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Sedimentology and Stratigraphy of an Ancient Progradational Terrigenous Clastic Shelf Margin, Mississauga Formation (Upper Jurassic-Lower Cretaceous), Offshore Nova Scotia, Canada

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SEDIMENTOLOGY AND STRATIGRAPHY OF AN ANCIENT PROGRADATIONAL TERRIGENOUS CLASTIC SHELF MARGIN, MISSISAUGA FORMATION (UPPER JURASSIC-LOWER CRETACEOUS), OFFSHORE NOVA SCOTIA, CANADA

by

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A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements of the degree of Ph.D. in Earth Sciences

OTTAWA-CARLETON GEOSCIENCE CENTRE UNIVERSITY OF OTTAWA OTTAWA, ONTARIO CANADA

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ABSTRACT

Large-scale stratal architecture, structure, and commonly hydrocarbon distribution in the Missisauga Formation, Sable Subbasin, offshore Nova Scotia, can be satisfactorily explained by shelf margin progradation. Using an integrated subsurface dataset (2-D and 3-D seismic data, biostratigraphy, geophysical well logs, core), the physical characteristics and depositional history of the Missisauga Formation (Tithonian-Barremian) were studied on both local and regional scales. These data suggest that during deposition of the Missisauga, the shelf margin prograded southward from an initial position just basinward of the Venture Field (Tithonian) to a final position just basinward of the Glenelg and Alma fields (Barremian). Growth-faulted, storm-dominated deltaic sandstones deposited at or near the shelf margin during this process are interpreted to contain over half of the discovered in-place gas reserves offshore Nova Scotia. Because shelf-margin delta sand-bodies are typically shore-elongate, tend to occur in groups along a shelf margin and commonly correlate downdip to turbidite sand-bodies, recognition of the shelf-margin delta play-type will not only improve hydrocarbon exploitation strategies offshore Nova Scotia, but will provide an important framework to guide the identification of new exploration opportunities in genetically related parts of the stratigraphic section.

In the Venture Field, Tithonian shelf-margin delta lobes are stacked vertically, suggesting that growth-fault related subsidence at the shelf margin negated depositional topography and created topographic lows through which fluvio-deltaic systems preferentially flowed. Over several relative sea level cycles, the positive feedback between sediment supply and subsidence at the shelf margin potentially focused enough
sediment to have constructed slope turbidite systems downdip, which in turn represent new exploration targets.

In the Glenelg Field, Barremian shelf-margin deltas were initially tide-influenced (dominated?) and then changed to a storm-dominated state, possibly because the shoreline initially prograded into a tidally resonant topographic depression, which upon being filled was converted to a wave-dominated setting. Along depositional strike of the main hydrocarbon-bearing sandstones at Glenelg, Barremian sandstone reservoirs in the Alma Field are interpreted to be storm-dominated shelf-margin delta deposits. However, unlike Glenelg, incised valleys were not identified at Alma, suggesting that downdip depocenters were fed by sediment that bypassed Glenelg during the Barremian.

Transgression at the end of the Barremian deposited mudstone of the Naskapi Member throughout the Sable Subbasin, forming a regional seal. Sharp-based, bioturbated shallow marine sandstones deposited locally during this transgression are an important play type in the western Sable Subbasin (e.g., Alma and Panuke fields).
RESUMÉ

L’architecture stratigraphique, les structures tectoniques, et souvent la distribution d’hydrocarbures dans la Formation Mississauga au large de la Nouvelle-Écosse peuvent être expliquées par la progradation de l’ancienne marge continentale. La sédimentologie et la stratigraphie de la Formation Mississauga (Tithonien-Barrémien) ont été étudiées dans le sous-bassin de Sable à l’aide d’une variété de données (diaphragmes électriques, carottes de forage, données biostratigraphiques, sismique 2-D et 3-D). Ces données suggèrent que pendant la déposition de la Formation Mississauga la marge continentale a progradé vers le sud d’une position initiale près du champs Venture (Tithonien) jusqu’à une position finale au sud des champs Glenelg et Alma (Barrémien). Les deltas de marge continentale déposés grâce à ce processus contiennent vraisemblablement plus de la moitié du gaz naturel déjà découvert au large de la Nouvelle-Écosse. Parce que les corps sableux des deltas de marge continentale sont typiquement alignés de façon parallèle au rivage et agissent souvent comme entrepôt pour les sédiments livrés aux systèmes de turbidites sur la pente continentale, l’identification des deltas de marge continentale peut aider l’exploitation et l’exploration d’hydrocarbures au large de la Nouvelle-Écosse.

Dans le champs Venture, les lobes deltaïques Tithonien se juxtaposent à la verticale. Ceci suggère que la subsidence différentielle à la marge continentale peut créer des dépressions topographiques qui “attirent” les systèmes fluvio-deltaïques. Au cours de quelques cycles de niveaux relatifs de la mer, le “feedback” positif entre l’apport en sédiments et la subsidence de la marge continentale pourrait peut-être concentrer la livraison de sédiments aux systèmes de turbidites sur la pente continentale.
Dans le champs Glenelg, les deltas de marge continentale Barrémien ont 
premièrement été dominés par les marées, puis par les vagues. Adjacents à Glenelg, les 
réservoirs Barrémien dans le champs Alma sont interprétés comme des dépôts de deltas 
de marge continentale. Contrairement aux champs Glenelg, aucune vallée incisée n’a été 
identifiée à Alma.

La transgression marine à la fin du Barrémien a déposé de l’argile du Membre 
Naskapi dans toute la région du sous-bassin de Sable. Les corps sableux à bases érosives 
qui on été deposés localement pendant cette transgression forment des réservoirs de 
pétroles au coté ouest du sous-bassin de Sable (e.g., les champs d’Alma et de Panuke).
ACKNOWLEDGEMENTS

This project was made possible thanks to financial support from Encana Energy, Norsk Hydro, Murphy Oil, and the Ontario Government. It was put together by Bill Arnott, Bruce Hart and John Hogg, three ex-Hamiltonians, two of whom were apparently born in a pub, wearing Speedos, and listening to bad ‘70s rock music (although, admittedly, Bruce has recently undergone a remarkable music-appreciation transformation). I owe a whole lot to all three of you, and especially Bill, for getting me a great project and supporting me throughout. Three lovely ladies, Mary Jean Verrall, Keri O’Kroneg and Nancy Williams, turned potentially dour summers in the Dartmouth core shack into a great experience. This thesis benefited from scientific discussions with Bill Arnott, Bruce Hart, Simone Dumas, Bob Dalrymple, Andrew MacRae, Dave Brown, Paul Harvey, Jack MacDonald, Gunilla Gard, Jason Crux, Sonia Dehler, John Schimeld, John Wade, Hazen Russell, Suzanne Leclair, Steven Goodbred, Bill Galloway, John Jaeger, Meade Allison, James MacEachern, Gisella Gerdes, Ron Steel, Shuji Yoshida, Kyungsik Choi, John Suter, Gela Crane, Rick Weirzbicki, and John Hogg. Thorough text editing by thesis committee members André Desrochers, Al Donaldson, Rob Rainbird and John Harper helped improve the final draft. Rob Fensome graciously analyzed palynology samples, Jim Fenton allowed me access to biostratigraphic data, and Paul Gammon helped identify skeletal fragments in thin section. Pat Allen provided much-needed technical support, and Hélène DeGouffe, the Earth Science Queen, made sure that I kept registered in school.

Mom and Dad, thanks for giving me the chance to even start this thesis. Diane, Margo, André, Sarah, Rob, Simon and Julie: thanks for helping out on the home front. Chris, Popo, Steve, Dave, Richard, John, and all members of the double-H express past and present (which covers just about everyone in town) are thanked for being great friends; I’m going to look back on all the late Ottawa nights with great fondness. Leo, I’d like to think that I did this thesis, in a large part, for you. And Simone, you were always there for me; I appreciate that more than anything.
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Chapter 1. Introduction

1.1 Rationale and objectives

Fluvial to continental slope sandstones of the Missisauga Formation contain ~75% of the original gas-in-place reserves discovered offshore Nova Scotia, Canada (Canada Nova Scotia Offshore Petroleum Board, 2000). Despite this, few studies have examined the sedimentology of the Missisauga in detail, and the formation has yet to be placed into a comprehensive sequence stratigraphic framework. The primary objective of this thesis, therefore, is to develop sequence stratigraphic-based depositional models for the Missisauga Formation at both local and regional scales in the hydrocarbon-rich Sable Subbasin, offshore Nova Scotia (Figure 1.1). Following a brief geological overview of the Sable Subbasin (Chapter 2), depositional models for selected parts of the Missisauga Formation are presented in a series of self-contained papers (Chapters 3, 4 and 5), followed by a short summary and conclusion (Chapter 6). Sedimentological logs are archived in appendices at the end of the thesis.

1.2 Statement of original contribution

All ideas, descriptions and interpretations presented in this thesis are my own, unless otherwise referenced. My supervisor and co-supervisor, Dr. R.W.C. Arnott (University of Ottawa) and Dr. B.S. Hart (McGill University), have contributed in minor but important ways, primarily during the text editing process.

1
1.3 Dataset

The results of this study are based on the analysis of geophysical well-log and cuttings data from 82 wells (Figure 1.2a), 2333 m of conventional core from 39 wells (Figure 1.2b), public and confidential biostratigraphic data (Figure 1.2c), ~1825 km of publicly available paper-format seismic data (Figure 1.2d) and an industry-donated digital 3-D seismic survey from the Panuke Field (96 km²) cut off at 2.2 seconds (Figure 1.2d). Additionally, Rob Fensome (Geological Survey of Canada) analyzed seven palynology samples collected from conventional cores from the West Venture C-62 well (see Chapter 4).

1.4 Methodology

Cores were described in 2.5 cm resolution (see Appendix 1), noting lithology, sedimentary textures and structures, body fossils, trace fossils, macroscopic diagenetic features, and the nature of stratigraphic contacts. Depositional processes and depositional environments were interpreted using a standard “process-oriented” facies analysis approach (e.g., Harms et al., 1975; Scholle and Spearing, 1982; Walker and James, 1992; Reading, 1996; Pemberton et al., 2002). Geophysical well logs were calibrated using core data, and were tied to seismic data using synthetic seismograms generated from sonic or sonic and density logs. Seismic, well log, and core data were interpreted using standard seismic and sequence stratigraphic techniques and concepts (e.g., Curray, 1964;

---

1 Two additional industry-donated 3-D seismic surveys (Annapolis and Annapolis East) were also loaded and analyzed, but proved unusable because of poor resolution at depth.

2 For digital seismic data, well ties were performed using a computer program (Landmark Geographix) at the McGill Seismic Research Lab. In the case of paper-copy seismic data, seismic and synthetic data were scanned into a computer program (Adobe Illustrator), and then the synthetics were adjusted (i.e., stretched) to “best fit” the seismic data. Where available, well ties were guided by checkshot data. The final well ties were checked against previously-reported well ties in MacLean and Wade (1993) and various unpublished reports (Sable Offshore Energy, 1996; Mobil 1997a,b,c, 1998a,b).
Vail et al., 1977; Posamentier and Vail, 1988; Van Wagoner et al., 1990; Emery and Myers, 1996; Posamentier and Allen, 1999).
Figure 1.1  Location of study area, Sable Subbasin, offshore Nova Scotia, Canada.
Figure 1.2a Location of oil and gas wells, Sable Subbasin, offshore Nova Scotia. A variety of geophysical well-log data (gamma ray, density, resistivity, dipmeter) were typically available for each well.
Figure 1.2b  Location of Missisauga Formation core used in this study, Sable Subbasin, offshore Nova Scotia. Cumulative core lengths for wells are given in meters.
Figure 1.2c  Location of biostratigraphic data used in this study, Sable Subbasin, offshore Nova Scotia.
Figure 1.2d  Location of seismic data used in this study, Sable Subbasin, offshore Nova Scotia.
Chapter 2. Geological Overview

The Scotian Basin is one of a series of sedimentary basins along the eastern seaboard of North America that formed during the break up of Pangea and the subsequent opening of the Atlantic Ocean (Figure 2.1). Although its development was initiated during a period of tectonic activity that involved crustal extension and rifting, the Scotian Basin is commonly referred to as a passive margin basin because it straddles the continental-oceanic crust transition on the now tectonically quiescent trailing margin of the North American continental plate (e.g., Allen and Allen, 1990; Busby and Ingersoll, 1995). Like most thick “Atlantic-type” passive margin basins, the Scotian Basin is characterized by 1) a distinct shelf-slope morphology, 2) basinward-increasing accommodation space for sediment accumulation, 3) a regional subsidence history driven by lithospheric cooling and sediment loading with zones of locally elevated subsidence related to salt withdrawal, 4) a rifted and “modified” continental crust basement, and 5) structural features (e.g., salt diapirs, growth faults) that formed predominantly as a result of gravity instability (Figure 2.2). However, despite these similarities, the stratigraphy of the Scotian Basin is ultimately unique, and reflects the complex interplay of intra- and extra-basinal controls active during its development.

2.1 Exploration history

Petroleum industry interest in offshore Nova Scotia was sparked in the 1950s by seismic refraction surveys that suggested the continental shelf and slope were underlain

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3 From a sedimentological point of view, the Atlantic Ocean is essentially unfilled accommodation space.
4 Rifted continental crust that underlies the Scotian Basin may have been “modified” locally by rift-related magmatic underplating and is “modified” locally by rift-related basaltic volcanics (Keen et al., 1994). The modified crust commonly has seismic velocities intermediate between those of continental and oceanic crust, and is commonly referred to as being “transitional” between continental and oceanic crust (Keen and Beaumont, 1990).
by a thick package of sedimentary rock similar to that of the U.S. Gulf Coast, a proven hydrocarbon province (e.g., Officer and Ewing, 1954). The first offshore exploration license was issued to Mobil Oil in 1959, and the first offshore well, Sable Island C-67, was drilled in 1967 by Mobil from a platform on Sable Island. Although this well confirmed the presence of a thick (~4.5 km) succession of predominantly siliciclastic sedimentary rock, it did not encounter any significant hydrocarbon-bearing intervals. The first significant gas and oil discoveries were made in 1969 at Onondaga E-84 and in 1971 at Sable Island E-48, respectively (Bell and Campbell, 1990).

Although oil is present locally in economic quantities offshore Nova Scotia (e.g., Cohasset and Panuke fields; LASMO, 1990), drilling results to date suggest that the Scotian Basin is largely gas-rich and oil-poor. In part, therefore, industry activity has been driven by the price of natural gas, not oil (Figure 2.3). The first wave of drilling activity, spurred on by the above mentioned discoveries, tailed off after 1973 when the Arab oil embargo forced western petroleum companies to shift exploration efforts to oil-rich basins (Paul Harvey, personal communication, 2002). Following a downturn in the late 1970s, a second wave of drilling was initiated when Mobil Oil discovered the giant Venture Field in 1978 under very favorable gas market conditions. This burst of activity was curtailed by a fall of gas prices in the mid-1980s. In the 1990s, a second wave of drilling activity started when several of the previously discovered oil and gas fields went into production under the Cohasset/Panuke and Sable Offshore Energy Projects (LASMO 1990; Sable Offshore Energy, 1996). Offshore Nova Scotia is currently experiencing a third wave of drilling activity as industry develops new fields and tests new shelf carbonate and siliciclastic slope turbidite plays (e.g., Deep Panuke and Annapolis wells).
As of January 2002, 176 wells have been drilled, 377, 299 km of 2-D seismic have been shot, and 23, 944 km$^2$ of 3-D seismic have been collected (Canada-Nova Scotia Offshore Petroleum Board website).

2.2 Basin physiography

In plan view, the Scotian Basin has an elongate oval shape that extends parallel to the modern coast between a basement high offshore of the U.S.-Canada border (the Yarmouth Arch) and a Late Jurassic-Early Cretaceous uplifted region southeast of Newfoundland (the Avalon Uplift; Figure 2.4). In dip cross-section, basin fill thickens southeastward (i.e., basinward) from a feather-edge to a zone of maximum thickness beneath the modern shelf margin, and then thins below the lower continental slope and merges with deposits of the Atlantic Ocean abyssal plain (Figure 2.5).

The Scotian Basin comprises several interconnected Mesozoic-Cenozoic depocenters or subbasins (Figure 2.4). Basin fill reaches an estimated maximum thickness of ~20 km in the Laurentian Subbasin (MacLean and Wade, 1992), the thickest sedimentary accumulation offshore Canada (Keen and Williams, 1990)$^5$. Subbasins are located outboard of the hinge zone, a series of normal faults and flexures in basement rock across which substantial thickening of the sedimentary fill occurs (Figures 2.4 and 2.5). Landward of the hinge zone, basin fill is generally thin (<4 km).

Basement rock underlying the Scotian Basin subbasins has never been drilled and in general cannot be imaged seismically because of the substantial thickness of the sedimentary cover. Where wells have penetrated the thin basin fill landward of the hinge

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$^5$ Other thick sedimentary accumulations, which likely exceed 14 km in thickness, include the Jean D'Arc Basin, offshore Newfoundland, and the Baffin Basin, offshore Baffin Island (Keen and Williams, 1990).
zone, basement consists of an offshore extension of continental igneous and metasedimentary rocks of the Cambrian-Ordovician Meguma Group (Pe-Piper and Loncarevic, 1989; Wade and MacLean, 1990). Basement seismic reflections in this region form a series of elongate, coast-parallel horst and grabens and half grabens interpreted to be Early Mesozoic rift basins (Welsink et al., 1989; Wade and MacLean, 1990). Although basement cannot be imaged seismically below the thick subbasins, the presence of salt diapirs suggests that they too generally overlie rifted continental crust.

To date, efforts to find oil and natural gas offshore Nova Scotia have focused on the Sable Subbasin, a thick (~18 km) and predominantly siliciclastic Mesozoic-Cenozoic depocenter located beneath Sable Island (Figure 2.4). As a result, the Sable Subbasin is the best understood of the Scotian Basin subbasins. The Sable Subbasin is separated to the north from the Abenaki Subbasin by a subtle basement high (the North Sable High; see Figure 2.5). To the northwest and west the hinge zone separates the Sable Subbasin from the Lahave Platform, a site of reduced subsidence and carbonate accumulation throughout much of the Mesozoic (Eliuk, 1978; Schalger, 1981). To the northeast, the Sable Subbasin thickens and becomes more carbonate rich before merging with the siliciclastic-rich Laurentian Subbasin (MacLean and Wade, 1992). The southeast boundary of the Sable Subbasin is the modern continental slope, a gently dipping (~1.4°) surface that separates basin fill from the Atlantic Ocean.

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6 The outermost, salt diapir-free region of the Scotian Basin likely overlies oceanic lithosphere (Wade and MacLean, 1990).
2.3 Tectonic evolution

During the Paleozoic, the eastern margin of North America was subjected to three convergent deformational events that accreted several allochthonous terranes onto the side of the continent, forming the Appalachian Mountains (Wilson, 1966). These deformational events, which occurred during the Ordovician, Silurian-Devonian, and Carboniferous-Permian, correspond to the Taconian, Acadian, and Alleghanian orogenies, respectively (Keen et al., 1990). Pangea was amalgamated during the last of these when Laurasia and Gondwana collided and sutured about the Appalachian-Mauretanide fold and thrust belt.

Migrating northward, Pangea began to rift in the Permian when the compressional stress regime associated with the Alleghanian orogeny relaxed and was replaced by a tensional regime. Rift systems in the North Sea and Tethys regions propagated southward and westward respectively, intersecting one another in the North Atlantic region. Between the mid-Triassic and the early-Jurassic, a series of rift basins developed on the eastern side of North America parallel to the Appalachian Mountains (Figure 2.6). Commonly, rift basins formed by reactivation of older, compressional Appalachian structures (Withjack et al., 1998). Graben and half-graben basins within the rift zone subsided and infilled with sediment as the continental crust thinned and underwent brittle extensional deformation. There is no current consensus as to whether rifting was active (i.e., it was instigated by a buoyant mantle plume) or passive (i.e., it was initiated by pre-existing horizontal tension in the lithosphere; Sonia Dehler, personal communication, 2004).
In the early-to mid-Jurassic, crust of central North America and West Africa separated when a linear seafloor-spreading ridge developed down the center of the rift system (Figure 2.6). This nascent spreading ridge was bracketed by transform faults south of Newfoundland and east of Florida (Withjack et al., 1998). The central North American rift-drift transition was characterized by widespread basaltic volcanism (Pe-Piper and Piper, 1999), thermal uplift and erosion (Ziegler, 1989), and a brief transition from a tensional to a compressional stress regime (Withjack et al., 1998). Following separation of central North America from West Africa, the spreading ridge “unzipped” and branched northward incrementally, with Newfoundland separating from Portugal in the Late Jurassic/Early Cretaceous, Labrador from Greenland in the early Paleocene, and Norway from Greenland in the mid to late Paleocene (Ziegler, 1989; Uchupi and Emery, 1991). Post-rift sediments began to accumulate on top of the rifted margin of North America, which appears to have started to subside during the early Jurassic as the lithosphere cooled and was loaded with sediment (Ryan and Zentilli, 1993). Through net progradation, these sediments eventually developed a large-scale (i.e., several hundred to thousands of meters relief) “shelf-slope-rise” clinoform morphology (e.g., Pirmez et al., 1998).

2.4 Stratigraphic evolution

Stratigraphic frameworks published for the Scotian Basin all recognize the same general succession of lithostratigraphic units outlined originally by McIver (1972), and

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7 Thermal subsidence of the oceanic lithosphere is reflected in the increase in water depth from the modern (hot) mid-oceanic spreading ridge towards the (cooler) continental margin (Keen and Williams, 1990)
subdivide the stratigraphy into syn- and post-rift units (Figures 2.7 and 2.8)\(^8\). Unlike western Canada, our understanding of the post-Paleozoic history of eastern Canada comes largely from study of subsurface offshore datasets like that of the Scotian Basin because few Mesozoic or Cenozoic strata crop out on the adjacent continent (Duk-Rodkin and Hughes, 1994; White et al., 2000; Stea and Pullen, 2001).

2.4.1 Syn-rift deposits

Halite and red-coloured continental deposits of the Argo and Eurydice formations were deposited in elongate half-graben and graben rift basins that formed between the Mid-Triassic and the Early Jurassic (Figure 2.9). Relatively little is known about these syn-rift deposits because they are deeply buried and are not traditional targets for petroleum exploration. The presence of thick (<2 km) syn-rift evaporites suggests that the climate was likely hot, arid and subtropical during rifting (Gradstein et al., 1990; Rees et al., 2000), and that rift basins were periodically connected with the Tethys Ocean to the east (Jansa et al., 1980; Holser et al., 1988). The Yarmouth Arch apparently limited southward extension of the main evaporite basin (Keen et al., 1990).

2.4.2 Post-rift deposits

Post-rift “passive margin” deposition started offshore Nova Scotia in the Early Jurassic following the transition from rifting to “drifting” (i.e., post-seafloor spreading). A prominent erosion surface, termed the break-up or post-rift unconformity, which

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\(^8\) Passive margin basins *sensu stricto* are “post-rift” features that develop following the transition from rifting to seafloor spreading (e.g., Bushby and Ingersoll, 1995). However, previous studies of the Scotian Basin typically include precursor “syn-rift” rift basin sediments as well as the “post-rift” passive margin sediments. This approach is followed here.
truncates syn-rift strata in proximal regions of the Scotian Basin, suggests that rift flank uplift occurred during the rift-drift transition (Wade and MacLean, 1990; Withjack et al., 1998). The break-up unconformity is onlapped by either dolomite of the Iroquois Formation or by Mohican Formation siliciclastics. These Lower to Middle Jurassic deposits reach a combined thickness of 4 km locally, and complete the infill of rift basins and overlap basement highs (Wade and MacLean, 1990). $^{40}$Ar/$^{39}$Ar radiogenic ages from the Mohican Formation are similar to those obtained from strata that crops out on the southern Nova Scotia mainland (ca. 250-350 Ma), suggesting that initial post-rift sediments were derived locally from uplifted rift flanks (Grist et al., 1992). Neither the breakup unconformity nor the Iroquois or Mohican formations have been drilled or imaged seismically basinward of the hinge zone in the Sable Subbasin (Wade and MacLean, 1990).

