black mudstone breaks occur at the base of coarser-grained units. Gradational contact with

4960.20-4962.70 m Sandstone. Main lithology as fine-grained sandstone in 4958.35-4960.20 m; increasingly very fine-grained, argillaceous and burrowed toward the base. Common inclined and vertical burrows to 4.5 cm; increased biogenic activity associated with increasing argillaceous material. Gradational contact with

4262.70-4964.45 m Sandstone. Medium light gray (N6) to yellowish gray (5 Y 8/1), very fine-grained, silty, moderate grading to very argillaceous, dolomitic, slightly micaceous. Common distinct plane-laminae and cross-laminae in truncated sets with several thin carbonaceous laminae; contains one 4 cm moderately burrowed layer associated with an increase in shalliness. Scoured and load-deformed basal contact with

4964.45-4970.80 m Interbedded sandstone and mudstone/argillaceous siltstone. Sandstone as 4962.7-4964.45 m. Mudstone and siltstone in layers 15-110 cm, commonly wavy-bedded and plapiar cross-laminated with moderate burrowing in muddy layers; rare carbonaceous, micaceous laminae, locally calcareous. Sandstone in layers 25-75 cm commonly with sharp, irregular bases and gradational to sharp tops, slightly to moderately calcareous, locally dolomitic; incorporates minor shale intraclasts in the upper part of some beds. The proportion of muddy lithologies and the frequency of biogenic activity decreases upward.

MOBIL TEXACO PEX VENFURE B-43 RT 30.5 m Lower Mississauga Unit (44°02'00.72"N; 59°36'37.37"W) Core 1

4423.70-4423.90 m Sandstone. Pale yellowish brown (10 YR 6/2) to light olive gray (5 Y 6/1), very fine- to fine-grained, well sorted, well indurated, calcareous, slightly argillaceous, trace muscovite and disseminated pyrite. Trace spotty, reddish brown ferruginous staining associated with a soft, dark green mineral—(chlorite ?); indistinct horizontal bedding. Incorporates one 2 cm graded bed, fine- to very coarse-grained, poorly sorted, with trace angular, wispy shale clasts (to 5 mm).

4423.90-4423.95 m Sandstone. Pale yellowish brown (10 YR 6/2), medium- to coarse-grained, moderately sorted, well indurated, very calcareous, rare pyrite as detrital grains and cement. Traces of wispy, carbonaceous fragments (1-4 mm) and partings, suggesting the sand may be rippled.
MOBIL TEXACO PEX VENTURE B-43

RT 30.5 m Lower Missisauga Unit
(44°02'00.72"N; 59°36'37.37"W)

4430.30-4430.55 m Sandstone. Pale yellowish brown (10 YR 6/2), medium- and coarse-grained, moderately sorted, slightly argillaceous, moderately indurated, calcareous, with rare smoky quartz, diagenetized pyrite, trace carbonaceous matter. Cross-stratification indicated by curved (15-20°) bedding planes with thin alternating layers of medium and coarse grains. Top of core is very fine-grained. Grades into

4430.55-4431.00 m Sandstone. Pale yellowish brown (10 YR 6/2), mostly medium-grained, fining down, moderately sorted, slightly argillaceous, well indurated, calcareous. Bedding indistinct due to broken core; some evidence of slightly curved bedding planes as above and some horizontal bedding. Very trace shale as clasts concentrated on bedding planes, and thin wavy carbonaceous, micaceous laminae. Local disseminated pyrite as matrix or cement. Near the base are several 2-3 cm lenses of very calcareous, medium-grained sandstone as trough infill, with rare shell fragments as a lag. One lens is overlain by small-scale symmetrical ripples. One horizontal mud lined, sand-filled burrow is associated with a shale parting. Grades into

4431.00-4431.40 m Sandstone. Pale yellowish brown (10 YR 6/2), medium-grained, well to moderately sorted, slightly argillaceous, variably indurated, slightly to moderately calcareous. Bedding is planar, horizontal to slightly inclined; upper part of unit shows irregular, very thin carbonaceous, burrowed laminae. Contact missing

4431.40-4431.60 m Sandstone. Grayish red (10 R.4/2), (drilling mud?). Coarse to granule size, conglomeratic, poorly sorted, poorly indurated, calcareous. Predominantly coarse-grained matrix at the top grading to fine-grained; frequency of clasts decreases towards the base. Grains to 5 mm, clasts include: common rounded dark gray shale, 10% detrital pyrite, traces of feldspar, chert and sandstone clasts. Gradational contact with

4431.60-4434.50 m Sandstone. Pale yellowish brown (10 YR 6/2) to light olive gray (5 Y 6/1) and locally light gray (N7). Medium-grained at the top grading gradually to fine and very fine-grained, well sorted; moderately to locally strongly indurated, particularly in coarser units, slightly calcareous in top 20 cm, remainder siliceous, with very patchy carbonate cement. Rare scattered spotty reddish brown ferruginous staining, slightly argillaceous, locally silty. Top 40 cm displays clear cross-stratification to 20°, grades to less distinct horizontal, slightly inclined bedding and discontinuous, planar, non-parallel laminae. Lower portion contains (1.0

262
m) common thin carbonaceous, micaceous laminae, indicating rippled and planar horizontal bedding becoming somewhat discontinuous where bioturbated. Occasional silt-filled burrows on bedding planes toward the base.

4434.50-4435.15 m Sandstone. Light gray (N7) to mottled pale yellowish brown (10 YR 6/2), fine-grained, silty, argillaceous, moderately sorted, siliceous; top 15 cm dolomitic. Abundant irregular, continuous, thin, micaceous, carbonaceous, cross-laminations in the top 15 cm becoming locally abundant but discontinuous. Frequent horizontal and vertical mud-lined, sand-filled tubular burrows, averaging 1.5 cm in diameter; traces of pelecypod shell debris throughout.

4435.15-4437.80 m Sandstone. Pale yellowish brown (10 YR 6/2), fine- to medium-grained with local burrowed silty, very fine- to fine-grained layers, siliceous, well-sorted increasingly argillaceous and silty toward the base. Incorporates scattered clay-poor and rare clay-rich, micaceous, burrowed laminations dipping 5-15°; slightly dolomitic between 4437.3-4437.55 m. Gradational contact with

4437.80-4438.20 m Sandstone. Pale yellowish brown (10 YR 6/2), very fine- to fine-grained, silty, increasingly argillaceous toward the base. Exhibits alternating layers of strongly burrowed sandstone and ripple cross-laminated layers, which truncate the burrowed layers. Burrows are typically mud-lined, sand-filled; larger burrows (1-2 cm) occasionally display well developed spreite.

4438.20-4438.15 m Sandstone. Main lithology as 4434.5-4435.15 m.

4438.85-4439.15 m Sandstone. Light gray (N7), very fine-grained, slightly argillaceous and silty, micaceous with local disseminated pyrite. Moderately burrowed; dominantly argillaceous silt-filled, tubular burrows to 1 cm.

4439.15-4441.10 m Sandstone. Main lithology as 4435.15-4437.8 m grading into 4437.8-4438.2 m. Includes several burrows up to 7 cm in length and 1.5 cm in width. The lower laminated layers display several scour-and-fill structures truncating laminations. Common tubular and U-shaped, sand-filled burrows in the lower portion of the interval; local traces of glauconite near the base.

4441.10-4441.75 m Sandstone. Main lithology as 4434.5-4435.15 m. Incorporates several thin lenticular-bedded layers.

4441.75-4442.60 m Sandstone. Light olive gray (5 Y 6/1), fine-grained, silty, slightly argillaceous, micaceous and pyritic. Displays distinct planar-laminations and rare low-angle, plane cross-laminations with local, horizontal sand-
filled, tubular burrows in the top 20 cm. Mudstone laminae become thicker (average < 2 mm to 7 mm), more distinct, and increasingly micaceous toward the base. Incorporates several thin (1 cm) irregular graded units in the basal 30 cm; coarse- to fine-grained, poorly sorted, overlying mudstone laminae.

4672.80-4673.15 m Sandstone. Medium gray (N5), very fine-grained, silty, argillaceous, glauconitic, calcareous, micaceous (chlorite, muscovite), with trace disseminated pyrite. Common horizontal and vertical, argillaceous sand-filled tubular burrows up to 3.5 cm long. Abrupt contact with

4673.15-4674.65 m Sandstone. Light gray (N7) to light olive gray (5 Y 6/1), fine- to very fine-grained with rare local coarse and medium grains, silty, slightly micaceous, glauconitic incorporating moderately to poorly developed slightly inclined carbonaceous mudstone laminae. Top 50 cm include two 17 cm thick layers where laminae are disturbed by scarce to relatively common tubular burrows. Top 15 cm is calcareous, becoming dolomitic for the next 1 m, then calcareous in the basal section; variably indurated.