Strata of the Western Bank Group were deposited on the Iroquois and Mohican formations following establishment of normal marine conditions across the Scotian Basin (McIver, 1972). The West Bank Group comprises the Abenaki, Mohawk, Mic Mac and Verrill Canyon formations (Figures 2.7 and 2.10). These lithostratigraphic units were deposited contemporaneously in different parts of the Scotian Basin between the Middle and Upper Jurassic (McIver, 1972; Eliuk, 1978). The deepest wells in the Sable Subbasin encounter but do not fully penetrate the West Bank Group (e.g., Olympia A-12).

The Abenaki Formation consists of shallow-marine, oolite-rich limestone of the Scatarie and Baccaro members, lithistid sponge-rich limestone of the Artimon Member, and terrigenous shale of the Misaine Member (Eliuk, 1978; Eliuk and Levesque, 1989; Jansa et al., 1989; PanCanadian Energy, 2002; Weirzbicki et al., 2003, 2004). The
Abenaki Formation is best developed above the hinge zone along the western edge of the Sable Subbasin, where it locally reaches thicknesses of about 1.2 km. The top of the Abenaki Formation, which downlapped by Mesozoic siliciclastics and is locally karsted (Weirzbicki et al., 2004), has been interpreted to be a drowning unconformity (Schlager, 1981). Abenaki shelf-margin carbonates grade basinward into deep-water mudstones of the Verrill Canyon Formation.

The Mic Mac Formation is a predominantly siliciclastic unit deposited coevally with and adjacent to the Abenaki Formation (Figures 2.10 and 2.11). The Late Jurassic shelf margin near Sable Island consisted of Abenaki Formation carbonates in the east where terrigenous sediment input was low, and Mic Mac Formation siliciclastics in the west where terrigenous sediment input was high (Figure 2.10). The Mic Mac has been encountered but not fully penetrated in deeper wells just east of Sable Island. In this region, the Mic Mac and overlying Lower Missisauga formations form large-scale (i.e., about 1 second), southward-dipping seismic reflections that suggest shelf margin progradation occurred during Mic Mac deposition (Figure 2.12).9

The Nova Scotia Group, which comprises terrigenous clastics of the Missisauga and Logan Canyon formations, overlies the Western Bank Group in the Sable Subbasin (McIver, 1972). In seismic data, reflections associated with the Missisauga and Logan Canyon formations are generally parallel ("railroad track") and dip gently southwest; clinoform-shaped reflections and erosional truncation surfaces are typically absent,

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9 Because of their relief (i.e., hundreds of meters), these clinoform-shaped reflections most likely record outbuilding of the entire continental slope during deposition of the Mic Mac and Missisauga formations. Although deltas are believed to be the primary sediment delivery system to the continental shelf edge, they typically have clinoforms that are an order of magnitude smaller than continental slope clinoforms, and unlike slope clinoforms, are rarely associated with substantial turbidite fans (Porebski and Steel, 2003; Donovan, 2003). As such, the use of the term "delta" when describing large-scale clinoform reflections in the Sable Subbasin (e.g., "Sable Island delta" or "Sable Island delta complex") is somewhat misleading, and should be avoided.
although important exceptions exist (e.g., Figures 2.12 and 2.15). Lack of obvious onlap-offlap lapout geometries complicates subdivision of the Nova Scotia Group using standard Vail-type seismic stratigraphic techniques (Cloetingh et al., 1989).

The Missisauga Formation\(^{10}\) (Portlandian-Aptian) consists of fluvial to slope siliciclastics with minor carbonates that reach an estimated maximum thickness of \(\sim 3.5\) km below the modern shelf edge south of Sable Island (Figures 2.13 and 2.14). Net shelf-margin progradation during Missisauga deposition is inferred based on coarsening-upward grain size trends observed in well logs (e.g., MacLean and Wade, 1993) and large-scale (i.e., hundreds-of-meters plus relief) accretionary clinoform reflections observed in seismic data (e.g., Figures 2.12 and 2.15). \(^{40}\)Ar/\(^{39}\)Ar ages of K-feldspars from the Missisauga Formation suggest that sediment was derived from the Grenville Province of the Canadian Shield (Grist et al., 1992). This in turn suggests that much of the terrigenous sediment was supplied to the basin via an ancestral version of the modern St. Lawrence River, which, during the Lower Cretaceous, was likely a large, continent-scale river system that drained much of the interior of eastern Canada (Wade and MacLean, 1990; Grist et al., 1992).

Deposition of the Missisauga Formation in the Sable Subbasin is roughly coeval with break-up of Newfoundland from Europe, which uplifted offshore Newfoundland and proximal parts of the Laurentian Subbasin, generating the Avalon (angular) Unconformity (Jansa and Wade, 1975a,b; MacLean and Wade, 1992). In seismic data,

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the angularity of the discordance diminishes towards the southwest, and is no longer visible in lowermost Cretaceous strata in the Sable Subbasin (Wade and MacLean, 1990). Causal relationships between Newfoundland-Europe break-up and deposition of the Missisauga Formation in the Sable Subbasin, although hypothesized, have not been fully investigated. Answering this question, although important in understanding the origin of the Missisauga Formation offshore Nova Scotia, requires a basin-wide data base, and is therefore beyond the scope of this thesis.

In the central Sable Subbasin, the Missisauga overlies lithologically similar deposits of the Mic Mac Formation, whereas it downlaps a maximum flooding surface at the top of Abenaki carbonates along the western subbasin rim (Figure 2.15). Although the maximum flooding surface would be the most logical place to pick the base of the Missisauga, the maximum flooding surface is in fact difficult to correlate into the central subbasin using geophysical well logs or seismic data (cf. Welsink et al., 1989; MacLean and Wade, 1993). As a consequence, the base of the Missisauga is typically picked at the top of the Abenaki Formation along the western subbasin rim, and at a Kimmeridgian limestone in the central Sable Subbasin (the Venture limestone 9; e.g., MacLean and Wade, 1993). However, because the Venture limestone 9 does not generate a seismic reflection or well log marker outside of the Venture and West Venture gas fields, regional lithostratigraphic correlation of the base of the Missisauga is problematic. Attempts to identify an alternative base-Missisauga marker bed in this study have been unsuccessful.

The O Marker is the only prominent, regionally extensive reflection occurring in the Missisauga Formation (Figure 2.16). The O Marker reflection is generated by a mixed mudstone-sandstone-oolitic limestone unit at the base of the Upper Missisauga.
Although it is identifiable throughout the inner Sable Subbasin northwest of the Onondaga Field, the apparent absence of the O Marker in seismic and well data basinward (i.e., southeast) of Onondaga has proven to be a major impediment to correlating inner to outer shelf strata and beyond (cf. Figure 18 in Welsink et al., 1989; Wade, 1991a; MacLean and Wade, 1993).

Typically, the Missisauga Formation is subdivided into two or three members (Figure 2.7). The three-member framework, proposed by Wade and MacLean (1990) and elaborated upon by MacLean and Wade (1993), is similar to the two-member frameworks of Given (1977) and Welsink et al., (1989), but recognizes a third, older member in the central Sable Subbasin that is coeval with the terminal phases of Abenaki carbonate deposition. Although offering potentially better stratigraphic resolution, regional correlation of the top of the lowermost member of Wade and MacLean (1990) in both seismic and well log data is equivocal (cf. Figure 9 in Wade, 1991a; MacLean and Wade, 1993), which makes the three-member framework difficult to apply in practice.

Fluvial to slope siliciclastics of the Logan Canyon Formation (Barremian to Cenomanian) overlie the Missisauga throughout the Sable Subbasin (Figure 2.17). The Logan Canyon consists of two mudstone-rich units (the Naskapi and Sable members) and two sandstone-rich units (the Cree and Marmora members; Wade, 1991b; MacLean and Wade, 1993). The formation displays a net upward-fining trend, and is generally interpreted to have been deposited during net long-term transgression that culminated in deposition of mudstone and chalk during the Late Cretaceous global sea level maximum (Grant et al., 1986; see below). However, seismic data from the western Sable Subbasin suggest that shelf margin progradation occurred periodically during deposition of the
Logan Canyon Formation (e.g., note that the sharp-based Cree Member in Figure 2.15 is associated with renewed shelf-margin progradation).

Although it does not generate a strong seismic reflection, the Missisauga-Logan Canyon contact is the most prominent and regionally extensive well-log marker associated with the Missisauga Formation. However, it has a variable expression in different regions of the Sable Subbasin (Figure 2.18). In proximal regions (e.g., Panuke, Thebaud and Venture fields), Missisauga sandstone and mudstone with blocky to serrated gamma ray log profiles “grade” upward over several tens of meters into a monotonous succession of offshore mudstone (Naskapi Member)\(^\text{11}\). In more basinward regions of the subbasin (e.g., Alma and Glenelg fields), however, the contact is generally relatively abrupt and easier to identify\(^\text{12}\). The “gradational” nature of the contact in proximal regions of the subbasin makes it difficult to assign a single surface to the contact across the Sable Subbasin.

The Gully Group (Cenomanian to Pliocene) overlies the Nova Scotia Group throughout the Sable Subbasin. Stratigraphically upward, the Gully Group consists of Dawson Canyon, Wyandot, and Banquereau formations.

The Dawson Canyon Formation (Cenomanian to Santonian) is generally considered to be a transgressive unit deposited in association with the aforementioned Late Cretaceous eustatic rise (Gradstein et al., 1990). The Dawson Canyon Formation gradationally overlies the Logan Canyon Formation, and consists predominantly of mudstone. It is typically thin (~100 m) in the Sable Subbasin, and thickens

\(^{11}\) Although gradational in appearance, several fluvially incised unconformities (sequence boundaries) are inferred to exist within the transition – see later in this chapter, and also Chapter 3.

\(^{12}\) Locally, however, the Missisauga-Logan Canyon contact is difficult to identify without supporting biostratigraphic data, especially in the most distal wells that sample the Early Cretaceous paleoshelf-slope transition zone (e.g., the Chebucto K-90 well).
northeastward to a maximum of ~500 m in the South Whale Subbasin (Wade and MacLean, 1990). One thin limestone unit within Dawson Canyon Formation, the Petrel Member, generates a strong seismic reflection throughout the Sable Subbasin.

The Wyandot Formation (Santonian-Paleocene) is a widespread coccolith-dominated limestone (chalk) deposited in association with Late Cretaceous maximum flooding. On average it is ~150 m thick in the Sable Subbasin, although it varies from 50 to 400 m in the Scotian Basin (Wade and MacLean, 1990; MacRae, 2001b). The Wyandot generates a strong regional seismic reflection, below which there is commonly a considerable decrease in the signal-to-noise ratio.

In contrast to sub-Wyandot deposits, which generally form “railroad track” seismic reflections, deposits above the Wyandot form large-scale (i.e., hundreds of meters thick) clinoform-shaped reflections in seismic data that exhibit multiple cycles of onlap and offlap (Wade et al., 1995; Kidston et al., 2002). Despite this, pre-Quaternary deposits above the Wyandot are typically grouped into a single unit called the Banquereau Formation. The Banquereau Formation is composed predominantly of mudstone, although topset beds are locally sandstone-rich (MacRae, 2001b). It is typically ~1 km thick below the modern continental shelf, but thickens considerably below the continental slope.

2.5 Petroleum geology

Although minor amounts of gas are trapped locally within the Wyandot, Dawson Canyon and Abenaki formations (e.g., Primrose, West Sable and Deep Panuke wells) and in slope sandstones of the Missisaugua Formation (e.g., Annapolis well), the most
important hydrocarbon reservoirs in the Scotian Basin are fluvial to shelf-margin Upper Jurassic-Lower Cretaceous sandstones of the Mic Mac, Missisauga, and Logan Canyon formations, which contain >95% of all discovered gas offshore Nova Scotia (Grant et al., 1986; Canada-Nova Scotia Offshore Petroleum Board, 2000). Of these, the Missisauga Formation contains most of the currently discovered gas reserves (~192 x 10^6 m^3, or ~75%; Canada-Nova Scotia Offshore Petroleum Board, 2000). Hydrocarbons were likely generated from Type III kerogen disseminated in marine shale of the Verrill Canyon Formation\textsuperscript{13}, (Powell, 1982; Grant et al., 1986; Bell and Campbell, 1990), which may explain the apparent gas-rich/oil-poor nature of the Scotian Basin. Marine shales form the top seal for all currently discovered commercial hydrocarbon accumulations. Of note are mudstones of the Naskapi Member of the Logan Canyon Formation, which seal gas-rich Upper Missisauga sandstone reservoirs in the Alma, Panuke, North Triumph, and Glenelg fields. The most important traps are rollover “anticlines” (domes) formed in association with “down-to-the-basin” listric growth-faults (e.g., Thebaud, Venture, Glenelg, Alma fields). Other important trap types include compactional drapes over antecedent topography (e.g., Panuke, Cohasset fields) and salt-diapir related traps (e.g., West Sable, Slope Diapir Province; Wade et al., 1989; Kidston et al., 2002; Shimeld, 2004).

\textsuperscript{13} Core data suggest that marine condensed sections associated with maximum flooding surfaces are commonly rich in disseminated organic matter (e.g., in the Alma Field)
Figure 2.1  Mesozoic-Cenozoic passive margin basins offshore eastern North America (modified from Hutchinson and Klitgord, 1988). These basins formed during the breakup of Pangea and the subsequent opening of the Atlantic Ocean.
Figure 2.2  Schematic diagram showing the key features of the Scotian Basin, the passive margin basin offshore Nova Scotia.
Figure 2.3  Exploration history offshore Nova Scotia (in part from Mary Jean Verrall, personal communication and Paul Harvey, personal communication). Because the Scotian Basin, to date, has proven to be gas-rich and oil-poor, petroleum exploration offshore Nova Scotia has been driven, at least in part, by the price of natural gas.
Figure 2.4  Isopach map, Scotian Basin (in part estimated). Contours are in kilometers (modified from MacLean and Wade, 1992).
Figure 2.5  Interpreted seismic dip cross section, Sable Subbasin, offshore Nova Scotia (modified from Wade and MacLean, 1990).
Figure 2.6 Schematic diagram depicting the rifting and breakup of Pangea and subsequent opening of the Atlantic Ocean (modified from Withjack et al., 1998).
Figure 2.7  Lithostratigraphic frameworks published for the Sable Subbasin, offshore Nova Scotia. Note that the original framework by McIver (1972) is not included because, at the time, lithostratigraphic data were constrained by relatively few biostratigraphic data.
The image is a geological time diagram showing the stratigraphy of various formations over different time periods. The diagram includes key events and layers represented by different symbols:

- **Evaporite**
- **Carbonate**
- **Terrigenous Sandstone**
- **Terrigenous Mudstone**

The timeline is divided into different geological eras and time periods, with key stratigraphic units and events marked along the vertical axis. The periods marked include:

- **Triassic**
  - Late Triassic
  - Early Triassic
  - Norian
  - Carnian
  - Ladinian
  - Antignan

- **Jurassic**
  - Late Jurassic
  - Middle Jurassic
  - Early Jurassic

- **Cretaceous**
  - Late Cretaceous
  - Early Cretaceous

- **Tertiary**
  - Pliocene
  - Miocene
  - Oligocene
  - Eocene
  - Paleocene

- **Recent**

The diagram also includes specific stratigraphic units and formations identified by their names, such as the "Norka Fm," "Terrigenous Fm," and "Evaporite Fm." Each unit is color-coded and labeled to indicate its position and characteristics within the stratigraphic column.
Figure 2.8  Schematic section across the Sable Subbasin showing major stratigraphic and structural relationships. Vertical exaggeration 10:1 (modified from Grant et al., 1986).
Figure 2.9 Distribution of Late Triassic to Early Jurassic syn-rift salt in relation to Triassic paleogeography (modified from Holser et al., 1988).
Figure 2.10  Late Jurassic paleogeography, Sable Subbasin (modified from Wade and MacLean, 1990). Note that the shelf edge during this time was defined by terrigenous siliciclastics near Sable Island, and by carbonates west of Sable Island.
NEWFOUNDLAND

sediment transport

200 km

Erosional limit of Jurassic

Oxfordian paleoshelf edge
Kimmeridgian paleoshelf edge
Tithonian paleoshelf edge

progradational
siliciclastic shelf margin
(high terrigenous sediment input)

aggradational
carbonate shelf margin
(low terrigenous sediment input)

Abenaki Fm
mixed shale, limestone facies

Abenaki Fm
limestone facies

Verrill Canyon Fm
basinal shale facies

Mic Mac & Lower Missisauga
fluvial to shallow marine clastics, minor carbonates

Mic Mac & Mohawk
fluvial to shallow margin clastics, higher % carbonates
Figure 2.11  Schematic diagram illustrating interfingering of Upper Jurassic siliciclastic and carbonate rocks near Sable Island (modified from Wade and MacLean, 1990).
Vertical exaggeration 10:1

1. No. 3 limestone
2. No. 6 limestone
3. No. 9 limestone (top of Mic Mac Fm)
4. Y limestone
5. Arcadia limestone
6. Cirtalta limestone
7. Penoiscot limestone
Figure 2.12  Uninterpreted and interpreted dip-oriented seismic cross-sections, Sable Subbasin (PRX-GSI-83-1042 seismic line). Note accretionary Mic Mac and Lower Missisauge slope clinoforms. Well-to-seismic ties are the same as those outlined in MacLean and Wade (1993) and Mobil Oil Canada (1997b).
Figure 2.13  Isopach map, Missisauga Formation, offshore Nova Scotia (modified from Wade, 1991a).
Figure 2.14  Percentage of sandstone and siltstone, Missisaugua Formation, offshore Nova Scotia (modified from Wade, 1991a).
Figure 2.15  Uninterpreted and interpreted dip-oriented seismic cross-sections from the western rim of the Sable Subbasin that clearly show the progradational nature (upward and basinward shelf-margin trajectory) of the Missisaugan Formation. Relief from the clinoform break-point to toe is approximately 400 m.
Figure 2.16   O Marker structure (time), Sable Subbasin, reconstructed from 2-D seismic data (see Figure 1.2d for location of seismic lines). Note how the O Marker dips and becomes increasingly hard to identify toward the southeast.
Figure 2.17  Isopach map, Logan Canyon Formation, offshore Nova Scotia (modified from Wade, 1991b).
Figure 2.18  Comparison of the Missisauga-Naskapi contact in proximal versus distal wells, Sable Subbasin. Note how the contact appears gradational and has an upward-fining motif in proximal wells, whereas it is typically sharp and underlain by stacked, upward-coarsening units in distal wells.
Proximal  
Panuke B90  
GR  
2200 m -  
upward-fining  
(blocky to  
serrated) log  
motif  
2300 m -  
Naskapi  
Upper  
Mississauga  
3400 m -  
Distal  
Glenelg N49  
GR  
3300 m -  
stacked,  
coarsening-  
upward  
units
Chapter 3. Sedimentology, 3-D seismic geomorphology, and sequence stratigraphy of a thick and laterally extensive fluvial-marine transition (Hauterivian-Aptian), Missisauga Formation, offshore Nova Scotia, Canada

3.1 Introduction

Stratigraphic successions that pass upward from fluvial into marine deposits, here called fluvial-marine transitions, form during transgression following an episode of forced or normal regression. Over the past half-century, they have been the subject of much geological research (Fisk, 1944; Suter and Berryhill, 1985; Posamentier and Vail, 1988; Penland et al., 1988; Dalrymple et al., 1992; Muto and Steel, 1992; Wood et al., 1993; Dalrymple et al., 1994; Leeder and Stewart, 1996; Blum and Törnqvist, 2000; Swenson et al., 2000; Posamentier, 2001; Heller et al., 2001; Cattaneo and Steel, 2002), not only because they commonly host economic quantities of oil and natural gas, but because they can be used to estimate long-term rates of coastal land loss (e.g., Milliman and Haq, 1996), reconstruct paleogeography, and unravel the history of eustatic, tectonic, and climate change. With the recent attention on offshore hydrocarbon exploration in deep-water areas basinward of the shelf edge (e.g., Weimer et al., 2000), fluvial-marine transitions have come under increased scrutiny because, when incised, they commonly correlate downdip with sand-bodies on the shelf edge, slope and basin-floor. As such, geologists are currently striving to understand how the sedimentologic and stratigraphic characteristics of incised fluvial-marine transitions on the shelf can be used to better predict sand-body distribution at the shelf edge and basinward (e.g., Reading and Richards, 1994; Porebski and Steel, 2003).
Sheet-like fluvial-marine transitions have seldom been reported on continental shelves (Olsen et al., 1995; Holbrook, 1996; Pulham et al., 1997; Posamentier, 2001), and as a result, how (and if) they feed sediment downdip to the shelf edge, slope and basin-floor is not well understood. Using core and well log data from the western edge of the Sable Subbasin, offshore Nova Scotia, coupled with a 3-D seismic survey from the Panuke Field, this study identifies and describes a thick, laterally extensive fluvial-marine transition in the Lower Cretaceous Missisauga Formation, and uses regional 2-D seismic lines to correlate it downdip to the undrilled shelf-edge and slope. Implications for reservoir distribution within the Panuke Field are discussed, and the potential of the fluvial system as a deep-water feeder system is evaluated.

3.2 Geological setting

The Sable Subbasin is one of several interconnected Mesozoic-Cenozoic depocenters that make up the Scotia Basin, offshore Nova Scotia (Figure 3.1). The center of the subbasin is underlain by unstable syn-rift salt, and contains numerous growth faults and salt diapirs (Figure 3.2). In contrast, the western edge of the subbasin, where the Panuke Field is situated, is underlain by stable Jurassic carbonate rocks and lacks such features. Siliciclastic strata of the Missisauga Formation thin significantly when correlated onto the western edge of the subbasin (MacLean and Wade, 1993), suggesting that the western subbasin edge was relatively low accommodation setting during Missisauga deposition. Terrigenous clastic sediments are interpreted to have been fed southward into the subbasin by the paleo-St. Lawrence River, a sediment-charged, continent-scale fluvial system that drained much of Eastern Canada (Wade and MacLean,
1990; Grist et al., 1992). During deposition of the Missisauga, Nova Scotia was located approximately 30°N of the equator (Irving et al., 1993), the receiving basin (i.e., the Atlantic Ocean) was ~1000 km wide (Ziegler, 1989), and climate was warm and temperate, having become colder, wetter, and less seasonal following Pangean rifting in the Early Mesozoic (Rees et al., 2000).

3.3 Lithostratigraphy

In the Sable Subbasin, the Missisauga Formation forms a southeastward-thickening wedge of fluvial and shallow-marine siliciclastic rocks with minor carbonate rocks. It reaches a maximum drilled thickness of ~2100 m in the central Sable Subbasin, and thins to ~950 m in the Panuke Field (MacLean and Wade, 1993). The Missisauga is underlain by the lithologically similar Mic Mac Formation, except along the western subbasin edge where it is underlain by Jurassic carbonates of the Abenaki Formation (Figure 3.3). The Missisauga Formation is overlain throughout the Sable Subbasin by offshore marine shale of the Naskapi Member of the Logan Canyon Formation.