4674.65-4676.35 m Sandstone. Medium light gray (N6), medium-grained, silty and very fine sandy, micaceous, friable with patchy carbonate cemented layers, partially glauconitic. Rare discrete sand-filled tubular burrows disturb common, undulose and inclined, micaceous mudstone laminae; ripple cross-laminations locally well developed. Gradational contact with

4676.35-4677.05 m Sandstone. Distinctly mottled light gray (N7) with disseminated medium dark gray (N4), coarse-grained, poorly sorted, traces of mica, pyrite and glauconite (?); incorporates rare discrete sand-filled burrows. Local indistinct cross-bedding is defined by subtle grain size variations. Upper 40 cm are friable and dolomitic; the basal section is well indurated and calcareous. Lower contact is a scour structure.

4677.05-4677.45 m Sandstone. Medium gray (N5), fine- to medium-grained becoming medium- to coarse-grained in the basal part. Basal part exhibits poorly developed horizontal mudstone partings grading upward into better developed low-angle cross-bedding; top 8 cm is ripple cross-laminated.

4677.45-4678.85 m Sandstone. Light gray (N7), fine-grained, silty, micaceous incorporating rare 1-2 cm, sand-filled, tubular burrows; variably indurated, calcareous and dolomitic.
The basal 20 cm are fossiliferous with scattered pelecypod debris. Rare planar and undulose mudstone partings occur locally.

4678.85-4687.80 m No core recovered.

MOBIL TEXACO PEX VENTURE B-43
(44°02'00.72"N; 59°26'37.37"W) RT 30.5 m Lower Mississauga Unit
Core 5

4875.40-4875.95 m Sandstone. Light olive gray (5 Y 6/1), fine-grained with minor medium grains, silty, micaceous, moderately indurated, siliceous with minor patchy dolomitic cement and disseminated pyrite. Contains abundant, very thin horizontal and undulose micaceous and carbonaceous mudstone partings and siltstone laminae; minor plane cross-bedding occurs locally. One 4 cm very silty pyritic coaly layer occurs at 4875.65 m.

4875.95-4877.55 m Sandstone. Light olive gray (5 Y 6/1) to pale yellowish brown (10 YR 6/2), very fine-grained, silty with minor interbeds of siltstone and fine-grained sandstone; argillaceous, dolomitic, glauconitic in the lower part. Strongly burrowed and bioturbated with numerous sand/silt and less common mud-filled tubular burrows to 2 cm; degree of churning increases downward. The basal 5 cm consists of poorly sorted, silty, fine- to medium-grained sand with abundant wispy rip-up clasts of dark gray shale. Lower contact is an abrupt scour structure.

4877.55-4878.20 m Sandstone. Pale yellowish brown (10 YR 6/2), medium- to fine-grained with minor coarse grains that are more frequent toward the base, well indurated at the top grading to friable at the base; calcareous and dolomitic with local disseminated pyrite. Rare inclined mudstone partings occur locally.

4878.20-4879.05 m Sandstone. Light gray (N7), fine-grained, silty, calcareous and siliceous moderately indurated. Contains scarce to common plane and ripple cross-laminations in layers; incorporates rare dark gray shale rip-up clasts and coal fragments.

4879.05-4883.40 m No core recovered.

MOBIL TEXACO PEX VENTURE B-43
(44°02'00.72"N; 59°36'37.37"W) RT 30.5 m Lower Mississauga Unit
Core 6

4954.60-4956.50 m Sandstone. Light gray (N7), fine-grained, well sorted, glauconitic, ? kaolinitic, slightly dolomitic. Plane- and cross-laminations are poorly developed; rare tubular...
burrows are associated with mudstone partings. Gradational contact with

4956.50-4957.05 m Sandstone. Light olive gray (5 Y 6/1) to light gray (N7), very fine-grained, silty, well sorted, glauconitic; dolomitic and calcareous, particularly in burrowed sections. Incorporates common, very thin, plane-laminations, becoming ripple-laminated toward the base.

4957.05-4957.50 m Mudstone. Recovered 6 cm only. Pale blue green (5 BG 7/2), fossiliferous (pelecypods and crinoid oscicles), with traces of pyrite, mica and carbonaceous detritus.

4957.50-4958.80 m Sandstone. Very light gray (N8) to light gray (N7), fine-to medium-grained, well sorted with traces of glauconite, pyrite, mica and shell debris. Contains common to abundant planar, micaceous mudstone laminae; dominantly horizontal with rare truncation of laminae observed. Basal contact abrupt with

4958.80-4961.00 m Sandstone. Pale yellowish brown (10 YR 6/2), coarsening-upward, medium-to coarse-grained with minor pebbles, coal fragments, wispy carbonaceous shale clasts, jasper and dark gray chert. Cross-beded in truncated sets with several scour-and-fill structures displaying pebbly bases. The basal 30 cm contains common 2 mm to 2 cm carbonaceous, micaceous mudstone laminae. Gradational contact with

4961.00-4961.55 m Sandstone. Mottled medium gray (N5) and pale yellowish brown (10 YR 6/2), medium-grained, calcareous with minor mica and aggregates of pyrite. Structureless with rare faint, discontinuous micaceous mudstone partings. Basal 6 cm contains abundant wavy, carbonaceous mudstone laminae. Gradational contact with

4961.55-4962.00 m Sandstone. Main lithology as 4958.8-4961.0 m. Top 9 cm is slightly calcareous.

4962.00-4962.20 m Sandstone. Medium dark gray (N4), fine-grained, well sorted, very calcareous with rare mudstone laminae. The lower contact is a prominent wave ripple.

4962.20-4963.90 m Sandstone. Main lithology as 4958.8-4961.0 m, siliceous and dolomitic; basal 10 cm slightly calcareous. Incorporates two 3-5 cm layers containing abundant undulose, carbonaceous, pyritic mudstone laminae. Scoured lower contact with

4963.90-4964.45 m Sandstone. Light olive gray (5 Y 6/1) to pale yellowish brown (10 YR 6/2), coarse-grained with common, very coarse, granule and pebble size grains, poorly sorted with patchy calcareous and dolomitic cement. Structureless with several scour-and-fill structures
having pebble lags. Incorporates common elongate, angular shale clasts which display crude imbrication, also rounded fine-grained sandstone fragments and minor pelecypod shell debris. The lower 1.5 cm are a scoured black (N1) silty, micaceous, carbonaceous shale bed.

4964.45-4965.00 m Sandstone. Light gray (N7), medium-grained, moderately-well sorted with patchy calcareous cement and pyrite incorporating rare mudstone laminae with opposing dips indicating cross-bedding. Scoured lower contact with

4965.00-4968.00 m Shale. Medium dark gray (N4) to dark gray (N3), blocky, micritic micaceous incorporating rare thin siltstone lenticles, particularly in the top 1.5 m; contains rare silt-filled, flattened, tubular structures of probable biogenic origin. Gradational contact with

4968.00-4972.35 m Interbedded and interlaminated sandstone, siltstone and shale/mudstone. Sandstone is medium light gray (N6) to light olive gray (5 Y 6/1), very fine- to medium-grained, well sorted, argillaceous with patchy calcareous cement; occurring in poorly defined beds (< 5-30 cm), moderately to extensively bioturbated and burrowed with rare discontinuous mudstone laminae evident. The proportion of sandstone, the thickness of beds and average grain size increases toward the base; the degree of biogenic activity decreases toward the base. Siltstone is medium-gray (N5), argillaceous in layers 1-30 cm thick with micaceous, carbonaceous, mudstone laminae. Shale as 4963.0-4968.0 m. Common wavy and lenticular-bedding where biogenic activity has not totally disrupted the primary structures. Lower sandstone beds have scoured bases, are only slightly burrowed with shale clasts at the base. A dewatering structure occurs at 4970.3 m (small mud volcano).