Internally, the Missisauga is divided into Upper, Middle and Lower members (Wade and MacLean, 1990; MacLean and Wade, 1993) or alternatively Upper and Lower members (Welsink et al., 1989). The Upper and Lower members (sensu Welsink et al., 1989) are separated by the O Marker, a mixed carbonate-siliciclastic unit that generates a strong seismic reflection in the proximal subbasin (e.g., northwest of the Onondaga Field). In the distal Sable Subbasin (i.e., southeast of Onondaga), the O Marker becomes difficult to identify in both seismic and well log data (cf. Welsink et al., 1989) due to
growth faults, poor quality seismic data below the modern shelf margin, and facies change and/or erosion.

3.4 Panuke Field history and reservoir stratigraphy

The Panuke Field discovery well, Panuke B-90, was drilled in 1986 to test for the presence of hydrocarbons in a drape structure formed by differential compaction of Lower Cretaceous clastics over underlying Abenaki carbonates (LASMO, 1990; Canada-Nova Scotia Offshore Petroleum Board, 2000). The B-90 well penetrated five condensate-bearing sandstones in the top ~40 m of the Upper Missisauga (Figure 3.4). The field was subsequently delineated in 1987 with a second vertical well, Panuke F99, and four directionally drilled development wells, Panuke J-99 PP1 to PP4, were drilled between 1991 and 1992. Original oil in place was estimated to be 6.676 m$^3$ x 10$^6$ (Canada Nova Scotia Offshore Petroleum Board, 2000). Production began in 1992, and proceeded in two separate phases. During phase one, the two main reservoirs, the P2 and P3 sandstones, were perforated and produced as a co-mingled zone under natural flow. Pressure data collected during this phase suggested that 75% of the hydrocarbons were coming from the P2 sandstone and the remaining 25% from the P3 sandstone (Encana, unpublished data, 2002). Primary production was suspended in 1995. In 1997, a waterflood program was started. During this phase, the P2 and P3 sandstones, along with the P4 sandstone and the C9 sandstone (C9 is the basal sandstone in the Creek Member of the Logan Canyon Formation; LASMO, 1990), were perforated and produced as a co-mingled zone under pump flow. However, production ceased in 1999 because of high
water production and low hydrocarbon volumes. In total, 38.5% of the original oil in place, or $2.2568 \times 10^6$ (16.155 MMbbls), was recovered from the Panuke Field.

3.5 Dataset and methodology

This study integrates 8 cores (~320 m) and geophysical well log data from 20 wells in the western Sable Subbasin with a 3-D seismic survey shot over the Panuke Field and regional 2-D seismic lines (Figure 3.2). Cores were described in 2.5 cm detail, noting sedimentary textures, physical and biogenic sedimentary structures, macrofossils, and macroscopic diagenetic features. These data were used to calibrate well logs, which were then tied to the 3-D seismic data using synthetic traces generated from sonic logs, or a combination of sonic and density logs when both were available (Figure 3.5).

Subsurface geomorphology, which is the description and interpretation of depositional features observed in 3-D seismic plan view, was performed using 3-D seismic horizon slices flattened to the O Marker. A flooding surface near the base of the Naskapi Formation was used as a stratigraphic datum for well log cross-sections. Lithostratigraphic and seismic stratigraphic picks used in this study are the same as MacLean and Wade (1993) and LASMO (1990), except for the top of the Missisauga, which, for convenience, was picked at an easily correlatable surface at the top of the main reservoir, the P2 sandstone (Figure 3.4).

3.6 Facies

The ten facies identified in core data (Table 3.1) are described below.
Facies 1: *Upward-fining, high-angle (>15°) cross-stratified coarse to medium sandstone*

Facies 1 is composed of moderately well to well-sorted, brown sandstone (Figure 3.6). This sandstone is usually coarse to medium grained, although a few beds of very fine sandstone are present. Beds are typically thick (10-100 cm thick) and are high-angle (>15°) cross-stratified or planar laminated. Beds are organized into sharp-based, upward-fining units that are several meters thick (maximum ~8 m). Mud intraclasts and coal fragments are common at the base of the upward-fining units. No trace fossils or shells were observed. Mudstone interbeds are rare and unbioturbated.

*Interpretation: Braided fluvial channel fills*

Facies 1 is interpreted to be a fluvial channel-fill deposit. Large-scale high-angle cross-stratification likely formed by the downstream migration and aggradation of dunes under unidirectional flow (Southard and Boguchwal, 1990; Ashley, 1990; Leclair and Bridge, 2001). Planar-laminated sandstone beds are interpreted to have formed by aggradation of millimeter-high, low-relief bed waves under upper-flow-regime plane bed conditions (Jopling, 1964; Bridge and Best, 1988; Paola et al., 1989; Best and Bridge, 1992). Based on the thickness of cross-beds and fining-upward units, flow depths were likely on the order of 7-10 m deep (see Leclair and Bridge, 2001; Bridge and Tye, 2000). A braided channel pattern is inferred based on the predominant medium to coarse sandstone sediment caliber, general lack of cohesive bank mudstone, and the presence of a braid-bar feature interpreted from 3-D seismic plan view (see below). The sharp-based, upward-fining units indicate decreasing depositional energy upwards, and are interpreted to have formed by downstream building of braid bars into channel confluences, or
alternatively, if the braided fluvial system was slightly sinuous, by the building of point bars into downstream bends (Shelton and Noble, 1974; Bridge, 2003).

Table 3.1 Facies descriptions and interpretations, Panuke Field region

<table>
<thead>
<tr>
<th>Facies</th>
<th>Texture</th>
<th>Physical sedimentary structures</th>
<th>Biogenic features</th>
<th>Diagenetic features</th>
<th>Gamma ray log character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>very fine to coarse sandstone</td>
<td>dune cross-stratification (max. 10m); planar lamination; mud rip-ups</td>
<td>coal chunks common; no bioturbation or shells</td>
<td>rare dm-scale patches of carbonate cement</td>
<td>sharp-based and blocky to upward-fining</td>
<td>braided fluvial channel deposits</td>
</tr>
<tr>
<td>2</td>
<td>same as Facies 1; also wispy mud laminae on dune foresets; rare double mud drapes</td>
<td>same as Facies 1</td>
<td>Rare Skolithos and escape traces; coal chunks common</td>
<td>same as Facies 1</td>
<td>blocky to slightly upward-fining; always grades up from Facies 1</td>
<td>tidally-influenced braided fluvial channel deposits</td>
</tr>
<tr>
<td>3</td>
<td>mudstone with thin siltstone beds and laminae</td>
<td>silstone beds are typically normally graded, and are commonly small-scale wave ripple cross-stratified, wavy parallel laminated, or flat parallel laminated</td>
<td>bioturbation is typically absent, but locally intense; trace fossils include small Planolites, Teichichius, Atrichosoma, Zoophycos, ?Cylindrichnus and Rosella</td>
<td>thin siderite bands and nodules are common</td>
<td>exhibits both coarsening and fining upward trends</td>
<td>lagoon deposits</td>
</tr>
<tr>
<td>4</td>
<td>mudstone with thin fine sandstone beds and laminae</td>
<td>sandstone laminae are centripetal, waxy or plaited shaped; internally, they are planar laminated or high-angle (&gt;15 degrees) current and small wave ripple cross-laminated; rare small rotational slumps and microfaults; rare dm-scale rhythmic “overprint”; rare synaeresis cracks</td>
<td>bioturbation is typically absent or low, but locally intense. Trace fossils include small Planolites, Arenicolites, Teichichius, Chondrites, Diplocraterion, ?Skolithos, ?Thalassinoides, and ?Rosselia, rare oyster shells</td>
<td>serrated</td>
<td>serrated</td>
<td>tidal flat deposits</td>
</tr>
<tr>
<td>5</td>
<td>very fine to fine sandstone</td>
<td>current ripple cross-stratification; dune cross-stratification (max. 60cm); planar lamination; rare bipolar cross-stratification; mud wisp to thin layers common</td>
<td>rare roots; rare Ophiomorpha and Skolithos burrows, small Planolites burrows (in mudstone laminae), and escape traces</td>
<td>disseminated mm-scale organic flecks abundant; rare Ophiomorpha in sandstone and small Planolites in mudstone laminae; rare oyster shells</td>
<td>sharp-based and blocky to upward-fining</td>
<td>small tidal channel deposits</td>
</tr>
<tr>
<td>6</td>
<td>very fine to fine sandstone</td>
<td>current ripple, small wave ripple, and dune cross-stratification; mud rip-ups present</td>
<td>disseminated mm-scale organic flecks abundant; rare Ophiomorpha in sandstone and small Planolites in mudstone laminae; rare oyster shells</td>
<td>disseminated mm-scale patches of carbonate cement</td>
<td>grainwaxly based and coarsening upwards</td>
<td>bayhead delta barform deposits</td>
</tr>
<tr>
<td>No.</td>
<td>Facies Description</td>
<td>Characteristics</td>
<td>Sedimentary Structure</td>
<td>Comment</td>
<td></td>
<td></td>
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<tr>
<td>7</td>
<td>poorly sorted sandstone with many isolated, white quartz sand grains and granules (&quot;paint-speckles&quot;)</td>
<td>oblitermated by bioturbation</td>
<td>intensely bioturbated; unlined <em>Thalassinoides</em> burrows (and rarely large <em>Teichichnus</em> burrows) overlay from lower contact; trace fossils include <em>Ophiomorphia</em>, <em>Palaeophycus</em>, <em>?Cylindrichnus</em>, <em>Teichichnus</em>, and <em>Chondrites</em>; oyster shell fragments very abundant; other shell fragments ( gastropod, scaphopod) common</td>
<td>cm-scale siderite patches common; pervasive carbonate cementation; pebbles occasionally have &quot;diagenetic&quot; rims and are rarely coated with carbonate; occasionally glassy rich</td>
<td>sharp based, thin blocky units; &lt;2 m thick; commonly overlies a fine-grained burrowed lag deposits</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>very fine to medium sandstone</td>
<td>typically hard to see, but includes small-scale wave ripple cross-stratification, high-angle, decimeter-scale wave cross-stratification and hummocky cross-stratification</td>
<td>moderately to intensely bioturbated; trace fossils include <em>Ophiomorphia</em>, <em>Cylindrichnus</em>, <em>?Rostelia</em>, <em>Chondrites (in the Roseltia)</em>, <em>?Teichichnus</em></td>
<td>cm-scale patches of siderite cement; m-scale patches of carbonate cement; trace fossil linings often oxidized</td>
<td>sharp based and blocky to coarsening upward</td>
<td>transgressive shallow marine sandstone sheet</td>
</tr>
<tr>
<td>9</td>
<td>mudstone with thin silty layers and very fine sandstone beds and lamination</td>
<td>hummocky cross-stratification; small- to medium-scale wave ripple cross-stratification</td>
<td>low to moderately bioturbated; trace fossils include <em>Planolites</em>, <em>Teichichnus</em>, <em>Palaeophycus</em>, <em>Terebellina</em>, <em>Chondrites</em>, <em>Cylindrichnus</em>, <em>?Australosoma</em>, <em>Ophiomorphia</em>, <em>?Rostelia</em></td>
<td>rare small siderite nodules</td>
<td>coarsening-upwards</td>
<td>offshore storm-dominated shelf deposits close to base of storm weather wave base</td>
</tr>
<tr>
<td>10</td>
<td>very fine sandstone; some mudstone interbeds</td>
<td>amalgamated hummocky cross-stratification; small- to medium-scale wave ripple cross-stratification</td>
<td>rare <em>Ophiomorphia</em> burrows</td>
<td>coarsening-upwards</td>
<td>storm-dominated lower shoreface deposits</td>
<td></td>
</tr>
</tbody>
</table>

**Facies 2: Upward-fining, high-angle (>15°) cross-stratified coarse to medium sandstone with mud drapes**

Facies 2 is similar to Facies 1 in terms of texture and sedimentary structures. However, double mud-drapes and rare *Skolithos* and escape traces are present, and millimeter-thick wispy mudstone veneers on cross-beds are common (Figure 3.7). Facies 2 always gradationally overlies Facies 1.
**Interpretation:** *Tidally influenced braided fluvial deposits*

Because it gradationally overlies braided fluvial deposits with similar characteristics (Facies 1), Facies 2 is also interpreted to be braided fluvial channel fill. However, the presence of double mud-drapes and *Skolithos* burrows suggests that the depositional environment was both tidally influenced and brackish during deposition (cf. Nio and Yang, 1991; Pemberton *et al.*, 2002). As such, Facies 2 is interpreted to have been deposited in brackish, tidally influenced braided fluvial channels.

**Facies 3: Mudstone with thin siltstone laminae and oyster shells**

Facies 3 comprises mudstone with common thin (<5 cm) siltstone beds and laminae (Figures 3.8a to 3.8c). Sandstone interbeds thicker than several centimeters are generally absent. Siltstone beds are either normally graded, wavy to planar laminated and normally graded, or low-angle (<10°) cross-stratified (Figures 3.8a and 3.8b). Commonly, siltstone laminae pinch and swell across the core and have slightly loaded basal contacts. Oyster shells are locally abundant (Figure 3.8c), as are swelling clays and siderite nodules and bands. Bioturbation is generally absent, but is locally intense. Trace fossils include small *Planolites*, *Teichichnus*, *Asterosoma*, *Zoophycos*, *?Cylindrichnus* and *Rosselia*. Facies 3 commonly grades upwards into Facies 4 or 6, or is erosionally overlain by Facies 7.

**Interpretation: Lagoonal deposits**

Facies 3 is interpreted to be a lagoonal deposit. Normally graded siltstone laminae are interpreted to have been deposited from suspension, possibly during storm-
related barrier-washover and bottom agitation, or, alternatively, during flood-related fluvial inflow into the lagoon (e.g., Nemec, 1995). Episodic, intense bioturbation suggests that the environment was periodically less ecologically stressed, as would be expected in a lagoonal environment subject to temporal and spatial variations in salinity, turbidity, temperature, nutrient supply, etc. (e.g., Ward and Ashley, 1989).

Apparently inconsistent with a lagoonal interpretation is the presence of rare Aterosoma, Zoophycos and Rosselia burrows. Although previously reported in lagoon-type deposits (e.g., Murakoshi and Masuda, 1991; Pemberton et al., 2002), these traces are more commonly associated with fully marine deposits (Pemberton et al., 2002). However, it seems unlikely that Facies 3 is an open marine deposit, given the abundance of oyster shells (oysters are generally most prolific in ecologically stressed lagoon-type depositional environments; see Merill et al., 1965; Donaldson et al., 1970; Israel et al., 1987; van Heerdon and Roberts, 1988; Pemberton et al., 2002). Also, the general absence of cross-stratification formed by large waves (hummocky cross-stratification; see Southard et al., 1990; Amott and Southard, 1990; Dumas, 2004) and the common upward gradation into lenticular-bedded mudstone interpreted to be tidal flat deposits (Facies 4) differentiate Facies 3 from mudstone interpreted to have been deposited in a storm-dominated, open marine environment (Facies 9). The presence of Aterosoma, Zoophycos and Rosselia burrows in Facies 3, therefore, suggests a relatively open connection between the lagoon and open marine basin during deposition as opposed to the existence of unrestricted, fully marine conditions.
**Facies 4: Mudstone with pinstripe, lenticular and wavy sandstone laminae**

Facies 4 is composed of mudstone with thin fine sandstone beds and laminae (Figures 3.9a to 3.9d). Sandstone laminae (<1 cm thick) are lenticular (pod-shaped), wavy (undulating top and bottom contacts), or pinstripe shaped (mm-thick, flat, and discontinuous across the core; Figure 3.9a). Internally, sandstone laminae are either flat-parallel laminated, wavy-parallel laminated, or are high-angle (>15°) cross-stratified. In cross-section parallel to maximum foreset dip (i.e., parallel to flow), high-angle cross-sets either have scoop-shaped bases and are laterally discontinuous over several centimeters, or have flat bases and are laterally continuous across the core. Synaeresis cracks (Figure 3.9d), small-scale concave-up normal faults (Figure 3.9c), and microfaults are present locally. Decimeter-thick, rhythmically interstratified mudstone and fine sandstone also occur rarely (Figure 3.9b). Coal fragments and flakes are common. Bioturbation is generally low, but locally intense. Trace fossils include small *Planolites*, *Arenicolites*, *Teichichnus*, *Chondrites*, *Diplocraterion*, *?Skolithos*, *?Thalassinoides*, and *?Rosselia*. Facies 4 commonly overlies Facies 3, 7, or 6.

**Interpretation: Tidal flat deposits**

Strata of Facies 4 are interpreted to be tidal flat deposits. Small-scale, scoop-based and flat-based cross-sets are interpreted to have been deposited by wave- and current-formed ripples, respectively (e.g., Boersma, 1970; de Raaf, 1977). The occurrence of 1) a low diversity of trace fossils, 2) the admixture of vertical and horizontal burrows (a mixed *Cruziana*/*Skolithos* assemblage), 3) diminutive burrows (e.g., *Planolites*), and 4) synaeresis cracks suggest that the environment was most likely
brackish during deposition (Pemberton et al., 2002; Plummer and Gostin, 1981). Abundant coal fragments and carbonaceous flakes suggest deposition close to a terrestrial organic source. The heterolithic nature of Facies 4 indicates that episodes of mud deposition from suspension alternated with sand bedload transport by small waves and/or weak unidirectional flows, as would be expected to occur on sheltered tidal flats in a back-barrier environment (Postma, 1961; Reineck and Wunderlich, 1968; Amos and Collins, 1978; Dingler and Clifton, 1984). Furthermore, the lenticular, wavy, and pinstriped sandstone laminae, although not unique to tidal flats (e.g., Coleman and Gagliano, 1965), are commonly observed in tidal flat deposits (Evans, 1965; Reineck and Wunderlich, 1968; Weimer et al., 1982; Ginsburg, 1975; Klein, 1976; Amos, 1995; Gingras et al., 1999).

**Facies 5: Upward-fining, high-angle (>15°) cross-stratified fine sandstone**

Facies 5 consists of planar laminated and small- (<5 cm) to large-scale (5-20 cm) high-angle (>15°) cross-stratified fine to very fine sandstone (Figures 3.10a and 3.10b). Bidirectional cross-stratification is present, but rare. Millimeter-thick mudstone laminae are common, as are mudstone veneers on cross-strata. Trace fossils are rare, and include *Skolithos, Ophiomorpha*, small *Planolites* and escape traces. Beds are organized into sharp-based, upward-fining to ungraded units that are several tens to a maximum of 300 cm thick (Figure 3.10a). Unlined, passively filled *Thalassinoides* burrows commonly subtend from the base of the units (Figure 3.10b). Roots, carbonaceous mudstone, and a thin cm-thick coal bed occur at the top of one of the sharp-based units (Figure 3.10a). Facies 5 typically erosively overlies Facies 3, and less commonly, Facies 4.
Interpretation: Tidal channel deposits

Facies 5 is interpreted to be tidal channel deposits. Small- and large-scale, high-angle cross-sets are interpreted to have formed by migrating current ripples and dunes under unidirectional flow conditions (Southard and Boguchwal, 1990). The thinness of dune cross-sets (maximum ~20 cm) and upward-fining units (maximum ~3 m) suggests that flows were at most several meters deep (cf. Leclair and Bridge, 2001; Bridge and Tye, 2000). Roots at the top of one of the Facies 5 sand-bodies indicate subaerial exposure. On the other hand, unlined *Thalassinoides* burrows that subextend from the base of the upward-fining units suggest exhumation of firm mud by subaqueous tidal-channel scour (e.g., Pemberton et al., 1985; Gingras et al., 2000). Double mud-drapes and bidirectional cross-strata suggest deposition from reversing tidal currents (cf. Nio and Yang, 1991). Furthermore, the low-diversity, *Skolithos*-type trace fossil assemblage suggests that the depositional environment was marine-influenced (cf. Pemberton et al., 2002). Together, these observations are consistent with a shallow tidal channel interpretation. Lateral building of tidal channel point-bars into channel thalwegs is known to form sharp-based, upward-fining sand-bodies that contain *Skolithos*-type trace fossil assemblages and overlie burrowed, muddy firmground surfaces (van Straaten, 1952; Barwis, 1978; Pemberton and Frey, 1985; Fenies and Faugères, 1998; Gingras et al., 1999; Gingras et al., 2000).

Facies 6: Coarsening-upward high-angle(>15°) cross-stratified sandstone

Facies 6 is composed of well-sorted, fine to very fine sandstone (Figures 3.11a and 3.11b). Beds are either planar laminated or small- (<5 cm) to large-scale (5-10 cm)
high-angle (>15°) cross-stratified (Figure 3.11a). Small-scale (<5 cm), high-angle cross-sets are typically flat-based and laterally-continuous, but small-scale (<5 cm) laterally discontinuous, scoop-based cross-sets are present locally. Millimeter-sized disseminated organic flecks are abundant, and commonly highlight ripple and dune cross-strata. In general, bioturbation is absent, but small Planolites burrows occur in thin mudstone interbeds, and rare Ophiomorpha burrows occur in sandstone. Sub-angular to round mudstone clasts are common (Figure 3.11a). Shell material is generally absent. Beds are organized into upward-coarsening units (maximum ~5 m thick) that gradationally overlie Facies 3 (Figure 3.11b). In some upward-coarsening units, small-scale (<2 cm thick) high-angle cross-stratified and planar-laminated beds grade upward into large-scale (5-10 cm thick) cross-stratified beds.

**Interpretation: Bayhead delta deposits**

Facies 6 is interpreted to have been deposited by small bayhead delta lobes that prograded into low-energy lagoons. The gradational contact with underlying lagoonal mudstone (Facies 2) and upward-coarsening nature of Facies 6 suggests a progressive increase in flow energy during deposition, most likely related to upward shallowing during progradation. The thinness of the upward-coarsening units (maximum 5 m), diminutive size of some burrows (*e.g.*, Planolites), low-diversity trace fossil assemblage, and lack of hummocky cross-stratification suggests that the receiving basin was likely shallow, sheltered, and brackish. Small-scale, flat- and scoop-based high-angle cross-sets are interpreted to have been deposited by current and small wave-ripples, respectively, whereas large-scale, high-angle cross-sets are interpreted to have been deposited by
subaqueous dunes (Boersma, 1970; de Raaf et al., 1977; Southard and Boguchwal, 1990; Ashley, 1990), as might be expected in a fluvially dominated bayhead delta influenced by small waves. Although landward progradation of flood-tidal deltas into backbarrier lagoons can also generate upward-coarsening sand-bodies (e.g., Roy et al., 1980; Heron et al., 1984; Barwis and Hayes, 1985; Hennessy and Zarillo, 1987; Isreal et al., 1987; Murakoshi and Masuda, 1991), the low diversity trace fossil assemblage, lack of evidence of storm washover deposits (e.g., climbing ripples, sand volcanoes, plane bed and/or antidune cross-stratification), presence of mud clasts and high organic content in Facies 6 are more consistent with deposition in a bayhead delta as opposed to a flood-tidal delta (e.g., Donaldson et al., 1970; van Heerden and Roberts, 1988; Nichol et al., 1997).

**Facies 7: Sharp-based, poorly-sorted muddy sandstone**

Facies 7 is composed of poorly sorted muddy sandstone (Figure 3.12). Units are typically less than 2 m thick. Bioturbation is typically intense and includes *Ophiomorpha, Palaeophycus, ?Cylindrichnus, Teichichnus*, and *Chondrites*. Burrows are commonly robust and thick-walled (Figures 3.12a and 3.12c). Shell fragments (oyster, gastropod, scaphopod), isolated white quartz sand grains and granules ("paint-speckles"), and patches of siderite cement are common. Facies 7 commonly reacts strongly with hydrochloric acid, and rarely contains glauconite and carbonate-coated granules and sandstone pebbles. Physical sedimentary structures are obliterated by bioturbation. Lower contacts are sharp, and typically have subtending, unlined
*Thalassinoides* burrows (Figure 3.12b). Facies 7 erosively overlies either Facies 3, 4 or 8, and grades upward into Facies 8 or 9.

**Interpretation:** *Wave ravinement lag deposits*

Facies 7 is interpreted to be a lag deposit formed by wave ravinement during shoreface retreat. The high-diversity *Skolithos*-type trace fossil assemblage with common robust, thick-walled burrows suggests that the environment was most likely fully marine during deposition (*e.g.*, Pemberton *et al.*, 2002). This interpretation is supported by the common upward gradation into well-sorted, shallow marine sandstone (Facies 8). Burrowed mud firmground surfaces, which typically occur at the base of Facies 7, are interpreted to be transgressive wave ravinement surfaces formed by the landward passage of the high-energy shoreface over the coastal plain during shoreface retreat. Transgressive ravinement commonly erodes thick successions of previously deposited sediment (*e.g.*, 10-20 m), exhumes mud firmgrounds, and then abruptly superimposes shallow marine sandstone on coastal plain deposits (Fischer, 1961; Suter and Berryhill, 1985; Demarest and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Pemberton *et al.*, 2002; Rodriguez *et al.*, 2001; Cattaneo and Steel, 2002).

**Facies 8:** *Well-sorted, bioturbated sandstone with high and low angle cross-stratification*

Facies 8 is composed of well sorted very fine to medium sandstone (Figure 3.13). Bioturbation is typically moderate to intense. The trace fossil assemblage is dominated by *Ophiomorpha* (Figure 3.13b), with less common *Cylindrichnus, Skolithos, ?Rosselia,*
and *Chondrites* (in the *Rosselia*). Dispersed, white-coloured quartz sand grains and granules ("paint-speckles") are common. Shells and decimeter-scale patches of pore-filling carbonate cement are present locally. Bed contacts and physical sedimentary structures are typically not identifiable. However, where visible, both high-angle (around 15°) and low-angle (<10°) cross-stratification were observed. Facies 8 always gradationally overlies poorly sorted lag deposits (Facies 7), and forms meter-scale units that are either upward-coarsening or ungraded (Figure 3.13c). Facies 8 is overlain either by Facies 9, 3 or 7.

*Interpretation: Transgressive shallow marine sandstone sheet*

Facies 8 is interpreted to have been deposited in a shallow marine shoreface environment during transgression and shoreface retreat. The high-diversity *Skolithos*-type trace fossil suggests deposition in an unstressed, fully marine setting (*e.g.*, Pemberton *et al.*, 2002). The stratigraphic position of Facies 8 above sharp-based lag deposits (Facies 7) that in turn overlie burrowed lagoonal mud firmground surfaces suggests deposition during shoreface retreat associated with relative sea level rise (*e.g.*, Fischer, 1961). Carbonate cementation, shell fragments, and a mix of high- and low-angle cross-stratified beds are features common to transgressive shelf sand-bodies (*e.g.*, Penland *et al.*, 1988; Snedden and Dalrymple, 1999; Molgat and Arnott, 2001; Posamentier, 2002).
Facies 9: Mudstone with thin siltstone and sandstone interbeds

Strata consist of mudstone with common thin (<5 cm) siltstone and rare thin (<5 cm) very fine sandstone beds and laminae. Siltstone and sandstone beds are commonly low-angle (<10°) cross-stratified, with rare concave low-angle truncations. Sandstone beds are rarely capped by small-scale, scoop-based wave ripple cross-sets. One ammonite shell was observed on a bedding plane surface. Oyster shells were not observed in Facies 9. Bioturbation is typically low but diverse and includes Planolites, Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma, and ?Rosselia. Facies 9 commonly overlies poorly sorted lag deposits (Facies 7) and coarsens upwards into well-sorted, low-angle cross-stratified sandstone (Facies 10).

Interpretation: Offshore mudstone

Facies 9 is interpreted to have been deposited near storm wave-base in a fully marine inner shelf/lower shoreface environment. Low-angle cross-stratification in sandstone interbeds is interpreted to be hummocky cross-stratification. Hummocky cross-stratification has been interpreted to form under the influence of large, long-period waves (i.e., wave period > 8 seconds; cf. Southard et al., 1990; Arnott and Southard, 1990; Dumas, 2004), suggesting deposition occurred in a large, unrestricted basin (Barnett and Wilkerson, 1967). This interpretation is supported by the presence of an ammonite shell and high-diversity trace fossil assemblage, both suggestive of a fully marine depositional environment.
Facies 10: Low-angle (<10°) laminated sandstone with mudstone interbeds

Facies 10 is composed of well-sorted, very fine to fine sandstone with rare to common mudstone interbeds (Figure 3.14). Sandstone beds are commonly amalgamated, form bedsets up to several meters thick, and are commonly low-angle (<10°) cross-stratified. Low-angle cross-strata are rarely gently curved either concave- or convex-up. Rare, concave, low-angle truncations are onlapped asymptotically by laminae that decrease in dip upwards (Figure 3.14). Small-scale (<2 cm) scoop-based high-angle (>15°) cross-sets commonly cap sandstone beds. Sandstones are sparsely bioturbated with rare Ophiomorpha burrows. Mudstone interbeds are also sparsely bioturbated, and contain Planolites, Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma, and ?Rosselia burrows. Facies 10 gradationally overlies marine mudstone (Facies 9), and together form upward-coarsening units that are capped by poorly sorted lag deposits (Facies 7).

Interpretation: Storm-dominated lower shoreface deposits

Facies 10 is interpreted to have been deposited at the base of an open marine shoreface subjected to large, long-period waves. Low-angle, gently curved cross-strata (both convex- and concave-up), low-angle internal truncation surfaces, and small-scale, scoop-based cross-sets that cap beds (small wave ripple cross-sets) are features commonly associated with hummocky cross-stratification (Campbell, 1967; Harms et al., 1975). The occurrence of hummocky cross-stratification suggests that the basin was relatively large (see discussion above), and the high-diversity trace fossil assemblage suggests that fully marine conditions existed during deposition.
3.7 Facies Associations

Based on observations from core, three facies associations were identified (Table 3.2). Stratigraphically upwards, these are interpreted to be 1) braided fluvial, 2) coastal plain, and 3) offshore marine/shoreface deposits (Figures 3.15 and 3.16a).

Table 3.2 Facies Associations, Panuke Field region

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Constituent facies</th>
<th>Nature of lower contact</th>
<th>Geomorphological features observed in 3-D seismic data (see Fig. 3.16)</th>
<th>Gamma log response</th>
<th>3-D distribution in the Panuke field region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies Association 1: Braided fluvial deposits</td>
<td>Predominantly Facies 1 and 2 (&gt;95%); minor amounts of Facies 3?</td>
<td>erosive, overlies undifferentiated shallow marine deposits</td>
<td>a NE-SW oriented braided-bar like feature in 3-D seismic plan view</td>
<td>blocky</td>
<td>~50 m thick sheet</td>
</tr>
<tr>
<td>Facies Association 2: Coastal plain deposits</td>
<td>Facies 5, 6, 7, 8</td>
<td>sharp (as observed in core) or gradational (inferred from logs); no lag</td>
<td>several curvilinear channel like features in 3-D seismic plan view</td>
<td>serrated</td>
<td>~50 m thick sheet</td>
</tr>
<tr>
<td>Facies Association 3: Storm-dominated offshore/shoreface</td>
<td>Facies 7, 9, 10</td>
<td>intertongued with coastal plain deposits; contact picked at highest transgressive lag deposit over which all deposits are marine (top of the P2 sandstone)</td>
<td>featureless in 3-D seismic plan view, save for one thin, deep channel that subdents from a surface near the lower contact</td>
<td>muddy, stacked coarsening-upward units</td>
<td>~150 m thick sheet</td>
</tr>
</tbody>
</table>

Facies Association 1: Braided fluvial deposits

Facies Association 1, which is composed predominantly of braided fluvial and tidally influenced braided fluvial deposits (Facies 1 and 2) with minor lagoonal mudstone (Facies 3), is interpreted to be a multi-storied braided-fluvial deposit. Facies Association 1 has a blocky gamma ray signature (Figure 3.15), and erosively overlies undifferentiated shallow marine deposits (Figure 3.17). In the low-accommodation western edge of the Sable Subbasin near Panuke, log data suggests that it forms a ~50 m thick sheet that...
overlies a low-relief erosion surface (Figure 3.15). When correlated southeast into the high-accommodation central Sable Subbasin, Facies Association 1 doubles in thickness to a maximum of ~100 m (Figure 3.15b). However, because of complications related to intervening growth faults and facies change and/or erosion (e.g., the O Marker is not identifiable in the distal subbasin), Facies Association 1 cannot be correlated into the distal part of the Sable Subbasin (i.e., southeast of the Onondaga Field).

Facies Association 2: Coastal plain deposits

Strata of Facies Association 2 are interpreted to be coastal plain deposit. Facies Association 2 forms a ~50 m thick sheet throughout the Panuke/Cohasset region (Figures 3.15a and 3.15b). Where cored (Panuke B-90 well only), the lower contact is sharp and lacks lag (Facies 2), although log data from adjacent wells suggests that the contact is locally gradational. In comparison to underlying braided fluvial deposits (Facies Association 1), Facies Association 2 is markedly heterolithic, and is characterized by a serrated gamma ray log profile (Figure 3.15). It is dominated by tidal flat and lagoonal mudstone (Facies 3 and 4), with subordinate tidal channel and bayhead delta sandstone bodies (Facies 5 and 6) that are difficult to correlate laterally for more than several kilometers. The upward transition from mudstone to sharp-based sandstone at the top of Facies Association 2 (the P3 and P2 sandstones) represents intertonguing of marine and coastal plain deposits (see discussion below; Figure 3.20).
Facies Association 3: Storm-dominated offshore marine/shoreface deposits

Facies Association 3 is interpreted to have been deposited in a storm-dominated shelf to shoreface environment. It forms a ~150 m thick, areally extensive sheet in the Panuke region (Figure 3.15). Facies Association 3 consists primarily of offshore mudstone and lower shoreface sandstone (Facies 9 and 10) organized into upward-coarsening units (max. ~20 m thick) that are capped by thin (<2 m), erosionally based lags (Facies 7). Because of the complicated nature of the contact between underlying coastal plain deposits and Facies Association 3, the base of the latter is placed at the base of a prominent, thin (<2 m) lag that mantles the top of the P2 sandstone, the main Panuke reservoir. This boundary corresponds to the Upper Missisauga-Naskapi contact as defined in this paper (Figure 3.4).

3.8 3-D seismic data

When the Panuke 3-D seismic data are flattened to the O Marker, four seismic features interpreted to be depositional or erosional in origin are observed in plan view between the O Marker and the Naskapi Member (Figure 3.16). Stratigraphically-upward, these features are described and interpreted below.

Seismic feature 1: Large E-W trending channel (1.928 to 1.936 ms)

A 1.5 to 3 km wide channel that erodes directly into the top of the O Marker is visible in seismic plan and cross-section view (Figure 3.16a and 3.16b). All Panuke wells penetrate this uncored feature, except for Panuke M-79 and H-08, which lie to the south of it. Log data suggest the channel is filled with mudstone, sandstone and
carbonate. The channel is 0.008 ms thick, which corresponds to an approximate thickness of 12 m\textsuperscript{14}. Furthermore, the channel is gently curved, broadens upward, and trends roughly E-W. Paleoflow direction is inferred to be westward because the shelf margin is located to the southwest of the Panuke Field (see below). The channel overlies the crest of a drape structure formed by differential compaction above the edge of the underlying Abenaki carbonate bank. It runs slightly oblique to the reef margin and also slightly oblique to normal faults along the reef margin. Fault control on channel position is therefore equivocal.

**Seismic feature 2: Diamond-shaped feature (1.896 to 1.900 ms)**

Near the top of the braided-fluvial deposits (Facies Association 1), a diamond-shaped feature is visible in seismic plan view (Figure 3.16a). It is 1.5 km wide, 2.5 km long, ~6 m thick, and is elongate in a NE-SW direction. Channel-like features on either side of the diamond-shaped feature are ~250 m wide, and curve around it in a general NE-SW direction. Based on its similarity with bars in large modern braided fluvial systems (e.g., the Brahmaputra River; Best \textit{et al.}, 2003), and similarity in thickness with upward-finising fluvial units (Facies 1), the diamond-shaped feature is interpreted to be a braid bar. Although Panuke F-09 and Panuke F-99 penetrate this feature no core was cut and because of its thinness, it is below resolution of the data in seismic cross-section (Figure 3.16c).

\textsuperscript{14} Although a rough approximation, the vertical dimension of a seismic feature is not equal to the thickness of the associated stratigraphic body (e.g. channel, barform etc) because seismic response can extend both above and below a stratigraphic body. This can make correlation of seismic features to stratigraphic surfaces problematic.
Seismic Feature 3: Thin, NE-SW oriented channel (1.872 to 1.900 ms)

A channel is visible in seismic plan view within the coastal plain deposits (Facies Association 2; Figure 3.16a and 3.16b). It has a crude oval shape in cross-section, is 350 to 700 m wide, and is about 40 m thick (0.028 ms). No wells penetrate the feature.

Seismic Feature 4: Thin, deep channel (1.852 to 1.892 ms)

Marine deposits (Facies Association 3) that overlie coastal plain deposits (Facies Association 2) are featureless in seismic plan view. However, a thin (~175 m), deep (0.040 ms, or ~60 m) channel subtends from a surface near the contact between Facies Association 3 and Facies Association 2 (Figure 3.16a and 3.16c). No wells penetrate this feature.

3.9 Regional seismic stratigraphy

The Upper Member of the Missisauga Formation in the Panuke Field correlates to progradational/aggradational clinoform-shaped reflections basinward to the southwest (Figure 3.18). Because there are no seismically distinct regional reflections within the Upper Missisauga in the Panuke Field region, the Upper Missisauga is correlated here as a single package of reflections. At present, no wells penetrate the clinoform-shaped reflections. Relief from clinoform brink-point to toe is of the order of 400 m, suggesting that the clinoforms are shelf margin and slope deposits that downlap onto Jurassic carbonates of the Abenaki Formation (e.g., Porebski and Steel, 2003; Donovan, 2003). The top of this package is onlapped by a landward-thinning group of reflections that has the stratigraphic character of a healing-phase wedge. Shoreface/offshore marine deposits
at the base of the Naskapi Member (Facies Association 3) drape the top of the healing-phase wedge. The base of the blocky Cree Member truncates the offshore/shoreface deposits (Facies Association 3) of the Naskapi Member (Figure 3.15), and is associated with renewed shelf margin progradation/aggradation (Figure 3.18).

When correlated across depositional strike from the Panuke Field into the central Sable Subbasin, the Upper Missisauga fluvial-marine succession thickens from \(\sim 100 \text{ m to } \sim 250 \text{ m} \) (Figure 3.19). Internally, the fluvial-marine transition cannot be differentiated seismically. Most of the thickening occurs across a narrow zone (\(\sim 10 \text{ km wide} \)) that overlies the Abenaki carbonate reef margin.

3.10 Depositional model

Two major, unconformity-bounded sequences are interpreted to occur between the O Marker and the base of the Cree Member in the western Sable Subbasin (Figure 3.16). Biostratigraphic data places the Upper Missisauga and Naskapi between the Hauterivian and Albian (Wade and MacLean, 1990), suggesting that these sequences were associated with low-frequency (1-10 m.y.) 3rd order relative sea-level fluctuations. The lowermost sequence, Sequence 1, lies between the channelized top of the O Marker and the low-relief base of the braided fluvial sheet (Facies Association 1). Sequence 1 is not cored in the Panuke Field region, and is interpreted based on 3-D seismic and limited log data. The second sequence, Sequence 2, lies between the base of the braided fluvial facies association and the base of the Cree. Core data locally sample Sequence 2, including its lower boundary.
**Sequence 1**

The wide channel eroded into the O Marker identified in 3-D seismic data is interpreted to be an incised valley formed during forced regression (i.e., falling relative sea-level) and lowstand (i.e. low but rising relative sea-level and normal regression; Figure 3.16). This interpretation is consistent with correlative progradational reflections at the coeval shelf-margin to the southwest that suggest sediment largely bypassed the channel and supplied the shelf margin (Figure 3.18)\(^\text{15}\). Although uncored, log data suggests that the valley is filled with a heterolithic assemblage of sandstone, mudstone, and carbonate. The presence of several meter-thick carbonate layers within the incised valley fill may be due to low fluvial sediment input during transgression, which led to underfilling of the incised valley (e.g., the Late Pleistocene Hudson Valley, offshore New York; see Posamentier, 2001).

**Sequence 2**

Thick (~50 m) braided fluvial deposits (Facies Association 1) are separated from underlying undifferentiated shallow marine deposits of Sequence 1 by an erosion surface over an area of at least ~20 km perpendicular and ~60 km parallel to interpreted paleoflow in the western Sable Subbasin (paleoflow based on braid bar orientation; see Figures 3.15 to 3.17). The erosion surface has little geomorphological expression in both log cross-sections and 3-D seismic data (Figures 3.15 and 3.16). The braided fluvial sheet is interpreted to occur in a wide, flat-based incised valley formed during forced regression

\(^{15}\) 3-D seismic data suggests that the O Marker is locally incised at the shelf edge in the Sable Subbasin (Gela Crane, personal communication, 2004).
regression and lowstand. This interpretation is based on the absence of underlying delta front facies in the Panuke Field (Figure 3.17), and the observation that sediment was fed to the shelf margin during deposition of the braided fluvial sheet (Figure 3.18). Because incised valleys typically require time to widen following initial flow-parallel incision (e.g., Zaitlin et al., 1994; Leeder and Stewart, 1996; Heller et al., 2001), the substantial width and low relief of the incised valley base perpendicular to interpreted paleoflow (>20 km) suggests that relative sea-level fall and lowstand was prolonged.

Although minor amounts of fluvial sediment may have been deposited during relative sea-level fall (cf. Blum and Törnquist, 2000), significant fluvial aggradation probably did not start until after sea level reached its lowest level and began to rise. The rate of accommodation increase associated with the relative sea-level rise was likely low compared to avulsion rate, which allowed for a sheet-like fluvial deposit to form over the sequence boundary (e.g., Blakey and Gubitosa, 1984; Holbrook, 1996; Arnott et al., 2001). The significant thickness of the braided fluvial sheet (~50 m in the Panuke field) suggests that sediment supply remained high in the face of net base level rise (cf. Curray, 1964). No unequivocal upward change in channel style (i.e., braided to meandering or anastomosing) or density of the channel stacking pattern is observed in either 3-D seismic or well log data.

The contact between braided fluvial (Facies Association 1) and coastal plain deposits (Facies Association 2) is gradational to sharp, does not have an associated lag, and is preceded by marine- and tidally-influenced braided fluvial deposits (Facies 2). These data suggest that the contact is conformable, and formed during progressive aggradational backstepping of the tidally- and marine-influenced coastal plain over the
alluvial plain (cf. Shanley et al., 1992). Given the considerable thickness of the coastal plain deposits (~50 m in the Panuke field), sediment supply likely remained high during transgression (cf. Curray, 1964).

The contact between the coastal plain and overlying offshore-marine facies associations is characterized by intertonguing of sharp-based shallow marine sandstone sheets (the P2 and P3 sandstones) and coastal plain mudstone (Figure 3.20). The sharp-based lower contacts, presence of basal lags, marine trace fossil assemblages, and well-sorted nature of the P2 and P3 sandstones suggest that they were emplaced on a shallow seafloor following episodes of transgressive wave ravinement (Figure 3.21). The basal contacts of both P2 and P3 sandstones are possible amalgamated sequence boundary/transgressive ravinement (SB/TR) surfaces formed during higher-frequency (4th or 5th order) fluctuations of relative sea-level. The top of the P2 sandstone, which is mantled by a sharp-based lag (Facies 7), is also a possible amalgamated high-order SB/TR surface because lags generally occur at the base of transgressively emplaced sandstone bodies (e.g., Posamentier, 2002). Thick sandbodies immediately below the top of the Upper Missisauga in wells adjacent to the Panuke Field (e.g., Cree E-35 well; Figure 3.15a) as well as the narrow (<1 km), deep (40-60 m) channels observed in 3-D seismic data (Figure 3.16; Seismic features 3 and 4) may be incised valleys that extend down from these higher-order amalgamated SB/TR surfaces. The occurrence of these amalgamated SB/TR surfaces suggests that the 3rd order relative sea-level rise associated with the Upper Missisauga/Naskapi boundary was punctuated by higher-frequency (4th and 5th order) relative sea-level fluctuations, and as a consequence complicated the stratigraphy.
Parasequences within the offshore marine deposits of the Naskapi (Facies Association 3) are aggradationally stacked in the Panuke Field region (Figure 3.15). The absence of either a turnaround to progradational parasequence stacking or an obvious seismic downlap within the Naskapi in the Panuke region may suggest that the maximum flooding surface of Sequence 2 was truncated in the Panuke region during relative sea-level fall and deposition of the Cree Member. The sharp contact between Cree and Naskapi members is interpreted to be the upper boundary of Sequence 2 (Figures 3.15 and 3.16). This surface is associated with renewed shelf-margin progradation to the southwest of Panuke (Figure 3.18).

3.11 Shelf margin accretion during transgression?

2-D seismic data (Figure 3.18) suggest that the shelf margin continued to be supplied with sediment until the end of coastal plain deposition in the Panuke Field, which corresponds to the Upper Missisauga/Naskapi boundary. This observation is apparently in contradiction with sequence stratigraphic models that suggest shelf-margin accretion typically stops as a result of relative sea-level rise overcoming fluvial sediment supply to the lowstand shelf-edge (e.g., Posamentier and Vail, 1988; Porebski and Steel, 2003). However, if the transgression is punctuated by higher-frequency episodes of relative sea-level fall and rise and fluvial sediment supply varies temporally, as is likely the norm for longer-period relative sea-level cycles (e.g. 1st, 2nd, or 3rd order), sediment has the potential to episodically bypass the shelf and prograde the shelf margin, even during net transgression. As such, sediment bypass across one or several of the 4th or 5th order amalgamated SB/TR surfaces present near the top of the coastal plain deposits.
(Facies Association 2) could have temporarily supplied the shelf edge with sediment and caused continued shelf margin progradation.

### 3.12 Exploration significance

This paper suggests that transgressively emplaced shallow-marine sand-bodies can constitute a significant stratigraphic play type in the western Sable Subbasin (Figures 3.20 and 3.21). These sand-bodies are sheet-like over tens of kilometers, are commonly several meters thick (maximum 9 m), and consist predominantly of well-sorted sandstone with good reservoir quality (permeability is commonly between 100-500 mD and reaches a maximum of about 2000 mD; Table 3.3; Figure 3.20). Although unresolvable in Panuke 3-D seismic data because of their thinness, the sheet-like sand-bodies may thicken close to local sources of sand such as tidal channels or incised valleys, as observed in late Pleistocene analogs (Snedden and Dalrymple, 1999), which may make them more easily identifiable in 3-D seismic data.