MOBIL et al. VENTURE B-52
(44°01'10.28"N; 59°38'07.69"W)
Core 1

4708.10-4710.40 m Sandstone. Light gray (N7) to light greenish gray (5 GY 8/1): Very fine-grained, well sorted, argillaceous, silty, slightly micaceous (chlorite), calcareous. Strongly bioturbated with a few discontinuous, grayish black (N2), micaceous mudstone partings. Gradational contact with

4710.40-4710.75 m Sandstone. Main lithology as 4708.1-4710.4 m with numerous, inclined, plane-laminations and rare shell debris. Minor coarse and very coarse sand grains occur in the basal 6 cm. Abrupt contact with

4710.75-4710.87 m Sandstone. Light gray (N7), dominantly very fine-grained sandstone with minor fine- to pebble-size grains and
approximately 20% carbonate grains consisting of mollusc debris, oolites, crinoid ossicles and bryozoans; very calcareous with rare pyrite and carbonaceous matter.

4710.87-4711.00 m Sandstone. Light gray (N7), medium- to coarse-grained with rare pebbles and granules, poorly sorted incorporating several large gray shale clasts and a 2 cm grayish black (N2), micriticaceous shale bed at the base.

4711.00-4714.50 m Sandstone. Light gray (N7) and yellowish gray (5 Y 8/1), very fine- to fine-grained, well sorted, locally argillaceous, calcareous, micaceous (chlorite), incorporating minor carbonaceous laminae and shell fragments. Moderately bioturbated and burrowed with two 15 and 25 cm thick, noncalcareous, plane-laminated beds in the lower part.

4714.50-4724.50 m No core recovered.

MOBL et al. VENTURE B-52 RT 35.4 m Lower Mississauga Unit (44°01'10.28"N; 59°38'07.69"W) Core 2

4942.50-4944.10 m Sandstone. Medium light gray (N6) to light olive gray (5 Y 6/1), fine- and very fine-grained, moderately well sorted, dolomitic, with wispy, grayish black (N2), carbonaceous, micaceous, mudstone partings and very thin laminae increasing in frequency toward the top; minor flaser-bedding evident. One 8 cm fine- to medium-grained layer contains rare tubular burrows. Several shale clasts occur in the basal 20 cm. Gradational contact with

4944.10-4944.50 m Sandstone. Very light gray (N8) to light gray (N7), very fine-grained, argillaceous, micaceous, calcareous and dolomitic incorporating common discrete burrows disturbing mudstone laminae. Gradational contact with

4944.50-4944.70 m Sandstone. Very light gray (N8) to yellowish gray (5 Y 8/1), fine-grained grading to very fine-grained, well sorted, calcareous. Top 40 cm is structureless with scattered, angular, black shale clasts and coaly partings; becoming cross-bedded in the lower part. Abrupt contact with

4945.70-4945.85 m Mudstone. Grayish black (N2), mostly structureless, micriticaceous, locally pyritic and carbonaceous with rare laminae and lenticles of silt/very fine-grained sand. Abrupt planar contact with

4945.85-4948.00 m Sandstone. Light gray (N7) to yellowish gray (5 Y 8/1), fine-grained, argillaceous, slightly calcareous incorporating low-angle inclined, micaceous mudstone laminae and several beds to 3 cm; includes several large
 (>1 cm) vertical tubular burrows and shale clasts. Basal contact sharp and planar with

4948.00-4948.50 m Mudstone/shale. Main lithology as 4945.7-4945.85 m incorporating several thin very fine- to fine-grained sandstone beds exhibiting ripple-laminations and occasional burrows. Abrupt contact with

4948.50-4950.25 m Sandstone. Yellowish gray (5 Y 8/1) to very light gray (N8) incorporating three 3-5 cm thick mudstone beds as in 4945.7-4945.85 m. Sandstone is medium- to coarse-grained grading downward to medium- and fine-grained, calcareous and dolomitic in beds 20-65 cm thick. The upper part of the sandstone beds are burrowed and plane-laminated; the lower unit displays planar cross-bedding to 20° and in truncated sets with scattered granules, shale clasts and coal fragments.

4950.25-4951.05 m Mudstone. Main lithology as 4945.7-4945.85 m incorporating one 5 cm argillaceous, fine- to medium-grained sandstone bed at 4950.65 m and rare lenticles of medium-grained sand.

4951.05-4952.20 m Sandstone. Main lithology as 4948.5-4950.25 m incorporating several argillaceous layers containing tubular burrows and undulate mudstone laminae; above a-2 cm black mudstone bed are abundant shale clasts in sandstone. Unit contains one 3 cm coal fragment.

4952.20-4954.30 m Interbedded mudstone as 4945.7-4945.85 m and sandstone as 4948.5-4950.25 m. Sandstone in beds 5 to 20 cm thick; mudstone in beds 6 to 55 cm thick. The proportion of sandstone, average grain size and sand bed thickness decreases toward the base. Granules and shale clasts are common within sand units. Coarse sand grains are commonly observed floating in the mudstone; sandy intervals are commonly burrowed.

4954.30-4954.60 m Mudstone. Dark greenish gray (5 GY 4/1), hard, very calcareous, micritic, locally silty with rare articulated bivalve shells, minor carbonaceous flakes and green reduction spots.

4954.60-4954.95 m Sandstone. Light gray (N7) to very light gray (N8), fine- to medium-grained, very calcareous, structureless with a few shale clasts at the base.

4954.95-4956.60 m Interbedded sandstone as 4948.50-4945.85 m and mudstone as 4945.7-4945.85 m. Sandstone in beds 15-55 cm thick; mudstone beds 6-12 cm thick. Sandstone beds have abrupt bases and are locally scoured. Mudstone beds contain rare floating coarse grains, in lenticles and as burrow-infilling.
4956.60-4957.05 m Sandstone. Yellowish gray (5 Y 8/1) to light olive gray (5 Y 6/1), fine- and medium-grained grading to very fine-grained at the base, slightly dolomitic with low-angle inclined mudstone partings and laminae.

4957.05-4958.95 m Interbedded very fine-grained sandstone as 4944.1-4944.5 m and medium- to fine-grained sandstone as in 4956.6-4957.05 m. Coarser-grained units in beds 10-15 cm thick and exhibiting plane cross-bedding; finer-grained units are in beds 20-55 cm thick and display minor ripple cross-laminations where not disturbed by biogenic activity.

Mobil et al. Venture B-52 RT 25.4 m Lower Mississauga Unit Core 3

5018.60-5020.05 m Sandstone. Light gray (N7) to light olive gray (5 Y 6/1), and yellowish gray (5 Y 8/1), fine-grained with minor medium to very coarse grains, fine to poorly sorted, calcareous. Moderately burrowed and bioturbated with common mud-lined, argillaceous sand-filled burrows; a few laminae locally preserved. Contains a shale clast rich layer at 5019.6 m. Abrupt contact with

5020.05-5020.65 m Sandstone. Medium dark gray (N4) to olive gray (5 Y 4/1), very fine-grained, silty, calcareous, with several indistinct plane-laminations and mollusc shell debris near the base.

5020.65-5021.05 m Sandstone. Yellowish gray (5 Y 8/1), very fine- to fine-grained, well sorted, friable, with minor planar inclined mudstone laminae.

5021.05-5022.25 m Sandstone. Main lithology as 5018.6-5020.05 m, dominantly very fine-grained.

5022.25-5022.45 m Sandstone. Main lithology as 5020.65-5021.05 m with rare horizontal, mud-lined burrows.

5022.45-5022.75 m Sandstone. Light brownish gray (5 YR 6/1), dominantly fine- to medium-grained with common coarse and very coarse grains, rare pebbles, black shale clasts and light olive gray (5 Y 6/1) siltstone clasts; locally pyritic with trace shell debris. Poorly to moderately indurated, with patchy calcareous cement as scattered 'knots'; structureless.

5022.75-5022.85 m Sandstone. Main lithology as 5020.65-5021.05 m incorporating common discontinuous mudstone laminae and scattered wispy coal fragments.

5022.85-5023.10 m Sandstone. Main lithology as 5022.45-5022.75 m, fining-upward; contains one tubular burrow and coal partings.
5023.10-5023.30 m Sandstone. Main lithology as 5020.65-5021.05 m with minor medium grains.

5023.30-5024.10 m Sandstone. Light gray (N7) to yellowish gray (5 Y 8/1), coarse-grained, moderately sorted, dolomitic. High-angle cross-bedding defined by grain size variations. Several vertical mud-lined burrows in the top 15 cm and the basal 5 cm and includes a few wispy coal partings.

5024.10-5024.25 m Sandstone. Main lithology as 5023.1-5023.3 m incorporating several coal partings.

5024.25-5024.50 m Sandstone. Light gray (N7), medium-grained, moderately well sorted, dolomitic, displaying plane-laminations inclined 20°.

5024.50-5036.00 m No core recovered.

MOBIL et al. VENTURE B-52 Core 4
RT 35.4 m Lower Missisauga Unit
(44°01'10.28"N; 59°38'07.69"W)

5033.05-5034.85 m Sandstone. Light gray (N7), yellowish gray (5 Y 8/1) and light olive gray (5 Y 6/1), coarse-grained, friable, dolomitic, moderately sorted with minor carbonaceous partings. Includes several large tubular burrows which disturb faint mudstone laminae defining low-angle, cross-stratification. Abrupt contact with

5034.85-5035.10 m Sandstone. Light olive gray (5 Y 6/1) to greenish gray (5 Gy 6/1), very fine- and fine-grained, silty, argillaceous with minor mica, pyrite and carbonaceous matter. Incorporates inclined, planar, micaceous, black mudstone laminae. The basal part contains thin layers of coarse-grained sand. Abrupt contact with

5035.10-5035.90 m Sandstone. Very light gray (N8) to light gray (N7), coarsening-upward from very fine- to coarse-grained with rare pebbles. Incorporates common undulose, very carbonaceous mudstone laminae inclined 5-10°, dark gray shale clasts and coal fragments.

5035.90-5036.10 m Siltstone. Medium gray (N5), argillaceous, micaceous incorporating abundant dark gray, carbonaceous, inclined mudstone laminae and medium- to coarse-grained sand laminae. Abrupt contact with

5036.10-5036.40 m Sandstone. Main lithology as 5035.1-5035.9 m, dominantly medium-grained.

5036.40-5036.60 m Sandstone. Medium light gray (N6), very fine-grained, argillaceous, silty incorporating laminae and thin beds of micaceous, silty mudstone to argillaceous siltstone. Moderately burrowed with one 6 cm vertical burrow
displaying well developed concave-up spreite. Gradational contact with

5036.60-5038.00 m Sandstone. Medium gray (N5) to medium dark gray (N4), very fine sandy, argillaceous with rare floating medium and coarse grains, micaceous. Primary layering totally disrupted by biogenic activity with few burrows preserved; rare concave-up spreite and coal fragments observed near the base. Gradational contact with

5038.00-5039.90 m Sandstone. Grayish yellow green (5 GY 7/2) to light olive gray (5 Y 6/1), fine- to medium-grained, slightly argillaceous, dolomitic. Strongly to moderately burrowed, disrupting most primary layering; contains several large vertical burrows with well developed, horizontal, spreite and discontinuous, carbonaceous partings. Logged only 90 cm.

5039.90-5040.25 m Sandstone. Light olive gray (5 Y 6/1) to pale brown (5 YR 5/2), coarse- and medium-grained, poorly sorted, slightly calcareous, friable, structureless except for several tubular burrows.

5040.25-5041.25 m Sandstone. Main lithology as 5038.0-5039.9 m with a few disrupted mudstone laminae near the base.

5041.25-5044.50 m Sandstone. Main lithology as 5039.9-5040.25 m with faint, low-angle inclined stratification evident. Logged only 1.25 m.

5044.40-5044.75 m Sandstone. Yellowish gray (5 Y 8/1), fine-grained, well-sorted, calcareous, containing layers of wispy, carbonaceous mudstone fragments and partings.

5044.75-5044.90 m Sandstone. Light olive gray (5 Y 6/1), fine- to medium-grained, moderately sorted, micaceous, incorporating inclined argillaceous laminae. Base defined by a 1 cm dark gray, micaceous mudstone bed.

5044.90-5045.15 m Sandstone. Very light gray (N8), fine-grained, moderately well sorted, dolomitic with several discontinuous, argillaceous partings. Top 5 cm is olive gray (5 Y 4/1) and very calcareous. Scoured basal contact with

5045.15-5045.55 m Sandstone. Main lithology as 5038.0-5039.9 m, incorporating a 2.5 cm fine-grained sandstone bed not disturbed by biogenic activity.

5045.55-5045.65 m Sandstone. Main lithology as 5044.9-5045.15 m.

5045.65-5045.75 m Sandstone. Main lithology as 5045.15-5045.55 m.
5045.75-5045.95 m Sandstone. Main lithology as 5044.9-5045.15 m, incorporating a 5 mm mudstone layer and rare shale clasts.

5045.95-5046.10 m Sandstone. Main lithology as 5045.15-5045.55 m.

5046.10-5047.15 m Sandstone. Light olive gray (5 Y 6/1) to yellowish gray (5 Y 8/1) medium-grained, fine sorting, calcareous. High- and medium-angle planar cross-beded; the upper part contains abundant discontinuous, irregular, carbonaceous laminae and common-coarse grains.

5047.15-5047.45 m Sandstone. Olive black (5 Y 2/1), fine-grained, dolomite, argillaceous incorporating minor mudstone partings. Basal contact is at the base of a 1.5 cm mudstone bed.

5047.45-5048.00 m Sandstone. Main lithology as 5046.1-5047.15 m with rare tubular burrows, coal fragments, and shell debris in the upper 25 cm and shale clasts near the base. Cross-stratification is less distinctly defined.

5048.00-5049.05 m Mudstone. Grayish black (N2), micaceous, carbonaceous, locally fissile incorporating minor siltstone laminae and irregular pods and floating coarse- to medium-grained sand and minor coal partings.

MOBIL et al. VENTURE B-52  RT 35.4 m Lower Mississauga Unit
(44°01'10.28"N; 59°38'07.69"W) Core 5

5111.45-5113.00 m Shale. Grayish black (N2) to black (N1), fissile, micromicaceous incorporating increasingly common thin laminae and lenticles of siltstone and argillaceous very fine-grained sand which are commonly pyritic; common floating coarse sand grains scattered throughout. Contains two 6 and 11 cm thick layers near the top and base consisting of a very poorly sorted mixture of coarse-grained sand, angular black shale fragments, and coal fragments. Abrupt contact with

5113.00-5121.85 m Sandstone. Light gray (N7), pale yellowish brown (10 YR 6.2) and pale brown (5 YR 5/2), medium- to fine-grained with scattered coarse grains, moderately sorted, fissile, dolomitic with minor patchy calcareous cement; incorporates common coal fragments as framework grains and locally abundant angular shale clasts as 5111.45-
5113.0 m. Dominantly structureless with minor low-angle planar cross-stratification in the top 3 m and rare layers with abundant undulose, carbonaceous mudstone laminae. Logged 5.85 m only. Irregular basal contact with

5121.85-5123.65 m Interbedded shale and sandstone. Shale, main lithology as 5111.45-5113.0 m in beds 8 to 35 cm; includes several
Irregular 1.5-2 cm very poorly sorted coarse-grained sand layers. Sandstone, very light gray (N8), fine-grained, moderately well sorted, dolomitic and siliceous in beds 10-45 cm; incorporates common coal fragments and partings, irregular and undulose, micaceous, carbonaceous mudstone laminae, scattered coarse sand grains and minor wave-rippled sandstone near the base. The thickness of the shale beds systematically decreases toward the base. Gradational contact with

5123.65-5124.30 m Sandstone. Main lithology as 5113.0-5121.85 m, structureless with very rare wavy, carbonaceous, micaceous mudstone partings.

5124.30-5124.45 m Shale. Main lithology as 5111.45-5113.0 m with more distinct siltstone laminae.

5124.65-5124.55 m Sandstone. Main lithology as 5113.0-5121.85 m. Irregular base with shale clasts and coarse sand grains immediately above.

5124.55-5124.60 m Shale. Main lithology as 5111.45-5113.0 m.

5124.60-5126.25 m Sandstone. Pale yellowish brown (10 YR 6/2), very fine-to-fine-grained, silty, dolomitic, siliceous incorporating rare wavy, micaceous, carbonaceous mudstone partings and rare horizontal, sand-filled burrows (5125.55-5125.65 m). Top 6 cm includes a flood of large angular shale, siltstone, argillaceous very fine-to-fine-grained sandstone rip-up clasts and minor coarse sand grains.

5126.25-5126.35 m Shale. Main lithology as 5111.45-5113.0 m, silty, very calcareous, microfaulted.

5126.35-5126.65 m Sandstone. Main lithology as 5113.0-5121.85 m incorporating minor very fine-grained sandstone; calcareous, faulted, chaotic structure with bedding plane dipping up to 60° to core axis, locally pyritic with several rounded fine-grained sandstone fragments at the base.

5126.65-5127.50 m Fault Breccia. Light gray (N7) to medium dark gray (N4), matrix supported with clasts of siltstone and subordinate fine-grained sand from <0.5 to 15 cm in diameter. Matrix is dominantly silty and sandy mudstone containing common white calcite-filled fractures and sickenanes; very calcareous and dense.