### Table 3.3 P2 and P3 Sandstones: Sedimentology and Reservoir Quality

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Lower Contact</th>
<th>Underlain by...</th>
<th>Overlain by...</th>
<th>Facies (in stratigraphic order)</th>
<th>Permeability</th>
<th>Potential flow barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2 sandstone</td>
<td>erosive, with unlined Pholadomidae burrows subaequous from contact</td>
<td>lagoonal mudstone (Facies 3)</td>
<td>offshore mudstone (Facies 9)</td>
<td>poorly sorted, bioclastic-rich sandstone (Facies 7)</td>
<td>0 to 667</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>well-sorted, bioturbated fine sandstone (Facies 8)</td>
<td>58 to 1050</td>
<td>49 to 165</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>poorly sorted, bioturbated sandstone (Facies 7)</td>
<td>0 to 127</td>
<td>0 to 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>tidal channel (Facies 5)</td>
<td>not developed</td>
<td>not developed</td>
</tr>
<tr>
<td>P3 sandstone</td>
<td>erosive, with unlined Pholadomidae burrows subaequous from contact</td>
<td>lagoonal mudstone (Facies 3)</td>
<td>lagoonal mudstone (Facies 3)</td>
<td>well-sorted, bioturbated fine sandstone (Facies 8)</td>
<td>35 to 1980</td>
<td>3 to 941</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>transgressive lag (Facies 7)</td>
<td>0.01 to 5</td>
<td>0.1 to 0.75</td>
</tr>
</tbody>
</table>
As shelf-margin progradation is interpreted to have occurred during lowstand and fluvial sediment bypass at the base of both Sequence 1 and 2 (Figure 3.18), fluvial systems at the base of both sequences potentially supplied coarse clastic sediment to down-dip slope and basin-floor turbidite systems. Regional mapping of these fluvial systems using a combination of available data (especially 3-D seismic data flattened to the O Marker) may therefore help identify down-dip shelf margin and slope exploration targets in the Sable Subbasin.

3.13 Conclusions

A thick (~100 m), areally extensive (>20 km wide) fluvial-marine transition has been identified between the Upper Missisauga and Naskapi in the western Sable Subbasin. The thickness of the fluvial-marine transition suggests that sediment supply remained high during base level rise. Furthermore, the areal extent of the fluvial-marine transition suggests that the fluvial system was relatively unrestricted, which allowed it to avulse laterally and erode a flat basal contact. Delta front deposits are absent below fluvial deposits, and the shelf margin accreted during its deposition, suggesting that the base of the fluvial deposits is a sequence boundary formed at the base of a wide incised valley. Continued shelf margin progradation until the end of coastal plain deposition was apparently facilitated by episodes of high-frequency (4th and 5th order; i.e., <1 million year duration) relative sea-level rise and fall that caused sediment to episodically bypass the shelf and feed the shelf margin.

The two main Panuke reservoirs (P2 and P3 sandstones) are sharp-based sandstone sheets that intertongue with coastal plain mudstone just below the Upper
Missisauga/Naskapi boundary. They are commonly several meters thick in the western Sable Subbasin, and several tens of kilometers in area. They are interpreted to be shallow marine sand-bodies deposited above transgressive ravinement surfaces during shoreface retreat. Given their good reservoir quality and areally extensive geometry, transgressive sandstone sheets may represent an important reservoir play-type in the western Sable Subbasin.
Figure 3.1  Isopach map (in part estimated), Scotian Basin. Contours are in kilometers.

Modified from MacLean and Wade (1992).
Figure 3.2  Location of the Panuke Field, western edge of the Sable Subbasin, offshore Nova Scotia (modified after Welsink et al., 1989; Canada Nova Scotia Offshore Petroleum Board, 2000). Solid black dots designate cored wells.
Figure 3.3  Stratigraphic framework of Upper Jurassic/Lower Cretaceous strata in the Sable Subbasin of the Scotian Basin, offshore Nova Scotia (after Welsink et al., 1989 and Wade and MacLean et al., 1990)
Figure 3.4 Panuke sandstone reservoirs (P1 to P5 sandstones), Upper Missisagua-Naskapi transition, Panuke B-90 well. Lithostratigraphic picks are after MacLean and Wade (1993) and LASMO (1990). Reservoir picks are after LASMO (1990) and in-house data (Encana, unpublished). Note that for convenience, the Upper Missisauga is picked so that it coincides with the top of the main reservoir (the P2 sandstone).
**Figure 3.5** Well-to-seismic tie used for the Panuke 3-D seismic survey. Well log and seismic picks, except for the top of the Missisauga Formation (see Figure 3.3), are the same as those in MacLean and Wade (1993).
Figure 3.6  Facies 1 (interpretation - braided fluvial channel fill deposits). Note high-angle (dune) cross-stratification. Photo taken from Panuke B-90 well, core 11.
Figure 3.7  Facies 2 (interpretation – tidally influenced braided fluvial channel fill deposits). Note high-angle (dune) cross-stratification, with *Skolithos* burrow (top arrow) and double mud-drape (bottom arrow). Photo taken from Panuke B-90 well, core 9, box 19, 2354.91 m (measured depth).
Figure 3.8  Facies 3 (interpretation – lagoonal mudstone). (a) Mudstone with normally graded siltstone laminae (Panuke F-99, core 3, box 24, 2316.31 m (measured depth)), (b) small-scale wave ripple cross-stratification (Panuke F-99, core 3, box 15, 2310.5 m (measured depth)), (c) oyster shells (Panuke J-99 PP2, core 1, box 12, 2305.8 m (measured depth)).
Figure 3.9  Facies 3 (interpretation – tidal flat deposits). (a) pinstripe- and lenticular-laminated sandstone (Panuke B-90, core 3, box 23, 2333.15 m (measured depth)), (b) rhythmic stratification (neap-spring cycles?; Panuke B-90, core 7, box 12, 2298.3 m (measured depth)), (c) small-scale slump (Panuke B-90, core 8, box 21, 2331.95 m (measured depth)), (d) synaeresis cracks (Panuke B-90, core 8, box 27, 2336.11 m (measured depth)).
Figure 3.10  Facies 5 (interpretation – tidal channel deposits). (a) sharp-based Facies 5 unit with rooted top contact (Panuke B-90, core 9, boxes 5 to 3, 2347.5-2345.4 m (measured depth)), (b) unlined Thalassinooides burrows subtending from the basal contact of Facies 5 unit (Lawrence D-14, core 2, box 11, 2280 m (measured depth)).
Figure 3.11  Facies 6 (interpretation – bayhead delta deposit).  (a) Gradationally based, coarsening-upward unit (Como P-21, core 1, boxes 25 to 18, 2205.75-2200.9 m (measured depth)), (b) dune cross-stratification, with rounded mudstone clast (Como P-21, core 1, box 20, 2202.3 m (measured depth)).
round mudstone clasts

carbonate-cemented patch

a mix of planar laminated and current ripple cross-stratified fine sandstone

thinly interbedded mudstone and lower fine sandstone (ripped)
Figure 3.12  Facies 7 (interpretation – wave ravinement lag). (a) Thick-walled, robust *Ophiomorpha* burrow. Note ubiquitous white “paint-speckle” quartz sand grains and granules (Panuke F-99, core 2, box 15, 2294.25 m (measured depth)), (b) unlined *Thalassinoides* burrows subtending from the base of a Facies 7 bed (Panuke J-99 PP2, core 1, box 24, 2314.0 m (measured depth)), (c) sandstone pebbles (peb) and *Ophiomorpha* (Oph) burrows in Facies 7 (Panuke F-99, core 2, box 12, 2292 m (measured depth)).
Figure 3.13  Facies 8 (interpretation – transgressively emplaced shallow-marine deposits).  (a) Bioturbated sandstone (Panuke F-99, core 2, box 13, 2292.8 m (measured depth)), (b) *Cylindrichnus* (Cy) and *Ophiomorpha* (Oph) burrows (Panuke F-99, core 2, box 13, 2292.5 m (measured depth)) (c) graphic log showing stratigraphic position of Facies 8, P2 sandstone (Panuke J-99 PP2, core 1, boxes 12 to 2, 2306.1-2298.35 m (measured depth)).
Figure 3.14 Facies 10 (interpretation – storm-dominated lower shoreface deposits).

Note low-angle truncation surface (arrow) with onlapping laminae whose dip shallows up core (interpretation – hummocky cross-stratification; Lawrence D-14, core 2, box 3, 2272.8 m (measured depth)).
Figure 3.15  Well log cross-sections (a) perpendicular and (b) parallel to interpreted paleoflow (paleoflow direction based on braid-bar orientation interpreted from 3-D seismic data). Shown also are synthetic traces generated from sonic logs used to tie well data to regional 2-D seismic data (note strong peak generated by the O Marker). See Figure 3.2 for cross-section locations.
Figure 3.16a  Facies associations and 3-D seismic geomorphology across the Upper Missisauga-Naskapi transition, Panuke Field. Two major (3rd-order) sequences are interpreted to occur in between the O Marker and the base of the Cree Member in the western Sable Subbasin. Several higher-order sequences (4th- and 5th-order) are interpreted to be “nested” within these lower-order sequences (e.g., candidate amalgamated sequence boundaries/ravinement surfaces at the base of the P2 and P3 sandstones).
Figure 3.16b  Cross-sectional view of seismic features 1 and 3, Panuke Field. Red lines in the seismic data are troughs, blue lines are peaks. Seismic feature 1 is interpreted to be a fluvial channel eroded into the O Marker. Seismic feature 3 is a channel-like feature in coastal plain deposits (Facies Association 2) just below the Missisauga-Naskapi boundary.
Figure 3.16c  Cross-sectional view of Seismic features 2 and 4, Panuke Field. Red lines in the seismic data are troughs, blue lines are peaks. Seismic feature 2, which is located near the top of the fluvial sandstone unit (Facies Association 1), is interpreted to be a braid-bar. Seismic feature 4 is interpreted to be a channel located very close to (at?) the top of the coastal plain unit (Facies Association 2).
Figure 3.17  Lower contact of Facies Association 1 (braided fluvial deposits), Panuke B-90 well. Note lack of underlying delta front deposits below the fluvial sandstone.
Figure 3.18  Uninterpreted and interpreted dip-oriented seismic cross-section, western Sable Subbasin (GSI-GSI-PA99-110). Note the decrease of clinoform dip angle at the Upper Missisaug-Naskapi contact. Subsequently, however, clinoform dip increases above the Naskapi-Cree contact, and is interpreted to indicate renewed progradation of the shelf margin. Red lines in the seismic data are troughs, blue lines are peaks. Well logs were tied to the seismic data by stretching them linearly between reflections associated with the Wyandot and the O Marker. See Figure 3.2 for location of the 2-D seismic line.
Figure 3.19  Uninterpreted and interpreted strike-oblique form line tracing of a seismic section, central Sable Subbasin (PRX-GSI-83-4481). Red lines in the seismic data are troughs, blue lines are peaks. Well logs were tied to the seismic data by stretching them linearly between reflections associated with the Wyandot and the O Marker. See Figure 3.2 for location of 2-D seismic line.
Figure 3.20  P2 and P3 sandstones, showing constituent facies, permeability variation, and sequence stratigraphic interpretation. Dashed lines along facies boundaries indicate gradational contacts; solid lines indicate sharp contacts. See text for facies details.
Figure 3.21  General depositional model for hydrocarbon-bearing sheet-like sandstones near the top of the Upper Missisaugia (e.g., P2 sandstone), western Sable Subbasin.
Chapter 4. Abrupt wave-tidal facies transitions in the Missisauga Formation, Venture Field region, offshore Nova Scotia, Canada

4.1 Introduction

Deltas have long been recognized as sensitive to changes in relative sea-level (e.g., Fisk 1944; Boyd et al., 1992). In passive margin basins, for example, deltas are commonly observed to become increasingly wave-influenced during regression, and then switch to a tidally influenced state during transgression (e.g., Fisher and McGowen, 1967; Oomkens, 1974; Demarest and Kraft, 1987; Morton and Suter, 1996; Suter, 2001). Theoretically, this happens because tidal prism volume and shelf width, and, accordingly, wave attenuation and tidal range, tend to decrease during regression and then increase during transgression, often in association with the transgressive drowning of tidally resonant incised river valleys (Yoshida et al., 2003). This relationship, which forms one of the theoretical underpinnings of the incised valley facies model (e.g., Dalrymple et al., 1992; Zaitlin et al., 1994), offers an elegant explanation for the erosive superposition of tide-influenced over wave-influenced deposits in the stratigraphic record (e.g., Mellere and Steel 1995; Marjanac and Steel 1997; Willis, 2000; Martinius et al., 2001).

However, it is theoretically possible to form abrupt wave-tidal transitions without regressive-to-transgressive shoreline turnaround (Figure 4.1; Table 4.1). For example, abrupt wave-tide transitions can form during normal regression of ‘mixed energy’ deltas, where tidally influenced deltaic distributaries prograde over and erode into wave-influenced delta front deposits (e.g., Oomkens, 1974). Also, although seldom documented, abrupt wave-tidal transitions can theoretically be produced during falling
Table 4.1 Characteristics of different types of abrupt wave-tidal transitions

<table>
<thead>
<tr>
<th>Process</th>
<th>Basal contact of tidally-influenced deposits</th>
<th>Geometry of contact</th>
<th>Associated pedogenesis</th>
<th>Architecture of tidally-influenced deposits</th>
<th>Evidence of marine influence in tidal deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regressive-to-transgressive shoreline turnaround and incised valley fill(^{1,2,9})</td>
<td>sequence boundary</td>
<td>channel-form (incised valley); typically narrow (&lt;10 km(^2)) and relatively deep (max. ~100 m(^2)); tributaries are incised(^{10})</td>
<td>pedogenesis of interfluve surfaces likely, pedogenesis of valley floor may also occur(^{14})</td>
<td>back stepping (low fluvial input) to forward stepping (high fluvial input)(^{15}), restricted laterally by the incised valley</td>
<td>increases stratigraphically upward</td>
</tr>
<tr>
<td>&quot;Mixed energy&quot; delta progradation(^{7,12,13})</td>
<td>channel diastem</td>
<td>channel-form; channels likely to be shallower (usually &lt;15 m(^2); max. ~30 m(^3)) and narrower (&lt;1 km(^2)); also likely less extensive down-dip due to autoretreation(^{6,7})</td>
<td>pedogenesis of inter-channel surfaces possible, but soils likely less well developed</td>
<td>forward stepping; likely channel-form</td>
<td>decreases stratigraphically upward</td>
</tr>
<tr>
<td>Switch from wave- to tide-dominated sedimentation during regression due to heightened tidal resonance(^{5,8,9,11})</td>
<td>regressive tidal scour surface</td>
<td>less likely channel-form, more likely areally-extensive (up to 300 km wide)(^{5,6})</td>
<td>no pedogenesis of contact</td>
<td>forward stepping, possibly aggradational; restricted laterally by the resonant antecedent topographic depression</td>
<td>Decreases stratigraphically upward</td>
</tr>
</tbody>
</table>

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relative sea level when a wave-dominated shoreline is forced into a fetch-limited, tidally resonant topographic constriction (Willis and Gabel, 2001, 2003; Yoshida et al., 2003).

Because proper identification of the mechanism responsible for producing a given wave-tide transition can significantly shift the focus of a hydrocarbon exploration or development strategy, care must be taken and multiple criteria must be used in their interpretation (e.g., Dalrymple et al., 1994; Zaitlin et al., 1994).

This paper describes several abrupt wave-tidal transitions in the Venture Field (Venture sandstones 8 to 5), offshore Nova Scotia, and interprets them to be incised.
valleys formed on the outer shelf several kilometers updip of the shelf margin. The implications of the interpretations presented are discussed with respect to reservoir distribution on both a local and regional scale.

4.2 Geological setting and lithostratigraphy

The Venture Field is several kilometers east of Sable Island near the center of the Sable Subbasin, one of several interconnected Mesozoic-Cenozoic depocenters that make up the passive margin basin offshore Nova Scotia (Figures 4.2 and 4.3). During the Mesozoic, clastic sediments were likely fed into the subbasin by an ancestral St. Lawrence River, a large, continental-scale river system that drained much of eastern Canada (Wade and MacLean, 1990; Grist et al., 1992). Sediment loaded underlying syn-rift salt and caused salt displacement and growth fault tectonism (Figure 4.3). At the time of deposition of the Venture sandstone reservoirs (Kimmeridgian to Berriasian-Valanginian), Nova Scotia was approximately 30°N of the equator (Irving et al., 1993), the receiving basin (i.e., the Atlantic Ocean) was ~1000 km wide (Ziegler, 1989), and climate was warm and temperate (Rees et al., 2000).

The Venture sandstone reservoirs occur partly in the Lower Member of the Mississauga Formation and partly in the underlying Mic Mac Formation (Figure 4.4). Correlating the Mississauga/Mic Mac contact throughout the Sable Subbasin is problematic because the two units are lithologically similar and their contact has no distinctive regional marker bed or seismic reflection. Following MacLean and Wade (1993), therefore, the base of the Mississauga in the Venture Field is picked at a locally-prominent Kimmeridgian-aged limestone unit (the Venture limestone 9).
The Lower Missisauga shelf edge is interpreted to be situated just south of the Venture Field (Figure 4.5; cf. Figure 5.31 in Wade and MacLean, 1990). Seismic reflections in the Venture Field, the strongest of which are associated with limestone units, are parallel and roughly horizontal. When traced basinward to the south, these reflections downdrop across a series of growth faults and appear to correlate roughly to a package of large-scale (i.e., >1 km relief) southward-dipping reflections located between 5 and 20 km south of the Venture Field. Although confident correlation of specific reflections across the growth faults is not possible, the relief and general stratigraphic and geographic position of the southward-dipping reflections suggests that they are Mic Mac and Lower Missisauga slope clinofoms (cf. Wade and MacLean, 1990).

4.3 Venture Field history and reservoir stratigraphy

The Venture Field contains an estimated 66 million cubic meters of original gas in place (Sable Offshore Energy, 1996), which is about 25% of the gas discovered to date offshore Nova Scotia (Canada Nova Scotia Offshore Petroleum Board, 2000). The discovery well, Venture D-23, was drilled in 1979 to test for hydrocarbons in a rollover anticline formed in the hanging wall of an east-west trending normal growth fault (Figure 4.5). Subsequently, five vertical delineation wells were drilled in the early 1980s, and four deviated development wells were drilled in the mid-1990s. A total of ten wells have now been drilled in the field.

In the Venture Field, gas is trapped in sandstone units within a succession of interstratified shale, sandstone, and limestone (Figure 4.4; Drummond, 1992). The upper two sandstone reservoirs, Venture sandstones 1 and 2, are hydropressured. Underlying
sandstones (below ~4.5 km) are overpressured and have anomalously high porosity, possibly because 1) early grain-coating chlorite inhibited silica cementation (Hutcheon, 1986), 2) increased pCO₂ from thermal cracking of kerogens promoted carbonate cement dissolution (Jansa and Norrega, 1990), and/or 3) rapid deposition that trapped and overpressured pore waters in underlying sediments (Mudford and Best, 1989). Venture sandstones 8 to 5, which form the focus of this paper, are estimated to contain 35.9 million cubic meters of gas, which is ~50% of the original in-place gas in the Venture Field (Sable Offshore Energy, 1996).

4.4 Dataset and methodology

This study integrates core (955 m), well log data (12 wells), palynological data, and 2-D seismic data (Figure 4.3). Cores were described in 2.5 cm detail, noting sedimentary textures, physical and biogenic sedimentary structures, macrofossils, and macroscopic diagenetic features. Core data were used to calibrate well logs, which were then tied to seismic data using synthetic traces generated from sonic logs. Lithostratigraphic and seismic stratigraphic picks used in this study are the same as MacLean and Wade (1993). Picks for the Venture reservoirs were taken from the Sable Offshore Energy Development Plan (Sable Offshore Energy, 1996). Because no paleoflow data are available for Venture sandstones 8 to 5, dip versus strike cross-sections are oriented by assuming shorelines trended parallel to and prograded toward the Lower Missisaugia shelf margin (i.e., progradation towards the south).
4.5 Facies

Nine facies were identified in core (Table 4.2). These are described below.

Facies 1: Carbonate mudstone

Facies 1 consists of dark to light blue-grey carbonate mudstone (Figure 4.6). Bedding surfaces are difficult to identify, and the facies is massive to faintly laminated with no discernable vertical grain size trends. No physical sedimentary structures were observed. In thin section, brachiopod, bryozoa, and foraminifera bioclasts were identified. No potential framework building organisms were observed. The basal contact of Facies 1 has not been cored, although gamma log signatures suggest that Facies 1 overlies Facies 2 mudstone.

Interpretation: Shelf carbonates

Based on the fine-grained texture, absence of potential framebuilding organisms, and brachiopod-bryozoan dominated faunal assemblage, Facies 1 is interpreted to have been deposited under normal marine conditions below storm wave base in a distal unrimmed shelf or upper slope environment. Similar carbonate facies commonly occur near the shelf edge of temperate, mid-latitude modern shelves (e.g., Collins, 1988; James, 1997).
Table 4.2 Facies descriptions and interpretations, Venture and West Venture fields

<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology</th>
<th>Lower Contact</th>
<th>Vertical textural change</th>
<th>Physical Sedimentary Structures</th>
<th>Detrital coal</th>
<th>Trace Fossils</th>
<th>Fossil dinoflagellates</th>
<th>Diagenetic Features</th>
<th>Porosity (%)</th>
<th>Permeability (millidarcies)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gradational</td>
<td>Upward-coarsening</td>
<td>None</td>
<td>High-angle x-strat (&lt;5 cm)</td>
<td>Low-angle x-strat (&lt;10') x-strat</td>
<td>Horizontal lamination</td>
<td>Soft sediment deformation</td>
<td>Detrital coal</td>
<td>Trace Fossils</td>
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<tr>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td>x</td>
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<td>&lt;10</td>
<td>&lt;0.1</td>
<td>Shelf carbonates</td>
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<td>x x x</td>
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<td>X</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>&lt;30</td>
<td>&lt;0.1; max 5360</td>
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<td>8</td>
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<td>x</td>
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<td>x</td>
<td>-</td>
<td>&lt;10</td>
<td>&lt;0.1</td>
<td>Marsh</td>
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<tr>
<td>9</td>
<td>X X X x</td>
<td>X</td>
<td>X</td>
<td>x</td>
<td>x x x X x x</td>
<td>x</td>
<td>x</td>
<td>X x</td>
<td>-</td>
<td>&lt;20</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

X is more common than x
"-" = not analyzed
Facies 2: Mudstone with low-angle cross-stratified sandstone beds

Facies 2 consists of mudstone with rare to common thin (<10 cm) siltstone and very fine sandstone beds (Figure 4.7). Siltstone and sandstone beds are typically planar to low-angle (<10°) cross-stratified and unbioturbated (rare Ophiomorpha). Low-angle cross-strata are flat to gently curved (concave or convex). Rare, low-angle truncation surfaces are present within sandstone beds. Sandstone beds are commonly capped by one to several thin, scoop-based high-angle (>15°) cross-sets (<5 cm thick). Bioturbation in the mudstone ranges from none to intense, and includes Planolites, Palaeophycus, Asterosoma, Helminthopsis, Chondrites, Zoophycos, Terebellina, Teichichnus, and Rosselia. Although palynomorph preservation was generally poor, several specimens of a Circulodium-like dinoflagellate and one Subtilisphaera-like specimen were observed in one of two collected palynology samples (Rob Fensome, personal communication, 2002). Facies 2 sharply overlies Facies 9 or gradationally overlies Facies 1.