5127.50-5130:20 m Siltstone grading to silty mudstone. Medium dark gray (N4) to dark gray (N3), very calcareous, micromicaceous with rare shell debris; siltstone-rich layers are biogenically churned.
5175.80-5181.35 m Siltstone incorporating subordinate silty mudstone and very fine-grained sandstone. Dusky brown (5 YR 2/2), dark gray (N3) to medium light gray (N6), argillaceous, micaceous, slightly carbonaceous, partially dolomitic with minor shell debris. Sandstone, silty, argillaceous, burrowed, plane-laminated in beds 9 to 22 cm thick, commonly with abrupt bases and gradational, burrowed and bioturbated tops. Gradational contact with

5181.35-5186.00 m Siltstone: Medium light gray (N6) to medium dark gray (N4), argillaceous, with rare very fine-grained sandstone; primary stratification totally disrupted by biogenic activity, rare mud-filled burrows preserved. Trace siderite and calcite nodules. Logged 2.65 m. Gradational contact with

5186.00-5190.30 m Siltstone and mudstone. Medium dark gray (N4) to grayish black (N2), silty, micromicaceous, partially dolomitic and calcareous with minor pyritic carbonaceous matter. Silty sections show some evidence of burrowing, otherwise the unit is structureless with very rare lenticles of siltstone in the mudstone.

5262.60-5262.85 m Sandstone. Light gray (N7) to light olive gray (5 Y 6/1), fining-upward from coarse-to medium-grained to very fine-grained, silty, poorly sorted, calcareous and partially dolomitic. Burrowed with common horizontal and inclined mud-lined, sand-filled tubular burrows. Basal contact abrupt and inclined.

5262.85-5269.60 m Sandstone. Interbedded strongly bioturbated very fine-grained sandstone and stratified very fine- to fine-grained sandstone. Bioturbated units are medium light gray (N6) to light olive gray (5 Y 6/1) silty, argillaceous, micaceous, partially carbonaceous, dolomitic in beds 8 to 55 cm thick; incorporates rare irregular, cross-laminated pods of sandstone. Stratified units are light gray (N7) to medium light gray (N6), silty, dolomitic, partially calcareous in layers 14 to 120 cm thick; contain common micaceous mudstone laminae, rare grouped horizontal sand-filled burrows, rare shale clasts and coal fragments. Thicker units have abrupt, locally accreted bases, gradational, burrowed tops with planar cross-bedding in the lower parts grading up to plane-laminated or wave- and ripple-laminated sandstone.
5269.60-5269.70 m Sandstone. Very light gray (N8) to medium light gray (N6), fine-grained, dolomitic, glauconitic with rare inclined tubular burrows and a 1.5 cm angular dark gray shale rip-up clast.

5269.70-5270.50 m Sandstone. Pale yellowish brown (10 YR 6/2) to light olive gray (5 Y 6/1), very fine- to fine-grained, well sorted, micaceous, dolomitic, slightly glauconitic, displaying distinct low-angle inclined bedding.

5270.50-5270.65 m Sandstone. Main lithology as the strongly bioturbated units described in 5262.85-5269.6 m.

5270.65-5271.10 m Sandstone. Light olive gray (5 Y 6/1), very fine-grained, silty, well sorted, partially calcareous incorporating grouped, inclined, micaceous mudstone laminae and partings with several small dark gray shale fragments at the base.

5271.10-5274.60 m Sandstone. Main lithology as 5269.7-5270.5 m, variably indurated and calcareous; incorporates several tubular burrows in the lower 50 cm. Logged only 3.0 m.

5274.60-5274.90 m Sandstone. Light gray (N7), very fine-grained, well sorted, calcareous exhibiting low-angle planar cross-bedding. Incorporates a few dark gray shale clasts and several large (to 2.5 cm) horizontal, sand-filled tubular burrows.

5274.90-5275.05 m Sandstone. Main lithology as strongly bioturbated units described in 5262.85-5269.6 m.

5275.05-5275.30 m Sandstone. Main lithology as 5270.65-5271.1 m, dolomitic with very rare tubular burrows. Contains a 1 mm wide discordant, white calcite vein near the base.

5275.30-5275.45 m Sandstone. Main lithology as stratified units in 5262.85-5269.6 m.

MOBIL et al. VENTURE B-52 RT 35.4 m Mic Mac Formation
(46°01'10.28"N; 59°38'07.69"W) Core 8

5544.90-5549.40 m Sandstone. Interbedded strongly bioturbated very fine- to fine-grained sandstone and subordinate stratified, very fine- to fine-grained sandstone. Bioturbated units are medium dark gray (N5) to light olive gray (5 Y 6/1) silty, argillaceous, micaceous, calcareous; churned with several irregular 1-3 cm thick undisturbed sandstone layers with shale clasts and plane- and current ripple-laminations. Stratified units are light gray (N7), silty, well sorted, micromaceous, slightly glauconitic, calcareous in layers 20-50 cm thick commonly with abrupt, irregular, scoured and local deformed bases and
bioturbated tops; planar cross-bedded incorporating rare tubular burrows and dark gray shale clasts. Stratified units are thicker and more frequent toward the top. Gradational contact with

5549.40-5562.30 m Siltstone. Medium dark gray (N4) to dark gray (N3), argillaceous, very fine sandy occasionally grading to silty, argillaceous very fine-grained sandstone or less commonly silty, sandy mudstone; micaceous, calcareous, strongly bioturbated and churned with rare preserved tubular burrows occasionally displaying well developed concave-up spreite. Unit incorporates several stratified very fine- to fine-grained sandstone beds at 5544.9-5549.4 m in layers 30 to 45 cm thick and slightly burrowed indistinct sandy layers 5 to 20 cm thick. Two light olive gray (5 Y 6/1) to pale yellowish brown (10 YR 6/2), 2 cm thick micritic beds with minor shell debris occur near the base.

MOBIL et al. VENTURE R-22 RT 38.0 m Lower Mississauga Unit Core 1

4714.70-4718.80 m Interbedded Limestone and sandstone. Sandstone, light gray (N7) to pale yellowish brown (10 YR 6/2), fine- to very fine-grained, silty, well sorted, slightly calcareous in layers 5-45 cm thick; incorporates common horizontal, rare inclined tubular burrows, locally common discontinuous mudstone laminae, rare ripple-laminations and thin oolitic laminations infilling ripple troughs. Sandstone beds have abrupt tops, often truncating laminae or are burrowed and irregular; lower contacts are gradational and irregular with common floating oolitic grains. Limestone, dusky brown (5 YR 2/2), coarse-grained, oolitic packstone with common superficially carbonate coated grains, well sorted in layers 7-40 cm thick; incorporates locally common fine-grained sand as matrix and stringers, rare pyritic coal fragments, mollusc, coral and bryozoan fragments and tubular burrows. Frequency and thickness of limestone beds increases toward the top. Gradational contact with

4718.80-4720.15 m Sandstone. Light gray (N7), light greenish gray (5 Gy 6/1) and greenish gray (5 Gy 6/1), very fine-grained, silty, argillaceous, well sorted, micromicaceous chloritic, locally calcareous with rare coal fragments. Common horizontal and inclined, micaceous, mudstone laminae with two 10-15 cm thick wave ripple-laminated and small-scale trough cross-laminated layers. Interval displays a discordant diagenetic interface between light gray, calcareous, tight sand and light greenish gray, porous sand with obscured primary stratification.

277
Siltstone. Pale yellowish brown (10 YR 6/2) fine- and very fine-grained, silty, argillaceous, calcareous, partially dolomitic incorporating rare coarse and granule size grains. Contains common, horizontal tubular burrows and discontinuous mudstone laminae with a 1 cm coarse-grained sandstone layer with shell debris as a ripple trough infilling.

Sandstone. Pale yellowish brown (10 YR 6/2), fine- to medium-grained with scattered and thin layers of coarse-grained sand, moderately sorted, dolomitic with traces of chlorite and shell debris. Sporadically burrowed, dominantly inclined, mud-lined, sand-filled burrows with several burrows over 9 cm long and 1.5 cm in diameter. Plane and undulose argillaceous laminae locally developed. Unit incorporates two 12 and 15 cm argillaceous, very fine- to fine-grained sandstone beds, calcareous, micaceous; displaying distinct plane-laminations and tubular burrows. Gradational contact with

Sandstone. Pale yellowish brown (10 YR 6/2), fine-grained, well sorted, chloritic with common, distinct plane-laminations and rare small-scale trough cross-laminations locally disrupted by tubular burrows.

Sandstone. Interbedded bioturbated and stratified sandstone. Bioturbated units are light olive gray (5 Y 6/1), very fine-grained, silty, argillaceous, dolomitic, partially calcareous in beds 8-38 cm thick; churned units are light gray (N7), fine- to very fine-grained, silty, slightly argillaceous, dolomitic, partially calcareous in beds 25-85 cm thick, commonly with load casts and bases and indistinct burrowed tops. Beds exhibit distinct, very micaceous (flakes to 3 mm) horizontal and slightly inclined plane-laminations and rare ripple-laminations with scattered, rounded dark gray shale fragments; microfaulted laminae at 4731.9 m.

Siltstone. Pale brown (5 YR 5/2), argillaceous, very fine sandy, micromicaceous, dolomitic, locally pyritic; Strongly bioturbated with rare undulose laminae preserved. Lower 40 cm contains several vertical white sparry calcite-filled fractures.

MOBIL et al. VENTURE H-22
(44°01'24.10"N; 59°33'06.70"W)
Core 2

Siltstone. Medium dark gray (N4) to dark gray (N3), argillaceous, micaceous, carbonaceous incorporating discontinuous pods and flat lenses of very fine- to fine-grained sandstone that is partially calcareous and micaceous. Strongly burrowed with few burrows.
recognisable. Thin coal stringers occur locally. Gradational contact with

4899.75-4900.45 m Interlaminated and thinly interbedded mudstone, siltstone and sandstone. Mudstone is medium dark gray (N4), silty, sandy, micaceous, carbonaceous. Siltstone and very fine-grained sandstone is medium light gray (N6), dolomitic and commonly with sole markings on the base of beds. Rare silt-filled horizontal, tubular burrows occur in muddy layers. One 30 cm layer contains several fining-upward graded, beds (fine sand to mudstone); top 20 cm is dominantly mudstone. Basal contact is sharp and irregular with common, angular shale clasts and minor coal fragments.

4900.45-4900.85 m Sandstone. Medium light gray (N6), very fine- to fine-grained, slightly dolomitic, moderately sorted. Contains rare low-angle, inclined mudstone and coal laminations with scattered angular to subrounded, slab-like, dark gray shale rip-up clasts (to 7 cm) and mollusc shell debris. Thin beds of laminated siltstone occur locally; a 1-2 cm pebbly sandstone layer at 4900.55 m contains clasts of gray chert, coal and carbonate. Basal contact is very irregular, scoured and underlain by convolute mudstone laminae.

4900.85-4901.05 m Siltstone. Main lithology as 4894.5-4894.9 m. Abrupt, planar contact with

4901.05-4901.45 m Sandstone. Main lithology as 4900.45-4900.85 m, dominantly fine-grained. Abrupt contact with

4901.45-4902.15 m Siltstone. Medium dark gray (N4), argillaceous, sandy, displaying wavy, discontinuous and convolute siltly very fine- to fine-grained sandstone laminations, flow rolls, rare silt-filled horizontal tubular burrows and several subrounded clasts (0.75-3 cm) of poorly sorted pebbly sandstone. Basal 10 cm as in 4899.35-4899.75 m. Gradational contact with

4902.15-4902.40 m Sandstone. Main lithology as 4900.45-4900.85 m, calcareous. Basal 5 cm is fossiliferous with scattered gastropod and bivalve shell debris. Abrupt contact with

4902.40-4902.75 m Siltstone. Main lithology as 4901.45-4902.15 m.

4902.75-4902.85 m Sandstone. Main lithology as 4900.45-4900.85 m, dolomitic with thin graded layers; unit is dominantly a flow roll structure.

4902.85-4903.25 m Mudstone, siltstone, sandstone. Main lithology as 4899.75-4900.45, locally moderately burrowed.
4903.25-4904.30 m Siltstone. Main lithology as 4899.35-4899.75 m, incorporating a 4 cm very fine-grained sandstone bed with a load-deformed base; trace glauconite. Gradational contact with

4904.30-4912.50 m Siltstone and mudstone/shale. Thinly interbedded, dark gray (N3) siltstone and mudstone with common planar silt and very fine sand laminae and rare burrows; blocky, micaceous, variably carbonaceous. Contains rare graded laminae, convolute laminae, lenticular-bedding, current ripple, load casts and shell debris; stratified intervals have abrupt contacts.

4912.50-4912.65 m Sandstone. Light gray (N7), fining-upward, very coarse-to very fine-grained, with shale clasts at the top. Abrupt, scoured contact with

4912.65-4915.35 m Siltstone and mudstone/shale. Main lithology as 4904.3-4912.5 m. Top of unit is microfaulted.

4915.35-4916.05 m Sandstone. Light gray (N7), includes four coarsening-upward cycles from 8 to 30 cm thick. Layers grade from micaceous, fine-grained sand with rare undulose micaceous mudstone laminae to poorly sorted, pebbly medium-grained sand with shale clasts, coal fragments, lithic grains and pebbly lags. Basal contact missing.

4916.05-4916.15 m Shale. Dark gray (N3), micaceous, incorporating minor silt to fine-grained sand laminae.

4916.15-4916.40 m Mudstone, siltstone and sandstone. Main Lithology as 4899.75-4900.45 m incorporating several graded, fining-upward laminae and thin beds with small pebble lags and trace burrowing.

4916.40-4916.60 m Sandstone. Main lithology as 4915.35-4916.05 m with one small tubular burrow.

4916.60-4916.80 m Shale. Main lithology as 4916.05-4916.15 m.

4916.80-4916.95 m Sandstone. Light gray (N7), coarse- to medium-grained, pebbly, moderately sorted, dolomitic with an occasional shale clast and siderite nodule; no pebbles in the top 6 cm.

4916.95-4917.25 m Shale. Main lithology as 4916.05-4916.15 m incorporating two irregular 2-3 cm fining-upward, coarse- to fine-grained sand layers.

4917.25-4917.50 m Sandstone. Main lithology as 4916.8-4916.95 m, dominantly coarse-grained.
Sandstone. Light olive gray (5 Y 6/1), to medium light gray (N6), fine- to medium-grained, slightly glauconitic, dolomitic and partially calcareous. Planar cross-bedded in truncated sets with several thin, coarse-grained, pebbly lags along some bedding surfaces. Incorporates shale and calcareous very fine-grained sandstone clasts to 4 cm that decrease in size upward, rare wispy carbonaceous partings and one vertical tubular burrow. A 6 cm carbonate concretionary layer occurs at 4963.2 m. Basal 30 cm contains several layers of coarse-grained, pebbly sand. Irregular, scoured basal contact with rip-up clasts overlying.

Sandstone. Light gray (N7) to pale yellowish brown (10 YR 6/2), fine- to medium-grained, micaceous, dolomitic, interlaminated and thinly interbedded with argillaceous very fine- to fine-grained sandstone. Cross-laminated grading to indistinctly plane-laminated with scattered shale clasts in the basal part. The lower 10 cm is pebbly. Scoured basal contact incorporating rip-up clasts overlying.

Sandstone. Light gray (N7), fine-grained, silty, micaceous. Common, variably oriented mud-lined, sand-filled tubular burrows with concave-up aperite; minor plane-laminated layers locally preserved. Rare shale rip-up clasts to 4 cm occur in the stratified sections. Two thin very coarse sand and pebble layers occur in the top 60 cm. Abrupt contact with.

Sandstone. Light gray (N7) to medium light gray (N6), fine-grained, silty, variably argillaceous in layers, micaceous, dolomitic. Incorporates abundant low-angle inclined plane-laminations with rare truncation of laminae. Scattered shale clasts are confined to the argillaceous layers. Scoured basal contact with.

Sandstone. Interbedded sandstone as 4967.2-4970.35 m in beds 25-90 cm and sandstone, medium gray (N5) to medium dark gray (N4), very fine-grained, argillaceous, silty, micaceous, slightly burrowed, irregularly laminated in beds 15-33 cm thick.

Sandstone. Yellowish gray (5 Y 8/1) to pale yellowish brown (10 YR 6/2), fine-grained, well sorted, dolomitic, slightly glauconitic. Indistinct horizontal and inclined planar-laminae. Contains minor scattered shale clasts and coal fragments.

Sandstone. Main lithology as 4965.35-4968.55 m. Top of unit displays well developed Chondrites burrows.

281
4977.45-4978.45 m Sandstone. Main lithology as 4967.7-4970.35 m incorporating minor bivalve shell debris.

4978.45-4980.30 m No core recovered.