Interpretation: Storm-dominated inner shelf/outer shoreface deposits

Facies 2 is interpreted to have been deposited below fairweather wave base at the transition between the lower shoreface and continental shelf (sensu Cowell et al., 1999). Low angle (<10°) cross-stratification in sandstone interbeds is interpreted to be hummocky cross-stratification formed under the influence of large, long-period storm waves (cf. Southard et al., 1990; Arnott and Southard, 1990; Dumas, 2004). Because long-period waves require sufficient distance (fetch), depth, and travel time to form (Barnett and Wilkerson, 1967), the presence of hummocky cross-stratification suggests that Facies 3 was deposited in a large and unrestricted basin. Sandstone interbeds are
interpreted to have been deposited during major storms that eroded sand from the upper shoreface and deposited it farther offshore on the lower shoreface and inner shelf (e.g. Niederoda et al., 1985; Inman et al., 1993). Because waves are effective at suspending sediment but not at transporting it 'quickly' (Bagnold, 1963), a downslope 'excess-weight' gravitational force (e.g., Bagnold, 1963; Wright, 1987; Myrow and Southard, 1996) and/or offshore-directed storm surge-generated downwelling flow (e.g., Morton, 1981; Niederoda et al., 1985) likely facilitated cross-shore sand transport from upper to lower shoreface and inner shelf.

**Facies 3: Low-angle (<10°) cross-stratified sandstone**

Facies 3 gradationally overlies Facies 2, and is composed of well-sorted, very fine to fine buff-coloured sandstone with rare mudstone interbeds (Figure 4.8). Sandstone beds are commonly amalgamated, forming bedsets several meters thick (Figure 4.8a). Facies 3 is horizontally laminated to low-angle (<10°) cross-stratified. Cross-strata are either flat or gently curved (either concave or convex; Figure 4.8b). Rare, concave low-angle truncations are onlapped asymptotically by laminae that decrease in dip upward (Figure 4.8b). Rarely, sandstone beds are normally graded (Figure 4.8b). Sandstone beds are typically unbioturbated, but local, rare to common *Ophiomorpha, Rosselia,* and *?Cylindrichnus* burrows were observed. Mudstone interbeds are sparsely bioturbated, but contain *Planolites, Teichichnus, Palaeophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichnus, ?Asterosoma,* and *?Rosselia* burrows.
**Interpretation: Storm-dominated lower shoreface deposits**

Facies 3 is also interpreted to have been deposited below fairweather wave base on the lower shoreface (lower shoreface *sensu* Cowell *et al.*, 1999). Like Facies 2, the high diversity trace fossil assemblage suggests deposition under fully marine conditions, and low-angle (<10°) cross-stratification is interpreted to be hummocky (and possibly swaley) cross-stratification formed under the influence of large, long-period swell and storm waves (Southard *et al.*, 1990; Arnott and Southard, 1990; Dumas, 2004). Small-scale, scoop-based, high-angle cross-sets are interpreted to be small-scale wave ripple structures (*e.g.*, Boersma, 1970; de Raaf *et al.*, 1977). In contrast to Facies 2, the general lack of mudstone in Facies 3 suggests deposition higher on the lower shoreface but still below the ‘transition depth’ (*sensu* Clifton, 1976), where episodic, high-energy storms eroded fairweather-deposited mudstone and caused amalgamation of hummocky cross-stratified sandstone beds.

**Facies 4: Interbedded high angle (>15°) and low angle (<10°) cross-stratified sandstone**

Facies 4 is composed of moderately to well-sorted medium sandstone (Figure 4.9). Beds are high-angle (>15°) to low-angle (<10°) cross-stratified, and are 1 to 25 cm thick. Commonly, beds are organized into stacked, sharp-based upward-fining units that are each on average ~1 m thick. The lower two-thirds of each unit is generally high-angle cross-stratified medium sandstone, which fines upward into low-angle cross-stratified fine sandstone with common concave, low-angle (<10°) truncation surfaces and sparsely disseminated organic flecks. In the lower two-thirds of the upward-fining units, significant variation in the orientation of high-angle cross-stratification is observed.
Facies 4 is typically unbioturbated, although rare *Ophiomorpha* burrows are present. Facies 4 sharply overlies Facies 3.

**Interpretation: Upper shoreface deposits**

The sharp-based, upward-fining nature of Facies 4 units with rare *Ophiomorpha* suggests deposition by channel cut-and-fill in a marine or marine-influenced environment. Channel-form features are common in wave-dominated coastal sedimentary environments, both associated with and behind the wave-built barrier (*e.g.*, tidal inlets, tidal creeks, deltaic distributaries, inter-bar channels in tidal estuaries *etc.*) and in the surf zone of the upper shoreface (*e.g.*, rip channels, longshore troughs). However, because the upward-fining units are mud-poor, thin (ave. ~1 m), and capped by low-angle cross-stratification interpreted to be wave-influenced, Facies 4 is interpreted to have formed by a channel cut-and-fill process within the upper shoreface (*e.g.*, Thornton *et al.*, 1998). This interpretation is based on previous work that suggests upper shoreface channel fills are likely to be less muddy, an order of magnitude shallower, and contain more wave-formed sedimentary structures (*e.g.*, Davidson-Arnott and Greenwood, 1976; Aagaard *et al.*, 1997; Thornton *et al.*, 1998; Short, 1999) with respect to barrier-associated and back-barrier channel fills (*e.g.*, Heron *et al.*, 1984; Vilas *et al.*, 1988; Dalrymple *et al.*, 1990; Gastaldo *et al.*, 1995; Baker *et al.*, 1995; Allison *et al.*, 2003; Dalrymple *et al.*, 2003).
Facies 5: Mudstone with high-angle (> 15°) cross-stratified sandstone interbeds

Facies 5 erosively overlies Facies 3, 4 or 6, and consists of mudstone with rare to common sandstone interbeds (Figure 4.10). Sandstone interbeds are fine to coarse grained, and are 10 to 75 cm thick. The ratio of sandstone interbeds to mudstone ranges from <10 to ~70%. Centimeter-scale load casts and synaeresis cracks are common at the bases of sandstone interbeds, and rarely sandstone occurs as isolated, internally-deformed balls in mudstone. Sandstone beds are either massive or composed of several stacked, high-angle (>15°) cross-sets that are on average ~10 cm thick to a maximum of ~40 cm thick. Subjacent cross-sets commonly dip in opposing directions and toesets are commonly highlighted by organic-rich mud. Double mud-drapes are present but rare. Pebble-sized coal fragments and disseminated organic flecks are common. Sandstone beds are typically unbioturbated, but rare intensely burrowed intervals of ?Taenidium occurring (Figure 4.10b), and rare Ophiomorpha and Diplocraterion burrows are observed locally.

Like the sandstone beds, mudstone beds are generally unbioturbated, although Teichichnus, Thalassinoides, ?Rhyzocorallium and small Planolites burrows are rarely present in monospecific, low- to high-density assemblages. Sharp-based, sharp-topped ‘pinstripe’ sandstone laminae (<2 mm thick) are common within mudstone beds, and rarely, sandstone laminae grade rhythmically in and out of mudstone (Figure 4.10c). One possible marine element, possibly a fossil dinoflagellate, was identified in one of four mudstone samples collected for palynological analysis (Rob Fensome, personal communication, 2002).
On a larger-scale, Facies 5 is either organized into sharp-based units that fine-upward over several meters (maximum ~11 m), or shows no obvious upward grain size trend (Figure 4.10a). In the upward-fining units, cross-set thickness tends to decrease and intensity of bioturbation and mudstone content tends to increase upward. Mud intraclasts are common near the base of upward-fining units. Elongate *Diplocraterion* burrows up to 30 cm in length are rarely observed in the ‘transition zone’ between basal sandstone-rich and upper mudstone-rich portions of the upward-fining units.

*Interpretation: Tide-influenced fluvial deposits*

Facies 5 is interpreted to be a channelized deposit strongly influenced both by fluvial outflow and tidal currents. Abundant coaly carbonaceous debris suggests deposition close to a terrestrial organic source. High-angle (>15°) sandstone cross sets are interpreted to have been deposited by ripple and dune bedforms migrating and aggrading under unidirectional flow (*e.g.*, Allen, 1973; Leclair and Bridge, 2001). Rhythmic stratification, bipolar dune and ripple cross-stratification, and double mud-drapes suggest deposition in a tidally influenced environment (*e.g.*, Nio and Yang, 1991). Furthermore, monospecific trace fossil assemblages, diminutive *Planolites* burrows, and general lack (but not complete absence) of fossil dinoflagellates suggest brackish water conditions (*Pemberton et al.*, 2002).

Sharp-based, upward-fining and thinning units indicate upward-decreasing depositional energy, and are interpreted to be channel fill deposits. Assuming that the upward-fining units and the dune cross-strata within them scale to channel flow depth (*e.g.*, Leclair and Bridge, 2001; Bridge and Tye, 2000), the channels were likely roughly
between 3 and 11 m deep. This suggests that deposition occurred in larger tidally- and fluvially-influenced coastal plain channels as opposed to small, shallow tidal-flat creeks (e.g., Gastaldo, 1995; Dalrymple et al., 2003). Given the abundance of thick mudstone beds (up to 70% of total thickness), some of which are interbedded with the coarsest sandstone at the base of upward-fining units, it is possible (likely?) that fluid muds, which can occur in turbid, high-energy, tidally dominated environments, may have resided alongside coarse sand patches at the base of channels (e.g., Dalrymple et al., 2003; Dalrymple and Choi, 2003). (Arguably, this facies could be referred to as fluvially-influenced tidal channel deposits.)

**Facies 6: Mudstone with pinstripe to lenticular laminated sandstone**

Facies 6 consists of mudstone with interlaminated fine to very fine sandstone (Figure 4.11). Sandstone laminae are common, and commonly reach equal abundance with mudstone. Sandstone laminae are either lenticular- (pod-shaped) or pinstripe-shaped (mm-thick, flat, and discontinuous across the core), are typically high-angle (>15°) cross-stratified, and either have flat or scoop-shaped bases. Rare medium sandstone beds (<25 cm) composed of high-angle cross-sets (1 to 10 cm thick) are observed. Mudstone is typically unbioturbated, although rare small *Planolites* are present. Synaeresis cracks are rare and small root traces were observed once.

**Interpretation: Tidal flat deposits**

Facies 6 is interpreted to be a tidal flat deposit. The combined presence of 1) a low-diversity trace fossil assemblage, 2) the mix of vertical and horizontal burrows (a
mixed *Cruziana/Skolithos* assemblage), 3) small burrow size, and 4) synaeresis cracks suggests that the environment was most likely brackish during deposition (Pemberton *et al.*, 2002; Plummer and Gostin, 1981). High-angle cross-stratified laminae with flat bases are interpreted to be current or current-dominated combined-flow ripples, whereas those with markedly scoop-shaped bases are interpreted to be small wave-ripples (Boersma, 1970; Harms *et al.*, 1975; de Raaf *et al.*, 1977). The heterolithic nature of Facies 6 indicates that episodes of suspension deposition (mud) alternated with sand bedload transport by small waves and weak unidirectional flows, which are conditions consistent with tidal flat sedimentation (Postma, 1961; Reineck and Wunderlich, 1968; Amos and Collins, 1978; Dingler and Clifton, 1984). Furthermore, lenticular- and pinstripe-shaped sandstone laminae, although not unique to tidal flats (*e.g.*, Coleman and Gagliano, 1965), are nevertheless very common in tidal flat deposits (Reineck and Wunderlich, 1968; Weimer *et al.*, 1982; Ginsburg, 1975; Klein, 1976; Amos, 1995; Gingras *et al.*, 1999).

**Facies 7: High angle (>15°) cross-stratified sandstone**

Facies 7 is composed of well-sorted coarse to medium sandstone (Figure 4.12). Oil staining is common. Strata of Facies 7 have excellent reservoir quality, with permeabilities on average between 100 to 700 milliDarcies and local maxima of >3 Darcies. Stratification is visible only where mudstone forms thin veneers on bedding surfaces and cross-strata. Beds are typically high-angle (>15°) cross-stratified, and are a maximum 1 m thick. Pore-filling carbonate cement and pebble-sized coal fragments are
present locally. No trace fossils were observed. Beds are organized into ungraded units that are up to 6.5 m thick. Facies 7 erosively overlies Facies 5.

**Interpretation: Fluvial deposits**

Facies 7 is interpreted to be a fluvial channel fill deposit. The presence of coal suggests deposition in proximity to a terrestrial organic source, and the absence of trace fossils suggests that the environment was ecologically stressed. High-angle cross-stratification likely formed by the downstream migration and aggradation of dunes under unidirectional flow (Southard and Boguchwal, 1990; Leclair and Bridge, 2001).

**Facies 8: Coal and pyrite-rich black mudstone**

Facies 8 is composed of massive black mudstone (<50 cm thick) with small (<0.25 cm), roughly circular pyrite ‘blebs’ (Figure 4.13). Organic partings (1-2 mm) are common. The mudstone typically overlies a thin (<5 cm) rooted coal. Thin roots (~1 mm thick) extend down 25 cm below the coal. The rooted zone commonly has a rusty yellowish orange colour. Facies 8 overlies Facies 4 or 7.

**Interpretation: Marsh deposits**

Pyrite in Facies 8 suggests that the depositional environment was most probably marine-influenced. \(\text{SO}_4^{2-}\), which is required to form early diagenetic pyrite, is typically abundant in the pore-waters of surficial sediments in marine environments but scarce in non-marine environments (Berner, 1970). Superposition of the pyrite-rich mudstone overtop of thin rooted coal suggests that the facies formed in conjunction with flooding of
a subareally exposed paleosol surface. As such, Facies 8 was likely deposited in a low-
lying, vegetated region of the coastal plain that became progressively inundated by
brackish or normal marine water (e.g., Frey and Basan, 1978; Bohacs and Suter, 1997).

**Facies 9: Poorly sorted sandstone**

Facies 9 consists of poorly sorted, muddy fine to medium sandstone (Figure 4.14). Sandstone pebbles are common, as are dispersed white quartz sand grains and granules
(‘paint-speckles’). Facies 9 almost always reacts strongly with 10% hydrochloric acid.
Pebble-size coal fragments, coal flakes, and mm-thick coal partings are common.
Bioturbation is typically intense, and burrows are commonly thick walled and robust.
The trace fossil assemblage is dominated by *Ophiomorpha* burrows, with less common
*Chondrites, Skolithos, Palaeophycus, ?Teichichnu*, and *?Rosselia/Cylindrichnus*. Facies
9 erosively overlies either Facies 8, 7, or 5.

**Interpretation: Wave-ravinement lag**

Facies 9 is interpreted to have formed by wave reworking of the shallow seafloor
during rising relative sea level and shoreface retreat (e.g., Fischer, 1961; Demarest and
Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999;
Rodriguez et al., 2001; Hwang and Heller, 2002; Cattaneo and Steel, 2002). Robust,
 thick walled burrows of the *Skolithos* ichnofacies suggest deposition in open marine
conditions (e.g. Pemberton *et al.*, 2002). Sandstone pebbles were likely eroded from
underlying cemented sandstone units during transgressive ravinement (e.g., Cleary *et al*.,
4.6 Facies associations and stratal architecture

Two facies associations were identified in the stratigraphic interval studied (Table 4.3; Figures 4.15a and 4.15b): Facies Association 1, which is interpreted to have been deposited in a storm-dominated shallow marine environment, and Facies Association 2, which is interpreted to have been deposited in a tidally-dominated coastal plain environment.

Facies Association 1 forms upward-coarsening, sheet-like units (20-60 m) that pass gradationally upward from shelf mudstone (Facies 2) to shoreface sandstone (Facies 3 and 4). Thin (<10 cm) rooted coals and pyrite-rich mudstone (Facies 8) occur locally at the top of shoreface deposits. Tabular units of shelf carbonate (Facies 1; 30-40 m thick) rarely gradationally underlie the upward-coarsening units (e.g., Venture limestone 9). Low-relief, areally-extensive erosion surfaces cap the upward-coarsening units; these are overlain by 1 to 2 meters of transgressive lag (Facies 9).

Table 4.3 Facies associations, Venture and West Venture fields

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Constituent facies</th>
<th>Nature of lower contact</th>
<th>Vertical textural change</th>
<th>Geometry parallel to depositional strike in Venture field</th>
<th>Geometry parallel to depositional dip in Venture field</th>
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<tr>
<td>Facies Association 1: Storm-dominated shallow marine deposits</td>
<td>1,2,3,4,8</td>
<td>Transgressive wave ravinement surfaces</td>
<td>upward-coarsening</td>
<td>sheet-like; thickens towards Venture B-52</td>
<td>sheet-like; thicken northward into master growth fault</td>
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<tr>
<td>Facies Association 2: Coastal and alluvial plain deposits</td>
<td>5,6,7</td>
<td>Sequence boundaries</td>
<td>either upward-coarsening or upward-fining</td>
<td>channel form; channels ‘hang’ from Facies Association 1 ‘sheets’</td>
<td>?...not enough well data</td>
</tr>
</tbody>
</table>
Strata of Facies Association 2 fill channels eroded into Facies Association 1 sandstone. Channels are 10-25 m thick and 7-13 km wide, and have multi-storied fills (usually at least 3 stories) that either consist of tidally-influenced fluvial and tidal flat deposits, or coarsen-upward from tidally-influenced fluvial (Facies 5) to continental fluvial sandstone (Facies 7). Locally, fluvial strata are overlain by thin (<10 cm) rooted coal and pyrite-rich mudstone (Facies 8). The top of each multi-storied Facies Association 2 channel fill is truncated by an erosion surface overlain by <2 meters of transgressive lag. The erosion surfaces correlate laterally to the low-relief, areally extensive erosion surfaces that cap the upward-coarsening units of Facies Association 1 (Figure 4.15a).

Parallel to depositional strike, all of the Venture sandstones studied thicken into a growth-faulted area located between the Venture and West Venture Fields (Figure 4.15a). Facies Association 2 channel fills consistently occur in this area. In dip cross section, Venture sandstones 8 to 5 thicken northward into the master growth fault within the Venture Field (Figure 15b). (Because of limited well control within the Venture Field (e.g., Figure 4.15b), this thickening trend is best imaged on 2-D seismic dip lines (e.g., Figure 4.5)). Correlation updip across growth faults to the Arcadia J-16 suggests that Venture sandstones 8 to 5 thin significantly in a proximal direction, and, with the exception of Venture sandstone 6m, pinch out downdip into mudstone when correlated across a growth fault to South Venture O-59 (Figure 4.15b). In contrast, the upward-coarsening Venture sandstone 6m thickens significantly across a growth fault from ~60 m in the Venture Field to ~250 m at South Venture O-59 (Figure 4.15b).
4.7 Depositional model

Each of the abrupt wave-tidal transitions at Venture is interpreted to have formed during a single cycle of relative sea level fall and rise (Figure 4.16). During relative sea level rise, shelf starvation occurred and condensed sections formed. Condensed sections are expressed either as shelf carbonate units (up to 40 m thick – Venture limestone 9) or as cryptic condensed sections within shelf mudstone, at the center of which occur maximum flooding surfaces. During subsequent highstand and falling relative sea level storm-wave dominated shorelines migrated towards the shelf edge, forming upward-coarsening shallow marine successions (Facies Association 1). Incision of any detached forced-regressive shelf-phase deltaic wedges located updip of the shelf margin would have occurred during this time. During the late falling stage and early lowstand, relative sea level likely dropped below the shelf edge, which completed the valley incision process (e.g., Butcher, 1989; Leeder and Stewart, 1996). As relative sea level started to rise, accommodation space was generated in coastal plain regions, and topsets began to onlap the sequence boundary (i.e., the base of the incised valley and any associated interfluve paleosols – which were not observed, likely due to transgressive erosion). Because of their elongate geometry, incised valleys are inferred to have become tidally resonant as they were inundated, which led to the suppression of wave-formed estuary mouth barriers and development of tide-dominated estuaries. When fluvial sediment supply increased during valley infilling, valleys were infilled progradationally (e.g., Venture sandstones 8 and 7), whereas valleys were infilled retrogradationally when fluvial sediment supply remained constant (e.g., Venture sandstone 6m). As the valleys infilled, heightened frictional resistance caused tidal currents to diminish, which allowed
waves to progressively control estuarine geomorphology. This culminated in wave-dominated shoreface retreat over the filled incised valleys, which formed erosion surfaces capped by 1 to 2 m of transgressive lag that locally contains hummocky cross-stratification.

Two of the Venture sandstones studied (6l and 6u sandstones) are of note because they lack abrupt wave-tide transitions, but instead are composed of storm-wave dominated shoreface deposits (Figure 4.15a and 4.15b). Venture sandstone 6l consists of lower shoreface sandstone (Facies 3) that gradationally overlies offshore mudstone (Facies 2). Given the absence of an associated overlying incised valley, it is unclear whether Venture 6l formed by forced regression (i.e., it is overlain by a sequence boundary) or by normal regression during lowstand (i.e., it onlaps a sequence boundary; see Plint and Nummedal, 2000). Venture sandstone 6u also lacks an incised valley fill, but in contrast to sandstone 6l, abruptly overlies a transgressive wave ravinement surface and fines upwards from upper and lower shoreface sandstone into offshore mudstone. As such, Venture sandstone 6u is interpreted to be a shallow marine sandstone body formed in association with transgressive wave ravinement and shoreface retreat (e.g., Snedden and Dalrymple, 1999).

4.8 Discussion

As argued previously, 2-D seismic data suggest that the stratigraphic interval investigated was deposited 5 to 20 kilometers updip of the shelf break (Figure 4.5). Supporting this interpretation is the significant stratigraphic variation observed when Venture sandstones 8 to 5 are correlated to the only well located downdip of the Venture
Field, South Venture O-59. In the Venture Field, upward-coarsening successions are between 20-60 m thick, but when correlated to South Venture O-59, either grade basinward into mudstone (Venture sandstones 8 and 7) or thicken significantly to ~250 m (Venture sandstone 6m; Figure 4.15b). Because shelf edge deltas are commonly several times thicker than their shelf-phase counterparts (e.g., Winn et al., 1998; Porebski and Steel, 2003; Sydow et al., 2003), the thicker (~250 m) upward-coarsening succession observed in South Venture O-59 likely formed by progradation of a delta across the shelf edge and onto the upper slope. Thinner (40-60 m) upward-coarsening successions at Venture likely formed in a more proximal position on the outer shelf. Location of the shelf margin between Venture and South Venture Fields during deposition of Venture sandstones 8 to 5 is also consistent with the absence of Venture sandstones 8 and 7 in South Venture O-59, because progradation of the Venture sandstone 8 and 7 shorelines likely terminated at the shelf edge prior to reaching South Venture.

The development of stratal architecture and sand-body distribution both within and downdip of the Venture Field was likely controlled by differential subsidence at the Lower Missisauga shelf margin. In the Venture Field, Venture sandstones 8 to 5 thicken towards the master Venture growth fault (Figure 4.5; Figure 4.15b), suggesting that sand-body thickness increases northward (updip) within the Venture Field. Venture sandstones 8 to 5 also thicken toward an extensively growth-faulted zone between the Venture and West Venture Fields (Figure 4.15a). Incised valleys consistently cross-cut this zone, suggesting that over the course of several cycles of relative sea-level rise and fall, the axes of fluvio-deltaic systems, despite a natural tendency to stack in a laterally-offset or ‘compensational’ pattern at the shelf margin (e.g., Sydow, 1996), were
consistently diverted into the zone of maximum subsidence (e.g., Bridge and Leeder, 1979; Mackay and Bridge, 1995; Morton and Suter, 1996; Sydow et al., 2003). Because growth faults at depth are commonly better imaged than incised valleys by seismic data, this relationship may help improve the effectiveness of predicting reservoir distribution downdip of the shelf margin in regions where seismic resolution is poor and well control is lacking.