4980.00-4980.30 m Sandstone and shale, interlaminated and thinly interbedded. Shale, dark gray (N3), blocky; micromicaceous. Sandstone, medium gray (N5), very fine-grained, silty, argillaceous, dolomitic. Moderately burrowed with minor wavy- and lenticular-beding preserved; burrows are all horizontal and sand-filled.

4980.30-4980.85 m Sandstone. Main lithology as 4967.7-4970.35 m incorporating several thin argillaceous, burrowed layers.

4980.85-4982.10 m Sandstone. Main lithology as 4973.55-4977.15 m, laminae inclined up to 15°.

4982.10-4982.45 m Sandstone. Main lithology as the basal 30 cm of 4962.0-4964.75 m. Coarse-grained layers incorporate minor mollusc shell debris and coal fragments.

4982.45-4985.95 m Sandstone. Main lithology as 4965.2-4967.7 m, incorporating a 14 cm bed containing abundant plane-laminae with rare tubular burrows. Contains several 1.5-2 cm calcareous concretionary nodules.

4985.95-4986.45 m Sandstone. Main lithology as 4967.7-4970.35 m, incorporating very rare horizontal, sand-filled tubular burrows. Gradational contact with

4986.45-4987.00 m Sandstone and shale. Main lithology as 4980.0-4980.3 m with subordinate shale.

4987.00-4987.90 m Sandstone. Main lithology as 4969.7-4970.35 m, with common medium grains and several large horizontal, tubular burrows. Truncated laminae evident near the base.

4987.90-4988.70 m Sandstone. Main lithology as 4973.55-4977.15 m incorporating several coarse-grained, pebbly lag deposits in troughs (? scour-and-fill). Pebbles to 1 cm, angular, consisting of silty/sandy mudstone and argillaceous very fine-grained sandstone. Unit contains one sand-filled tubular burrow.

4988.70-4989.35 m Sandstone. Main lithology as 4965.25-4967.75 m, calcareous with minor medium grains toward the base. Burrows are all >1 cm; incorporated rare calcareous concretionary nodules.

4989.35-4989.60 m Sandstone. Medium light gray (N6), very fine-grained, silty, increasingly argillaceous toward the base, micaceous, very calcareous, fossiliferous (bivalves and
Interbedded sandstone and siltstone/sandstone. Main lithology similar to 4970.35-4973.55 m. Sandstone in layers 10-105 cm with rare mudstone beds to 3 cm, trace glauconite; commonly with burrowed tops and abrupt, rip-up clast or pebble-bearing undulose bases. Siltstone/argillaceous sandstone—moderately to strongly burrowed with minor lenticular- and wavy-bedding locally observed; in beds 20-100 cm that are thicker and more frequent toward the base.

No core recovered.

Siltstone, mudstone and shale. Medium gray (N5) to dark gray (N3), locally very fine sandy, micaceous, with scattered coaly partings, bivalve shell debris and calcareous concretionary bodies. Mostly structureless with rare to locally common sand/silt stringers. Silty and sandy sections exhibit minor biogenic disruption and rare irregular lenticular and ripple cross-laminated layers to 3 cm. Contains minor sparry calcite and pyrite filled fractures. Gradational contact with

Interbedded sandstone and siltstone/argillaceous sandstone. Main lithology as 4989.6-4997.8 m. Stratified units in beds 15-85 cm, averaging 20-30 cm; minor trough cross-laminae in the upper part of sandstone beds. Minor scattered shell debris in argillaceous beds. Scoured contact with

Sandstone. Mottled light gray (N7) and medium light gray (N6), medium- and fine-grained, pebbly to conglomeratic, with traces of shell debris, carbonaceous matter and mica; very calcareous. Clasts are 3 mm to 1.5 cm, rounded concentrated at the base and in a 7 cm layer in the middle. Clasts are dominantly of the underlying unit with minor argillaceous, very fine-grained sandstone clasts as in overlying units. Scoured basal contact with

Sandstone. Medium gray (N5) grading to salt and pepper, fine- grading to medium-­grained, moderately sorted, micaceous, calcareous with minor disseminated pyritic coaly matter and shell debris. Moderately burrowed, decreasing toward the base. Incorporates a coarse-grained pebbly, conglomeratic layer at the base; maximum clast size to 1 cm.

Sandstone. Light olive gray (5 Y 6/1), light brownish gray (5 YR 6/1) and pale yellowish brown (10 YR 6/2), medium-grading to coarse-grained, friable, slightly dolomitic at the top with scattered chlorite flakes and pyritic coal fragments. Structureless with very rare,
large (>1 cm) sand-filled, mud-lined tubular burrows. Gradational contact with

5021.85-5022.30 m Sandstone. Salt and pepper, medium-grained, moderately well sorted, siliceous with rare, mud-lined tubular burrows (1-2 cm) and coal fragments. Subtle grain size variations define concave-up laminae indicating probable trough cross-stratification. Abrupt contact with

5022.30-5022.80 m Sandstone. Olive gray (5 Y 4/1) to olive black (5 Y 2/1), medium grading to very fine-grained, silty, argillaceous, very dolomitic and siliceous, with common disseminated carbonaceous matter, coal fragments and minor bivalve shell debris and coarse grains; rare tubular burrows evident. The lower 25 cm incorporates well developed plane-laminations of mudstone. Abrupt contact with

5022.80-5027.70 m Sandstone. Main lithology as 5021.85-5022.3 m, also light olive gray (5 Y 6/1) where cemented by dolomite. Incorporates a 4 cm, carbonate cemented, laminated, very fine-grained layer at 5023.25 m. Locally pyritic at 5026.3-5026.8 m. Contains occasional calcareous concretionary nodules in the basal 1.5 m. Rare bipartite laminae occur locally.

5027.70-5034.70 m Sandstone. Main lithology as 4965.2-4967.7 m, increasingly argillaceous toward the base, trace glauconite. Incorporates a 25 cm fine- to medium-grained layer at 5028.1 m, calcareous with discontinuous, undulose mudstone laminae. Also contains a 20 cm, olive gray (5 Y 4/1), dolomite cemented, silty, very fine-grained unit at 5031.6 cm; slightly fossiliferous with rare mudstone partings.

5034.70-5035.20 m Sandstone. Main lithology as 4967.7-4970.35 m, with rare tubular burrows. Gradational contact with

5035.20-5038.15 m Sandstone. Main lithology as 4973.55-4977.15 m, laminae dipping to 15°. Very rare tubular burrows, shell debris and coal fragments near the base. Scoured contact with

5038.15-5054.80 m Interbedded sandstone and siltstone/argillaceous very fine-grained sandstone. Main lithology as 4989.6-4997.8 m: Stratified units in beds 10-115 cm, averaging 30-40 cm. Argillaceous units in beds 10-80 cm averaging <20 cm increasing in frequency toward the base. Thicker sandstone units commonly display low-angle planar cross-bedding in the lower part grading upward into ripple cross-laminations. Where the sands are calcareous, any incorporated carbonaceous matter is pyritic. Minor medium and coarse grains occur in the basal 20 cm.
5054.80-5055.40 m Sandstone. Light olive gray (5 Y 6/1) and olive gray (5 Y 4/1), very fine- to coarse-grained, poorly sorted, slightly carbonaceous, increasingly calcareous toward the base; incorporated minor shell debris including crinoid ossicles, corals and bivalves. Thin, very coarse- to medium-grained layers alternate with thin medium- to very fine-grained layers suggesting low-angle planar cross-bedding.

5055.40-5056.90 m Sandstone. Main lithology as 4960.20-4962.7 m, dominantly very fine-grained, increasingly argillaceous toward the base. Upper 30 cm is calcareous grading to dolomitic.

5056.90-5057.75 m Sandstone. Main lithology as 4962.7-4965.35 m with rare arcuate truncation surfaces interrupting plane-laminations; rare tubular burrows near the top.

5057.75-5059.30 m Sandstone. Main lithology as 5055.4-5056.9 m.

5059.30-5059.60 m Sandstone. Main lithology as 5056.9-5057.75 m with scattered angular, gray shale rip-up clasts in the basal 5 cm.

5059.60-5060.10 m Siltstone. Medium gray (N5), very fine sandy, argillaceous grading to silty, argillaceous very fine-grained sandstone. Partially calcareous, micaceous, strongly bioturbated, with minor discontinuous mudstone laminae.

5060.10-5064.20 m Sandstone. Main lithology as 4973.55-4977.15 m, partly calcareous, incorporating several 5-10 cm carbonaceous, micaceous layers with common mudstone laminae, tubular burrows and shell debris. Common, elongate, calcareous nodules inclined along bedding planes between 5062.5-5064.2 m.

5064.20-5065.25 m Sandstone. Pale yellowish brown (10 YR 6/2) to medium gray (N5), very fine- to fine-grained, silty, variably argillaceous, partially calcareous, micaceous, slightly carbonaceous near the top. Upper part contains indistinct, discontinuous, carbonaceous, micaceous mudstone laminae and scattered tubular burrows. Lower part incorporates well defined, abundant, plane-laminae that are very micaceous.

5065.25-5068.35 m Sandstone. Main lithology as 4973.55-4977.15 m with minor high-angle, planar cross-bedding. Abrupt contact with

5068.35-5068.60 m Siltstone. Main lithology as 5059.25-5060.1 m, with minor sandstone lenticles.

5068.60-5069.75 m Sandstone. Main lithology as 5065.25-5068.35 m; base of unit displays sole markings.
Interbedded sandstone and subordinate siltstone/very fine-grained sandstone. Main lithology as 4989.6-4997.8 m. Stratified units in beds 10-65 cm, bioturbated units in beds 8-55 cm with rare preserved wavy- and lenticular-bedding.

Mudstone. Medium dark gray (N4), very fine sandy grading locally to sandy siltstone, micromicaceous, locally carbonaceous. Strongly bioturbated with rare irregular sandstone stringers and rare bivalve fossil debris.

MOBIL et al. VENTURE H-22
(44°01'24.1"N; 59°33'06.7"W)
Core 8
RT 38.0 m Mic Mac Formation

Interbedded sandstone and siltstone. Sandstone is light gray (N7) to light olive gray (5 Y 6/1), very fine-grained, well sorted, argillaceous, silty, micaceous, dolomitic, slightly glauconitic incorporating indistinct plane-laminations and tubular burrows with rare ripple- and trough-cross laminations; in layers 9-16 cm thick. Sandstone beds typically have sharp, undulose bases with rip-up clasts and burrowed tops. Siltstone is medium gray (N5), medium light gray (N6) and pale yellowish brown (10 YR 6/2), micaceous, argillaceous, very fine sandy, dolomitic, strongly bioturbated with rare micaceous mudstone laminae in layers 5 to 21 cm. Gradational contact with

Siltstone. Pale yellowish brown (10 YR 6/2), argillaceous, very fine sandy, micaceous, carbonaceous with trace shell debris. Strongly burrowed with occasional sand-filled and rare mud-filled burrows and current-ripples preserved. Incorporates several irregular, laminated, slightly burrowed, dolomitic, argillaceous, very fine-grained beds (<5 cm). Gradational contact with

Sandstone. Main lithology similar to 5238.55-5243.55 m, sandier, carbonaceous with mud-filled tubular burrows more common than sand-filled burrows. Gradational contact with

Siltstone. Main lithology as 5238.55-5243.55 m, locally more carbonaceous.

Sandstone and siltstone. Main lithology as 5237.0-5238.55 m.

Sandstone. Light olive gray (5 Y 6/1), medium gray (N5) and yellowish gray (5 Y 8/1), interbedded strongly bioturbated very fine-grained sandstone in beds 4-18 cm thick, and stratified very fine- to fine-grained sand in beds 4-7 cm thick; argillaceous, silty, dolomitic. Stratified units contain minor carbonaceous, undulose
laminae, rare burrows and ripple-laminations with scattered coarse grains. The basal 1 cm is a very carbonaceous shale layer.

5245.45-5246.15 m Sandstone. Light gray (N7), light olive gray (5 Y 6/1) and pale yellowish brown (10 YR 6/2), fine-grained, moderate to poorly sorted, dolomitic containing common clasts (to 1.5 cm) of mudstone, coal, rounded very fine-grained sandstone pebbles, scattered granules and very coarse grains. Clasts occur sporadically or as discrete layers. Top 10 cm is conglomeratic with abundant clasts as above, and siltstone fragments and shell debris. Lower contact is an irregular pebble lag layer inclined 10-15°.

5246.15-5246.35 m Sandstone. Light gray (N7) to medium light gray (N6), very fine-grained, silty, argillaceous, well sorted, micaceous; moderately burrowed, decreasing toward the base. Lower part contains common irregular mudstone laminae and partings.

5246.35-5248.35 m Sandstone. Light gray (N7) to pale yellowish brown (10 YR 6/2), very fine- and fine-grained, well sorted, micaceous, dolomitic. Upper 1.35 m is mostly structureless with sporadic poorly developed planar laminae, several tubular burrows and shale clast-rich layers. Lower part incorporates abundant undulose and inclined mudstone laminae; one layer contains well-developed herringbone cross-laminations.

5248.35-5249.25 m Sandstone. Light gray (N7) to medium light gray (N6), fine-grained grading toward the base into very fine-grained, silty, micaceous, slightly glauconitic, partially calcareous toward the base. Incorporates common mudstone laminae and minor tubular burrows.

5249.25-5249.80 m Sandstone. Main lithology as the upper 1.25 m in 5246.35-5248.35 m, dominantly fine-grained with no evidence of biogenic activity.

5249.80-5250.50 m Sandstone. Light gray (N7) very fine- to fine-grained micaceous, plane-laminated interbedded with subordinate light olive gray (5 Y 6/1), very silty and argillaceous very fine-grained sand with rare wavy mudstone partings.

5250.50-5250.75 m Sandstone. Main lithology as 5246.15-5246.3 m, dominantly fine-grained.

5250.75-5251.25 m Sandstone. Main lithology as 5249.25-5249.8 m.

5251.25-5251.40 m Sandstone. Main lithology as 5246.15-5246.35 m.

5251.40-5252.20 m Sandstone. Light gray (N7) to yellowish gray (5 Y 8/1), very fine-grained, with common inclined and slightly
undulose mudstone laminae becoming plane cross-laminated near the base; includes very rare tubular burrows.

5252.20-5254.85 m Sandstone and siltstone. Main lithology as 5237.0-5238.55 m. Bioturbated units are very sandy and include rare shell debris and carbonaceous matter. The frequency and average thickness of the bioturbated units increases toward the base. Bioturbated layers are 10-60 cm thick; stratified layers are 4-52 cm thick.

MOBIL et al. VENTURE H-22 RT 38.0 m Mic Mac Formation Core 9

5397.15-5398.5 m Sandstone. Mottled light gray (N7) and light olive gray (5 Y 6/1), very fine-grained, well sorted, argillaceous, silty, locally grading to siltstone, micaceous with rare carbonaceous partings; strongly bioturbated to churned. Abrupt contact with

5398.50-5398.85 m Sandstone. Light gray (N7) to medium light gray (N6), fine- and medium-grained with minor scattered coarse grains, variably argillaceous, slightly micaceous, partially dolomitic. Argillaceous intervals are moderately burrowed with common flattened, horizontal and inclined, sand-filled, mud-lined burrows. Gradational contact with

5398.85-5399.15 m Sandstone. Light gray (N7), fine- and medium-grained, slightly argillaceous, dolomitic, slightly chloritic, incorporating minor discrete horizontal, tubular burrows (>1 cm) and coarse-grained laminae indicating inclined bedding. Gradational contact with

5399.15-5399.75 m Sandstone. Main lithology as 5398.5-5398.85 m incorporating rare undulose mudstone partings, mud-filled burrows and mollusc shell debris. Gradational contact with

5399.75-5400.15 m Sandstone. Light gray (N7), very fine-grained, silty, slightly argillaceous, dolomitic incorporating scattered undulose, discontinuous, micaceous mudstone partings, rare laminae; very rare tubular burrows and shell debris. Abrupt contact with

5400.15-5406.65 m Sandstone. Medium light gray (N6), fine-grained, locally medium-grained, slightly argillaceous, dolomitic, micaceous, locally glauconitic and carbonaceous. Top 1 m contains indistinct plane-laminations grading into distinct low- to moderate-angle cross-bedding in truncated sets and includes shale clasts and several 5 cm thick ripple cross-laminated layers in the lower 3 m. Abrupt contact with
Siltstone. Medium gray (N5) to dark gray (N3), sandy, argillaceous, locally grading to silty very fine-grained sand, micriticaceous, slightly dolomitic with minor scattered carbonaceous matter and bivalve shell debris. Churned with very rare ripple-laminations evident and increasingly common and thick, cross-laminated very fine-grained sand units commonly with abrupt, irregular bases with rip-up clasts and laminated, burrowed tops in layers 5 to 37 cm thick.
VITA AUCTORIS

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290
Figure E