4.9 Conclusions

The abrupt transition from wave- to tide-dominated deposition in Venture sandstones 8 to 5 likely formed on the outer shelf just landward of the shelf edge during repetitive episodes of storm-dominated forced regression and tidally-influenced transgressive incised valley fill. Stratal architecture within the Venture Field was likely controlled by differences in syn depositional subsidence, which caused Venture sandstones to thicken northward, or updip, towards the master growth fault, as well as westward parallel to depositional strike towards a high subsidence zone located between the West Venture and Venture Fields. Differential subsidence within the Venture Field most probably also controlled downdip sandbody distribution and sediment supply, because the axes of fluvio-deltaic systems, which are expressed by incised valleys, appear to have repeatedly reoccupied the zone of high subsidence between the West Venture and Venture Fields over the course of several relative sea level cycles.
Figure 4.1  Characteristics of abrupt wave-tidal transitions caused by (a) regressive-to-transgressive shoreline turnaround and estuarine incised valley fill, (b) normal regression of a 'mixed-energy' tide- and wave-influenced delta, and (c) enhancement of tidal currents during regression due to the onset of tidal resonance. Data and concepts from Oomkens (1974), Zaitlin et al. (1994), Gastaldo (1996), Posamentier and Vail (1988), Muto and Steel (1992), Best and Ashworth (1997), Suter (2001), Willis and Gabel (2001, 2003), Martinsen et al. (2001), Posamentier, 2001; Berné et al. (2002), Pemberton et al. (2002), Yoshida et al. (2003), and Dalrymple et al., 2003.
a) Regressive-to-transgressive shoreline turnaround and estuarine incised valley fill

**Dimensions of tidally-influenced lithosome (estuarine incised valley fill)**
- L is commonly large (no astute transect problem if regression is forced)
- D can be large (often > 30 m mean channel depth; typically < 100 m)
- W typically small (< 10 km unless protracted forced regression and lowstand)

**Stratal architecture of tidally-influenced lithosome (estuarine incised valley fill)**
- Usually backstepping, although may be progradationally filled if fluvial input increases
- Channel fills within valley fill are commonly stacked (multi-storied)
- What cuts valley during regression does not necessarily fill it (nonetheless, fluvial sediments are common at the base of incised valleys, however there is little fluvial accommodation during falling sea level; thus fluvial sediments can be eroded if tidal reinitiation occurs, which would superimpose estuarine sediments directly over basal erosion surface)

b) Normal regression of a wave- and tide-influenced 'mixed-energy' delta

**Dimensions of tidally-influenced lithosome (tidally-influenced channel fill)**
- L is commonly small (mean channel depth; typically < 30 m, typically < 15 m)
- D is typically small (< 5 km unless high fluvial input vs. subsidence)
- W is typically small (< several km unless high fluvial input)

**Stratal architecture of tidally-influenced lithosome (tidally-influenced channel fill)**
- Forwards-stepping
- Channel fills typically not stacked (usually single storied)
- What cuts channel during regression likely overlies it (i.e., channel base overlies by fluvial or tidally-influenced fluvial deposits)

C) Switch from wave- to tidally-dominated sedimentation during regression

**Dimensions of tidally-dominated lithosome (tidally-dominated delta)**
- L can be small or large (constrained by the shape of the tidally-resonant topographic depression)
- D is likely smaller (< 20 m), except where localized tidal scour is intense
- W can be large (up to 300 km, constrained laterally by the shape of the basin)

**Stratal architecture of tidally-dominated lithosome (tidally-dominated delta)**
- Forward stepping to aggradational (although individual distributary channels fill by lateral accretion)
- What erosive surface during regression likely overlies it (i.e., erosion surface overlain by subtidal/heterolithic deposits (e.g., distributary channels))
Figure 4.2  Isopach map, Scotian Basin, offshore Nova Scotia. Contours are in kilometers. Modified from MacLean and Wade (1992)
Figure 4.3  Dataset and structure, Venture Field region (modified from Canada Nova Scotia Offshore Petroleum Board, 2000).
Figure 4.4 Stratigraphy of sandstone reservoirs, Venture and West Venture fields (after Wade and MacLean (1990) and Sable Offshore Energy (1996)).
Figure 4.5  Dip-oriented seismic cross-section, Venture Field region. Southward-dipping reflections located south of the Venture Field are interpreted to be progradational shelf-margin clinoforms.
Figure 4.6  Facies 1: carbonate mudstone (interpretation – condensed outer-shelf carbonate deposits). Facies 1 is a massive to faintly laminated carbonate mudstone that contains brachiopod, bryozoan and foraminifera bioclasts and lacks potential framework building organisms. Photo taken from West Venture C-62, core 13, box 12, 5275.44 m (measured depth).
Figure 4.7  Facies 2: Mudstone with low angle (<10°) cross-stratified sandstone interbeds (interpretation – storm-dominated offshore to lower shoreface deposits). Photo taken from West Venture C-62, core 9, box 24, 5190.3 m (measured depth).
Figure 4.8  Facies 3: Low-angle (<10°) cross-stratified sandstone (interpretation – storm-dominated lower shoreface deposits). (a) Sedimentological log from West Venture C-62, core 9, boxes 17 to 20, 5182-5186.2 m (measured depth), and (b) low angle (<10°) cross-stratified sandstone (Facies 3 - see Figure 4.8a for location). Note truncation surface (arrow), fining upward trend, and gentle fanning of laminae – features common to hummocky cross-stratification.
Table 4.1: Facies Description

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>FACES ASSOCIATION</th>
<th>RESEROIR</th>
<th>LITHOSTRAT</th>
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<td>low-angle (&lt;10 degrees) cross stratified very fine to fine sandstone (hummocky cross-stratified); rare mudstone interbeds; HCS beds often have low angle internal truncations and thinning laminae, and are commonly capped by one or several small-scale wave ripple cross-sets that have low angle, scooped-shaped truncations; bioturbation is typically absent, although rare Ophiomorpha burrows are present; lower contact is arbitrary; no high angle (&gt;15 degrees) cross-stratification.</td>
<td>Facies 3: Storm-dominated shallow marine deposits</td>
<td>Lower Member, Mississauga Fm</td>
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<td>Siltstone/lower very fine sandstone beds are wavy low angle wave ripple cross-stratified, often with low angle truncations; laminae commonly fan internally within a sandstone bed and are gently curved to flat; sandstone beds often fine-upward; trace fossils include Asterosoma, Planolites, Helminthopsis, Trichichnus.</td>
<td>Facies 2: Storm-dominated shallow marine deposits</td>
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<td>Fig. 4.8b</td>
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(a) Diagram of sedimentary strata with labels and scale.

(b) Close-up image of sedimentary structures with scale.
Figure 4.9  Facies 4: Interstratified high angle (>15°) and low angle (<10°) cross-stratified sandstone (interpretation – upper shoreface deposits). Sedimentological log from West Venture N-91, core 8, boxes 16 to 7, 5124.65-5113.23 m (measured depth).
Figure 4.10  Facies 5: Mudstone with high-angle (>15°) cross-stratified sandstone interbeds (interpretation – tide-influenced fluvial deposits). (a) Upward-fining Facies 5 channel fill unit (West Venture C-62, core 5, boxes 25 to 18, 5099.6-5092 m (measured depth)), (b) ?Taenidium burrows (West Venture C-62, core 5, box 21, 5096.14 m (measured depth)), and (c) rhythmically laminated mudstone and very fine sandstone (interpretation – tidal rhythmites; Venture H-22, core 2, box 1, 4895 m (measured depth)).
<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOFACIES</th>
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<tr>
<td>5093.2 m (MD)</td>
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<td>Channel base</td>
<td>Facies 5</td>
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<td>Organic facies-rich double mud drapes</td>
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<td>Channel base</td>
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<tr>
<td>5099.6 m (MD)</td>
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Figure 4.11  Facies 6: Mudstone with lenticular and pinstripe-shaped sandstone laminae (interpretation – tidal flat deposits). Note small Planolites burrows (Pl), and lenticular (L) and pinstripe (P) shaped sandstone laminae. Photo taken from West Venture C-62, core 6, box 4, 5104.85 m (measured depth).
Figure 4.12  Facies 7: High angle (>15°) cross-stratified sandstone (interpretation – fluvial deposits). (a) Sedimentologic log from West Venture C-62, core 8, boxes 18 to 3, 5164.75-5148.75 m (measured depth), and (b) photo of Facies 7 showing intense local oil staining from West Venture C-62, core 8, boxes 9 to 7, 5156.22-5153.18 m (measured depth).
Figure 4.13  Facies 8: Coal and pyrite-rich black mudstone (interpretation – drowned, marine-influenced marsh deposits). Photo taken from West Venture C-62, core 8, box 6, 5153.18 m (measured depth).
Figure 4.14  Facies 9: Poorly sorted sandstone (interpretation – transgressive lag) erosively overlying mudstone with pyrite (Facies 7; interpretation – tidally influenced fluvial deposits). The erosion surface (interpretation – transgressive ravinement surface) is the contact between Venture sandstone 6m and Venture sandstone 6u. Photo taken from West Venture C-62, core 5, box 11, 5082.2 m (measured depth).
Figure 4.15a  Strike-oriented well log cross-section, Venture and West Venture fields.

Note how sandstones thicken into a zone of growth faults between the Venture and West Venture fields, which is also the site of most incised valleys.
Figure 4.15b  Dip-oriented well log cross-section, Venture Field. Note that correlation landward and basinward of the Venture Field is complicated by intervening growth faults. Also note the significantly more mudstone-rich nature of the South Venture O-59 well, located only ~8 km south of the Venture Field.
Figure 4.16  Depositional model, Venture sandstones 8 to 5, Venture and West Venture fields.
a) Maximum flooding surface
- carbonate deposition on shelf

b) Highstand

(c) Falling relative sea level
- deposition of upward-coarsening shallow marine deposits (Facies Association 1)

d) Lowstand

e) Initial transgression
tidally reworked incised valley

e) Transgressive systems tract
- valley fills, becomes tidally dissonant, and transgressive wave ravinement occurs
Chapter 5. Mesozoic shelf-margin deltas, offshore Nova Scotia, Canada:  

Significance to petroleum exploitation and exploration

5.1 Introduction

Following their identification in seismic data from the Gulf of Mexico in the 1960s (Curray and Moore, 1964; Lehner, 1969), shelf-margin deltas have been the focus of much research, not only because they commonly contain substantial hydrocarbon reserves (Hart et al., 1997; Meckel, 2003), but because they form the basic building blocks of accretionary continental margins, are useful in delineating ancient shelf margin positions, and commonly act as staging areas for sediment delivered to downdip slope turbidite systems (Winker and Edwards, 1983; Suter and Berryhill, 1985; Porebski and Steel, 2003). Although they have now been identified in most hydrocarbon-rich passive margin basins (e.g., offshore west Africa, Brazil, Gulf of Mexico), hydrocarbon-bearing shelf-margin deltas have not been explicitly recognized in the passive margin basin offshore Nova Scotia, perhaps because shelf-margin positions are rarely well resolved in seismic data at depth. However, it is argued that several of the largest hydrocarbon accumulations in the Missisauga Formation, the major hydrocarbon-bearing unit offshore Nova Scotia, are contained in deltaic sandstones deposited at or near the shelf margin. The objective of this article is to describe the sedimentology and stratigraphy of deposits in the Alma, Glenelg and Venture fields that are interpreted to have been deposited, at least in part, by shelf-margin deltas.
5.2 Dataset and methodology

The results of this study are based on the analysis of an integrated dataset from the Sable Subbasin, offshore Nova Scotia (Figure 5.1), including geophysical well logs and cuttings data from 89 wells, 1335 m of conventional core from 23 wells (Figure 5.2a), public and confidential biostratigraphic data (Figure 5.2b), ~1825 km of publicly available paper-format 2-D seismic data and an industry-donated digital 3-D seismic survey (96 km²) from the Panuke Field cut off at 2.2 seconds (Figure 5.2c). Additionally, Rob Fensome (Geological Survey of Canada) analyzed seven palynology samples collected from conventional cores from the West Venture C-62 well (see Chapter 4).

Cores were described in 2.5 cm resolution (see Appendix 1), noting lithology, sedimentary textures and structures, body fossils, trace fossils, macroscopic diagenetic features, and the nature of stratigraphic contacts. Depositional processes and depositional environments were interpreted using a standard “process-oriented” facies analysis approach (e.g., Harms et al., 1975; Scholle and Spearing, 1982; Walker and James, 1992; Reading, 1996; Pemberton et al., 2002). Geophysical well logs were calibrated using core data, and were tied to seismic data using synthetic seismograms generated from sonic or sonic and density logs. Seismic, well log, and core data were interpreted using standard sequence stratigraphic techniques and concepts (e.g., Curray, 1964; Vail et al. (1977); Posamentier and Vail, 1988; Van Wagoner et al., 1990; Emery and Myers, 1996; Posamentier and Allen, 1999).
5.3 Geological setting and stratigraphy

The Sable Subbasin is one of several interconnected Mesozoic-Cenozoic depocenters that make up the passive margin basin offshore Nova Scotia (Figure 5.1). The center of the Sable Subbasin is underlain by syn-rift salt, and contains numerous growth faults and salt tectonic features. Terrigenous clastic sediments are believed to have been fed southwestward into the subbasin by the paleo-St. Lawrence river, a sediment-charged, continental-scale fluvial system that likely drained much of Eastern Canada (Wade and MacLean, 1990; Grist et al., 1992).

Fluvial to slope siliciclastics of the Missisauga Formation (Portlandian-Aptian) form a seaward-thickening wedge in the Sable Subbasin that reaches an estimated maximum thickness of ~3.5 km below the modern shelf edge (Figures 5.3 to 5.5). The Missisauga Formation contains ~75% of the original-gas-in-place reserves discovered offshore Nova Scotia, or ~192 x 10^6 m^3 (Canada Nova Scotia Offshore Petroleum Board, 2000). In the central Sable Subbasin, the Missisauga overlies a slightly more mudstone- and carbonate-rich unit, the Mic Mac Formation, and is overlain by mudstone of the Naskapi Member of the Logan Canyon Formation. In the western edge of the subbasin, the Missisauga is underlain by Jurassic carbonates of the Abenaki Formation.

Typically, the Missisauga Formation is subdivided into two or three members (Figure 5.3). The three-member framework, which was proposed by Wade and MacLean (1990) and elaborated on by MacLean and Wade (1993), is similar to the two-member frameworks of Given (1977) and Welsink et al., (1989), but recognizes a third, older member in the central Sable Subbasin that is coeval with the terminal phases of Abenaki carbonate deposition. Although offering potentially better stratigraphic resolution,
regional correlation of the top of the lowermost member of Wade and MacLean (1990) in seismic or well log data is problematic (cf. Figure 9 in Wade, 1991; MacLean and Wade, 1993), which makes the three-member framework difficult to apply in practice.

The O Marker is the only prominent, regionally extensive seismic reflections occurring in the Mississauga Formation. The reflection is generated by a mixed mudstone-sandstone-oolitic limestone unit at the base of the Upper Mississauga. It is identifiable throughout the Sable Subbasin in regions northwest of the Onondaga field (Figure 5.6). On geophysical well logs, the most easily recognizable marker is the contact between sandstone of the Mississauga Formation and mudstone of the overlying Naskapi Member of the Logan Canyon Formation.

Below the modern continental shelf, the Mississauga Formation forms flat, parallel seismic reflections that dip gently toward the southeast (Figure 5.7)\textsuperscript{16}. Core data suggests that the reflections are associated with fluvial and shallow marine deposits, suggesting that they are continental shelf topsets. Cycles of onlap and offlap are not obvious, so the Mississauga Formation is not readily amenable to Vail-type seismic stratigraphic analysis (Cloetingh et al., 1989). When traced downdip, continental shelf topset reflections in the Mississauga Formation typically lose their coherency in a seismic noise zone below the modern continental shelf edge. As a result, large-scale clinoform reflections that would normally be interpreted as shelf margin and slope deposits are typically not resolved in seismic data, although important exceptions exist (see "Seismic Data" section below).

\textsuperscript{16} Rare, small (i.e. maximum tens of meters thick) clinoform reflections interpreted to be deltaic in origin are locally visible between the flat, parallel reflections (John Harper, personal communication, 2003)
5.4 Sedimentology

Parts of the Missisauga Formation in the Alma, Glenelg and Venture fields contain thick (i.e., typically tens- to hundreds-of-meters thick), upward-coarsening successions that overlie relatively mudstone-rich strata (Mic Mac or Verrill Canyon formations), that in turn are overlain by relatively sandstone-rich strata composed of thinner upward-coarsening successions (i.e., each is at most several tens-of-meters thick). The sedimentology of these deposits is described below. For brevity, facies descriptions and interpretations are presented in table format (Tables 5.1 to 5.3).\(^\textsuperscript{17}\)

5.4.1 Sedimentology - Venture Field (Lower Missisauga)

The Venture D-23 well was drilled by Mobil et al. in 1978 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of an east-west-trending growth fault (Figure 5.8). Gas was encountered in sixteen isolated sandstone reservoirs in an interval that straddles the boundary between the Mic Mac Formation and the overlying Lower Member of the Missisauga Formation (Figure 5.9; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). Four delineation wells (Venture B-13, B-43, B-52 and H22) were drilled in the early 1980s, and four production wells (Venture V1, V2, V3 and V5) were drilled between 1998 and 2002 (Sable Offshore Energy, 1996). Original gas in-place is estimated to be 2341 billion cubic feet (~66.3 m\(^3\) x 10\(^9\)), which is ~25% of the original in-place gas discovered to date offshore Nova Scotia (Canada-Nova Scotia Offshore Petroleum Board, 2000). Venture sandstones 8 to 5, which form the focus of this study, are all overpressured (Figure 5.10).

\(^{17}\) Extended facies analyses for the Alma and Glenelg fields are available in Appendix 2, and in Chapters 3 and 4 for the Panuke and Venture fields, respectively.
<table>
<thead>
<tr>
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<th>Interpretation</th>
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</thead>
<tbody>
<tr>
<td>V1</td>
<td>light blue-gray carbonate mudstone</td>
<td>massive to faintly laminated</td>
<td>brachiopod, bryozoan, and foraminifera bioclasts</td>
<td>blocky</td>
<td>shelf carbonate deposits</td>
</tr>
<tr>
<td>V2</td>
<td>mudstone with rare to common thin (&lt;10 cm) silstone and very fine sandstone beds</td>
<td>Siltstone and sandstone beds are typically planar to low-angle (&lt;10°) (hummocky) cross-stratified</td>
<td>sparse to intense bioturbation, with Planolites, Palaepolyus, Asteroidea, Helminthogast, Chondrites, Zoophycos, Terebellina, Teichichnus, and Rossellia; several specimens of a Circulatium-like dinoflagellate and one Subtilisphaera-like specimen observed (Rob Pensone, personal communication, 2002)</td>
<td>upward-coarsening</td>
<td>inner shelf/lower shoreface deposits</td>
</tr>
<tr>
<td>V3</td>
<td>well-sorted, very fine to fine buff-coloured sandstone</td>
<td>sandstone is horizontally laminated to low-angle (&lt;10°) (hummocky) cross-stratified</td>
<td>bioturbation is sparse, with Ophiomorpha, Rossella, and ?Cylindricalus in sandstone, and Teichichnus, Palaepolyus, Terebellina, Chondrites, Ophiomorpha, Cylindricalus, ?Asteroidea, and ?Rossellia in rare mudstone beds</td>
<td>upward-coarsening to blocky</td>
<td>storm-dominated lower shoreface deposits</td>
</tr>
<tr>
<td>V4</td>
<td>moderately to well-sorted medium sandstone</td>
<td>sandstone beds (1-25 cm thick) are high-angle (&gt;15°) to low-angle (&lt;10°) cross-stratified</td>
<td>bioturbation is sparse, with rare Ophiomorpha burrows; rare layers of sparsely disseminated organic flecks in sandstone</td>
<td>blocky to upward-coarsening</td>
<td>storm-dominated upper shoreface deposits</td>
</tr>
<tr>
<td>V5</td>
<td>Mudstone with common fine to coarse sandstone interbeds (10-75 cm thick)</td>
<td>sandstone is high-angle (&gt;15°) cross-stratified (subaqueous dunes); rare synaeresis cracks, local structures, double mud drapes, and rhythmically laminated intervals</td>
<td>bioturbation typically absent, but rare, intensely burrowed intervals of ?Planolites present in sandstone; also rare Ophiomorpha and Diplocraterion present in sandstone; mudstone contains rare Teichichnus, Thalassinoides, ?Bryozoridium and small Planolites pebbles-sized abundant coal clasts and disseminated organic flecks; one possible dinoflagellate observed (Rob Pensone, personal communication, 2002)</td>
<td>sharp-based and serrated, units commonly fine upward slightly</td>
<td>tide-influenced fluvial deposits</td>
</tr>
<tr>
<td>V6</td>
<td>mudstone with pinstripe, wavy, and lenticular laminated very fine sandstone</td>
<td>sandstone laminae are typically high-angle (&gt;15°) cross-stratified and have flat to scooped-shaped bases (wave and current ripples, respectively); rare synaeresis cracks</td>
<td>typically unbioturbated, although rare small Planolites burrows observed; root traces observed once</td>
<td>serrated</td>
<td>tidal flat deposits</td>
</tr>
<tr>
<td>V7</td>
<td>well sorted medium to coarse sandstone</td>
<td>beds are typically high-angle (&gt;15°) cross-stratified (subaqueous dunes); cross sets are a maximum of ~1 m thick</td>
<td>no trace fossils observed; coal fragments present locally</td>
<td>blocky</td>
<td>fluvial deposits</td>
</tr>
<tr>
<td>V8</td>
<td>coal and pyrite-rich black mudstone</td>
<td>no trace fossils observed</td>
<td>usually thin bed (&lt;1 m thick) with higher API values</td>
<td>marsh deposits</td>
<td></td>
</tr>
<tr>
<td>V9</td>
<td>poorly sorted, carbonate-cemented sandstone with a &quot;painted&quot; appearance</td>
<td>typically not visible due to intense bioturbation</td>
<td>bioturbation is commonly intense, with Ophiomorpha, Chondrites, Skolithos, Palaepolyus, ?Teichichnus, and ?Rossellia/Cylindricalus; pebble-size coal fragments, coal flakes, and mm-thick coal partings are common</td>
<td>usually thin bed (&lt;1 m thick) with low API values</td>
<td>transgressive lag deposits</td>
</tr>
<tr>
<td>Facies</td>
<td>Lithology and texture</td>
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</tr>
<tr>
<td>A1</td>
<td>mudstone</td>
<td>microfaults are present locally, and thin (&lt;1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical &quot;streaks&quot; lacking organic particles are also observed locally (interpretation: pillar structures formed by water escape (see Druitt, 1994; Middleton et al., 2003))</td>
<td>Bioturbation is absent or very minimal, and includes Teichichnus, Planolites, Asterosoma, Helminthopsis, Chondrites, Zoophycos, ? Arenicolites, Palaeophycus, Terebellina; shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on beddings surfaces</td>
<td>upward-coarsening</td>
<td>mudstone with evidence of gravity-flow deposition; deposited below storm-weather wave base</td>
</tr>
<tr>
<td>A2</td>
<td>interstratified mudstone and thin beds of (&lt;10 cm), very fine sandstone</td>
<td>thin sandstone beds are typically planar to low-angle (&lt;10°) cross-stratified (hummocky cross stratification), or rarely small-scale (&lt;5 cm) high-angle (&gt;15°) cross-stratified (current ripples – sometimes capping planar laminated beds – these are interpreted to be Bouna T5 turbidites)</td>
<td>Bioturbation in mudstone is generally low, and includes Asterosoma, Planolites, Teichichnus, Zoophycos, and ? Cylindricalis; rare escape traces and Ophiomorpha in sandstone</td>
<td>upward-coarsening</td>
<td>storm-influenced delta front (lower shoreface?) heteroliths deposited above storm wave base</td>
</tr>
<tr>
<td>A3</td>
<td>very fine to medium sandstone</td>
<td>where not obscured by bioturbation, sandstone is either planar laminated, low-angle (&lt;10°) cross-stratified (hummocky cross-stratified), or medium-scale (10-20 cm) high-angle cross-stratified</td>
<td>bioturbation is commonly intense, with Ophiomorpha Palaeophycus, Helminthopsis, Planolites, Skolithos, Teichichnus, Zoophycos, Asterosoma, ?Thalassinoides, ?Conicidus and ?Diplocraterion.</td>
<td>upward-coarsening</td>
<td>Unstressed delta front (shoreface?) deposits</td>
</tr>
<tr>
<td>A4</td>
<td>poorly-sorted, carbonate cemented sandstone with &quot;paint-speckled&quot; appearance</td>
<td>Sedimentary structures are rarely preserved due to bioturbation</td>
<td>Bioturbation is typically intense, and includes Ophiomorpha, Planolites, ?Asterosoma, ?Thalassinoides, and Helminthopsis; bivalve, scalchopod, and gastropod shell fragments are common</td>
<td>usually occurs as a thin bed (&lt;1 mm thick) with low API values</td>
<td>transgressive lag</td>
</tr>
<tr>
<td>A5</td>
<td>poorly-sorted, muddy coarse to very fine sandstone</td>
<td>typically not visible due to intense bioturbation</td>
<td>bioturbation is intense, with large Ophiomorpha and Palaeophycus (trace fossils hard to ID due to intense bioturbation)</td>
<td>sharp-based, upward fining</td>
<td>transgressive shelf sandstone</td>
</tr>
<tr>
<td>Facies</td>
<td>Lithology and texture</td>
<td>Physical sedimentary structures</td>
<td>Biogenic features</td>
<td>Gamma ray log character</td>
<td>Interpretation</td>
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</tr>
<tr>
<td>G1</td>
<td>mudstone with thin, very fine sandstone interbeds</td>
<td>sandstone beds are planar laminated to low-angle (&lt;10°) cross-stratified (hummocky cross-stratified); sandstone beds are rarely normally graded; some rhythmically laminated intervals in both mudstone and sandstone interbeds (bundled tidal rhythms); deformed muddy sandstone beds common</td>
<td>bioturbation in mudstone is typically very low, with Planolites, Teichichnus, Terebellina, and Asterosoma; rare Ophiomorpha in sandstone beds; disseminated organic flecks are common</td>
<td>upward-coarsening</td>
<td>Storm- and tide-influenced prodelta deposits</td>
</tr>
<tr>
<td>G2</td>
<td>interlaminated mudstone and very fine sandstone</td>
<td>rhythmically alternating mudstone and sandstone laminae (bundled tidal rhythms); rhythms typically form successions that progressively thicken and thin; contacts between sandstone and mudstone laminae are typically gradational</td>
<td>no bioturbation observed; disseminated coal flecks abundant throughout</td>
<td>slightly serrated</td>
<td>tide-dominated delta front deposits (delta front interpretation based on stratigraphic position above Facies G1 and below Facies G3)</td>
</tr>
<tr>
<td>G3</td>
<td>medium to very coarse sandstone with thick mudstone interbeds</td>
<td>sandstone beds (~20 cm ave.) are commonly high-angle (&gt;15°) cross-stratified (subaqueous dune cross-stratification); bipolar cross-sets and double mud drapes observed; mud intraclasts present; rare rhythmically laminated intervals (like Facies G2) present</td>
<td>bioturbation very sparse, and includes Skolithos, Diplocraterion and Ophiomorpha in sandstone, and small Planolites in mudstone; pebble-sized coal clasts and disseminated coal flecks abundant throughout</td>
<td>serrated, sharp-based upward-finishing</td>
<td>tide-influenced fluvial channel fill deposits</td>
</tr>
<tr>
<td>Facies G4</td>
<td>organic-rich mudstone with thin rooted coal beds</td>
<td>Stratification is typically not visible, although rare high-angle (&gt;15°) cross-sets (~15 cm thick) are visible locally (subaqueous dune cross-stratification)</td>
<td>bioturbation increases upward; trace fossils were hard to identify, but rare Teichichnus burrows observed locally</td>
<td>upward-fining</td>
<td>transgressive abandonment deposits (grades up from Facies G3 or G5)</td>
</tr>
<tr>
<td>Facies G5</td>
<td>coarse sandstone</td>
<td>bioturbation sparsely throughout (Ophiomorpha); rare pebble-sized coal clasts</td>
<td></td>
<td>sharp-based blocky</td>
<td>Tidal inlet fill (occurs over coastal plain (Facies G3 and G5) and under marine (Facies G6 and G7) deposits)</td>
</tr>
<tr>
<td>Facies G6</td>
<td>mudstone with thin, very fine sandstone interbeds</td>
<td>sandstone beds are horizontally laminated to low-angle (&lt;10°) cross-stratified (hummocky cross-stratification)</td>
<td>bioturbation in mudstone is typically low, with Planolites, Asterosoma, Zoophycos, Teichichnus, Terebellina, and Rosselia; rare Ophiomorpha, Cylindrichnus Chondrites and Palaephycus burrows are present in sandstone</td>
<td>upward-coarsening</td>
<td>Storm-dominated shoreface and offshore deposits</td>
</tr>
<tr>
<td>Facies G7</td>
<td>poorly sorted sandstone</td>
<td>typically not visible</td>
<td>bioturbation is locally intense, and Ophiomorpha burrows predominate; unlined, sandstone-filled Thalassinoides commonly penetrate down from Facies G7 into underlying mudstone</td>
<td>usually thin bed (&lt;1 m thick) with low API values</td>
<td>transgressive lag</td>
</tr>
</tbody>
</table>

Venture sandstones 8 to 5 occur at the base of the Lower Member of the Missisauga Formation, and overlie the slightly more mudstone-rich strata of the Mic Mac Formation. In the Venture and West Venture fields, Venture sandstones 8 to 5 each consist of an upward-coarsening unit overlain locally by a sharp-based, channel-form unit (Figures 5.11 and 5.12; Table 5.1). Upward-coarsening units are 20-60 m thick, and grade upward from mudstone with sparsely bioturbated, planar laminated and hummocky cross-stratified sandstone interbeds (Figures 5.12a and 5.12b; Facies V2) into sparsely bioturbated sandstone with interstratified low- (<10°) and high-angle (>15°) cross-stratification (Figures 5.12a and 5.12b; Facies V3 and V4). Rarely, carbonate mudstone units occur at the base of upward-coarsening successions (Facies V1). Channel-form units that erosively overlie upward-coarsening units are 10-25 m deep by 7-13 km wide and contain abundant mudstone and high-angle (>15°) cross-stratified sandstone, rare rhythmic lamination, little bioturbation, and rare rooted coal (Figures 5.12c and 5.12d; Facies V5 to V8). A continuous thin layer (<1 m) of bioturbated, poorly sorted sandstone (Facies V9) erosively overlies the top of each upward-coarsening and channel fill succession.
In strike cross section, Venture sandstones 8 to 5 thicken towards a growth fault zone between the Venture and West Venture fields, which is also the location of most of the channel-form units (Figure 5.11a). In dip-cross section, sandstones pinch out downdip over <5 km except for Venture sandstone 6, which appears to thicken downdip to a >200 m-thick upward-coarsening succession (Figure 5.11b). Above Venture sandstones 8 to 5, upward-coarsening units are typically more isopachous and easier to correlate between Venture and South Venture wells.

Each upward-coarsening succession is interpreted to have formed during a single cycle of relative sea level fall and rise. Upward-coarsening successions with abundant low-angle (<10°) cross-stratified sandstone are inferred to be regressive storm-dominated prodelta and delta front deposits. Carbonate mudstone present at the base of some upward-coarsening successions likely represent marine condensed sections formed during maximum transgression and terrigenous sediment starvation. Channel-form erosion surfaces at the top of the upward-coarsening units are interpreted to be incised valleys formed during sea level fall, which were then filled with heterolithic facies (tide-dominated estuarine deposits) emplaced during subsequent sea level rise. The change from regressive, storm-dominated sedimentation to tide-dominated transgressive sedimentation suggests that once relative sea level started to rise, tidal currents were strengthened as incised valleys became progressively drowned.

5.4.2 Sedimentology - Alma Field (Upper Missisauga)

The Alma F-67 well was drilled by Shell/Petro-Canada et al. in 1983 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of an east-west-
trending growth fault (Figure 5.13). Gas was encountered in three heterolithic, vertically stacked and isolated Barremian reservoir intervals informally termed the Alma A, B, and C "sands" (Figure 5.14; Lentin, 1987; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). A second well, Alma K-85, was drilled in 1985 to delineate the field. Development drilling started in 2003 under the Sable Offshore Project (Sable Offshore Energy, 1996). Original gas in-place is estimated to be 630 billion cubic feet (~17.8 m$^3 \times 10^9$), which is ~7% of the original gas in-place discovered offshore Nova Scotia prior to 2000 (Canada-Nova Scotia Offshore Petroleum Board, 2000). "Sand" A is the main Alma reservoir, and is estimated to contain ~77% of the original gas in-place in the Alma field (Canada-Nova Scotia Offshore Petroleum Board, 2000). Several unpublished studies contain data on the structure and sedimentology of the Alma field (Sable Offshore Energy, 1996; Mobil Oil Canada, 1998a; Canada-Nova Scotia Offshore Petroleum Board, 2000; Ingram, 2002).

At Alma, the Missisauga sandstone package is relatively thin (~268 m; MacLean and Wade, 1993) and young (Barremian to Aptian; Lentin, 1987; late Haueriuvian to Barremian, Jason Crux, personal communication, 2004), and is interpreted to correlate with the Upper Member of the Missisauga Formation (cf. MacLean and Wade, 1993). Microfossil data from the Alma F-67 well suggests that rapid and substantial shallowing started to occur ~125 m below the base of the Upper Missisauga sandstones within mudstone of the Verrill Canyon Formation, and that rapid deepening occurred at the top of the Upper Missisauga (Lentin, 1988; Figure 5.14). The onset of overpressuring occurs ~400 m below the sandstone-rich Upper Missisauga within Verrill Canyon mudstone (Figure 5.10 and 5.14).
The Upper Missisaugan at Alma consists entirely of stacked, upward-coarsening successions between 10 and ~200 m thick (Facies A1 to A4), with the exception of one ~30 m thick, intensely bioturbated, sharp-based upward-fining unit (Facies A5), which defines the transition between the sandstone-rich Upper Missisaugan and monotonous mudstone of the Naskapi Member. Upward-coarsening units are commonly capped by a thin (<1 m), sharp-based layer of poorly sorted sandstone (Facies A4) and internally consist of mudstone (Facies A1) that either grades up into or is sharply-overlain by variably bioturbated, planar laminated and hummocky cross-stratified sandstone (Figure 5.15; Facies A2 and A3). In general, the following upward trends were noted in the Upper Missisaugan at Alma: 1) soft-sediment deformation become less common, 2) upward-coarsening units become thinner, 3) well-sorted sandstone that makes up the top half of upward-coarsening units are more commonly sharp-based, 4) thin layers of poorly sorted sandstone (Facies A4) that cap upward-coarsening units become better developed, and 5) the only upward-fining-unit occurs at the top of the Upper Missisaugan immediately below thick, monotonous Naskapi mudstone.

Upward-coarsening units at Alma are interpreted to be regressive, storm-dominated prodelta and delta front deposits capped by thin lags formed by transgressive ravinement during shoreface retreat. Because no obvious incised-valley fills are present, the upward-coarsening units could equally be interpreted as regressive, storm-dominated shoreface deposits. The bioturbated, sharp-based, upward-fining unit at the top of the Upper Missisaugan at Alma is interpreted to be a transgressively reworked lowstand sand-body (e.g., Berné et al., 1998; Snedden and Dalrymple, 1999). Trends in the data mentioned above are discussed below.
5.4.3 Sedimentology – Glenelg Field (Upper Missisauga)

The Glenelg J-48 well was drilled by Shell/Petro-Canada et al. in 1983 to test for hydrocarbons in a rollover anticline trap formed in the hanging wall of a northeast-southwest-trending growth fault (Figure 5.16). Economic volumes of gas were encountered in several sandstone reservoirs in the Upper Member of the Missisauga Formation (Figure 5.17). Three delineation wells were subsequently drilled in the early 1980s (Glenelg E-58 (plus a whipstock, E-58A), H-38, and N-49), and development drilling started in 2003 under the Sable Offshore Project (Sable Offshore Energy, 1996). Original gas in place is estimated to be 672 billion cubic feet (~19 m³ x 10⁹), which is ~7.6% of the original gas in-place discovered offshore Nova Scotia prior to 2000 (Canada-Nova Scotia Offshore Petroleum Board, 2000). Almost half of the gas at Glenelg occurs in two pools located in the top ~200 m of the Missisauga immediately below shale of the Naskapi Member (the Glenelg B and C pools; Sable Offshore Energy, 1996; Canada-Nova Scotia Offshore Petroleum Board, 2000). Several published papers, unpublished reports and conference abstracts present data on the structure and sedimentology of the Glenelg field reservoirs (Sable Offshore Energy, 1996; Welsink et al., 1989; Canada-Nova Scotia Offshore Petroleum Board, 2000; Ingram, 2002; MacRae, 2003a).

At Glenelg, the Missisauga Formation forms a thick (up to 1.3 km), upward-coarsening succession that overlies monotonous shale of the Verrill Canyon Formation, which in turn is overlain by ~80 to 300 m of Naskapi shale (Figure 5.18). The onset of overpressurizing occurs within mudstone-rich strata immediately below ~200 m of sandstone-rich strata at the top of the Missisauga (Figures 5.10 and 5.18).
Biostratigraphic data indicate that this sandstone-rich interval is Hauterivian to Barremian (Ascoli, 1990; Robertson Research, unpublished data; MacLean and Wade, 1993), suggesting that sand arrived simultaneously at Glenelg and Alma during deposition of the Missisaugan Formation\(^\text{18}\). The O Marker, which is present at the base of the Upper Missisaugan throughout the proximal Sable Subbasin, is only locally developed in the Glenelg wells (MacLean and Wade, 1993) and was not identified in seismic data (see Figures 5.6 and 5.7).

Deposition of the sandstone-rich uppermost ~300 m of the Missisaugan Formation at Glenelg apparently occurred in three phases, and deposited three distinct units (Figures 5.18 and 5.19). The lowermost unit is a subtle, thick (~100 m) upward-coarsening succession that marks the transition from monotonous mudstone to sandstone approximately 350 m below the top of the Upper Missisaugan. The unit is composed predominantly of variably bioturbated mudstone, and contains deformed beds, low-angle (<10\(^\circ\)) cross-stratified sandstone beds, and thin (<1 m) rhythmically laminated intervals of sandstone and mudstone that become increasingly common upward (Figure 5.19a; Facies G1 and G2). Locally, this is erosively overlain by the second unit, a heterolithic, channel-form unit approximately ~50 m thick by (at least) 2.5 km wide. The heterolithic channel-form unit contains rare bioturbation and rare rhythmically laminated intervals, abundant dune cross-stratified sandstone, coarser-grained sandstone, and rare, thin (<10 cm) rooted coals (Figure 5.19b; Facies G3, G4). The heterolithic, channel-form unit is overlain by the third unit, which consists of stacked, upward-coarsening successions. Each upward-coarsening succession grades upward from mudstone into planar laminated and hummocky cross-stratified sandstone (Figure 5.19c; Facies G6). In contrast to the

\(^{18}\) Sandstones located below the Upper Missisaugan at Glenelg may be slope turbidite deposits – see later.
lowermost unit described above, which consists of a single, thick, upward-coarsening succession (~100 m), upward-coarsening successions in the uppermost unit are thinner (10 to 50 m), and contain no rhythmically laminated intervals and fewer deformed beds.

The three units identified at Glenelg are interpreted to reflect (1) an initial period of tide-influenced prodelta and delta front deposition, followed by (2) valley incision and tide-dominated estuarine infill, and (3) several episodes of storm-dominated deltaic regression. The upward-coarsening nature of the lowermost unit is interpreted to represent an initial phase of deltaic regression. Rhythmically laminated intervals and hummocky cross-stratified sandstone beds suggest that both tides and storms affected deposition (this point discussed more fully below). The sharp-based, heterolithic channel-form unit that locally erodes into the top of the upward-coarsening succession is interpreted to be a tide-dominated estuarine incised valley fill. This interpretation is based on its thickness (~50 m) and multi-storied fill (at least 3 upward-fining channel fills), on the abundance of mudstone, presence of tidal rhythmites and thin coals, and low density and diversity of trace fossils and fossil dinoflagellates. Stacked, upward-coarsening units that overlie the valley fill, which are the main hydrocarbon-reservoirs, contain abundant hummocky cross-stratified sandstone beds, and are interpreted to be regressive, storm-dominated prodelta and delta front deposits.

5.5 Seismic data

Large-scale (i.e., a minimum of several hundred meters relief) clinoform reflections are observed within or downdip of the stratigraphic sections investigated in
the Venture and Alma fields (Figures 5.20 and 5.21). The resolution of seismic data from the Glenelg field is too low to image stratigraphy (Figure 5.7).

Lower Missisauga and Mic Mac seismic reflections in the Venture Field are interpreted to correlate downdip to a package of large-scale (i.e., over one kilometer relief) clinoform reflections (Figure 5.20). The package of clinoform reflections is located 5 to 20 km downdip of the Venture Field. Although, correlation of individual reflections is not possible because of intervening faults, the general stratigraphic position of the clinoforms suggests that they are likely Upper Jurassic in age, and correlate with the upper parts of the Mic Mac Formation and the Lower Member of the Missisauga Formation. Because of their relief, Upper Jurassic clinoform reflections are interpreted to be continental slope as opposed to shelf delta deposits.

The Upper Missisauga at Alma correlates south-southeastward with a package of large-scale (i.e., >0.5 km relief) clinoform reflections (Figure 5.21). The O Marker, which demarcates the base of the Upper Missisauga, forms a gently southeastward-dipping reflections that plunges basinward of the master Alma growth fault that bounds the north side of the field. Basinward of the master Alma fault, the O Marker reflections is interpreted to downdrop and split into several strong, large-scale clinoform reflections located immediately below Upper Missisauga sandstones in the Alma Field (e.g., MacLean and Wade, 1993). The relief of the clinoform reflections at Alma (>0.5 km) suggests they are continental slope deposits.

Although the anticlinal geometry of the trap at Glenelg can be imaged seismically (Figure 5.7), Upper Missisauga strata are poorly resolved at Glenelg because of low signal-to-noise ratio at depth. Accordingly, few conclusions can be made regarding the
paleogeographic setting at Glenelg during deposition of the Upper Missisauga based solely on seismic data.

The Tithonian (i.e., Lower Missisauga) shelf margin is interpreted to be located between 5 and 25 km downdip of Venture. Limited seismic data suggests that the Tithonian shelf margin trends approximately E-W (Figure 5.23). The Barremian (i.e., Upper Missisauga) shelf margin trend can be traced from Alma westward onto the lower-accommodation western rim of the subbasin, where it is unfaulted and clearly resolved in seismic data (Figure 5.22). The region east of Alma is the only place in the Sable Subbasin where Barremian slope clinoforms are clearly resolved in seismic data from shelf edge to toe of slope (Figure 5.22). Here, Barremian slope clinoform reflections have a relief of ~400 m and run-out distance of ~13 km. Growth faults are absent and there is no seismic evidence for basin floor fans, although the progradational nature of the clinoforms suggests sediment was transferred to the slope. East of Alma, the Barremian shelf margin trend is increasingly disrupted by growth faults, and becomes difficult to identify in seismic data as it enters a seismic noise zone below the modern shelf margin.

5.6 Identifying ancient shelf margin positions

The following discussion summarizes the case that can be made for a shelf margin delta interpretation for deposits investigated in the Alma, Glenelg and Venture fields. A shelf margin origin is suggested based on the following characteristics, which occur in some number in each of the three fields: (1) association with thick, upward-coarsening successions (>100 m), (2) proximity to large-scale (i.e., at least several-hundred-meter relief) clinoform reflections, (3) occurrence above significantly more mudstone-rich
strata, (4) common occurrence of gravity-flow deposits, (5) association with conditions of pore fluid overpressure, (6) association with large-scale growth faults, and (7) paleoecological evidence suggesting rapid shallowing (Figure 5.24).

5.6.1 Thick upward-coarsening successions

Particularly thick upward-coarsening successions occur at the base of the stratal succession studied in the Alma, Glenelg and Venture fields (Figures 5.11, 5.14, and 5.18). At Alma, the upward-coarsening succession at the base of Upper Mississauga sandstones is ~100 m thick, and at Glenelg it is ~125 m thick. At Venture, the upward-coarsening succession associated with Venture sandstone 8 at the base of the Lower Mississauga is only ~55 m thick (measured from the middle of Venture limestone 9, which is interpreted to be a maximum flooding surface); however, in the top of the Mic Mac Formation upward-coarsening successions are typically more than 100 m thick. Also, Lower Mississauga upward-coarsening successions ~5 km south of Venture in the South Venture O-59 well are upwards of 250 m thick. These thick, upward-coarsening successions are interpreted to reflect shelf margin deposition and progradation.

Shelf margin deltas form where rivers cross the continental shelf and deposit their sediment on the outer shelf and upper slope. Although they can form during sea level highstand if sediment supply is sufficiently high (e.g., the modern Balize lobe of the Mississippi River delta), shelf-margin deltas more commonly form during sea level fall and lowstand, because long-distance regression is likely easier to achieve during forced regression (Muto and Steel, 2002), which is independent of sediment supply\(^\text{19}\). During

\(^{19}\) Relative sea level rises during normal regression (e.g., during deposition of the highstand and lowstand systems tracts \textit{sensu} Plint and Nummedal, 2000), which generates accommodation space in both deltaic topsets and foresets: the
the initial stages of forced regression in inner to mid shelf regions, deltas tend to deposit thin upward-coarsening successions, usually no more than several tens-of-meters, because water depths are shallow and accommodation remains negative as long as sea level keeps falling and shelf gradient does not increase (Posamentier et al., 1992; Porebski and Steel, 2003). However, as deltas reach the outer shelf, they deposit thicker upward-coarsening successions because the rate of sea level fall tends to slow while subsidence rate and seafloor gradient tend to increase. If the delta shoreline reaches the shelf edge, sediment is delivered to the continental slope; at an extreme, delta foresets will downlap the entire continental slope\(^ {20}\). Shelf-margin deltas, therefore, typically deposit much thicker upward-coarsening successions than their “shelf-phase” counterparts (Winker and Edwards, 1983; Suter and Berryhill, 1985).

5.6.2 Large-scale clinoform reflections

The large-scale (i.e., hundreds-of-meters plus relief) clinoform reflections observed at Venture and Alma support a shelf margin paleogeographic setting (Figures 5.20 and 5.21). Regional subsidence associated with thermal cooling of the lithosphere and sediment loading cause water depth in front of an accreting passive continental margin to increase with time. As a consequence, the relief of continental slope clinoforms tends to increase with time as the passive margin basin matures. In modern

\(^{20}\) A continental slope (or simply “slope”), in contrast to a deltaic slope, is defined here as a clinoform surface that has surpassed some critical limit of relief and inclination, which observation suggests is commonly on the order of >180 m relief and \(>2^\circ\) inclination, which in turn renders it sufficiently unstable to develop thick, sandy to heterolithic slope and basin-floor turbidite depositional systems (Porebski and Steel, 2003; Donovan, 2003)
passive margin basins, continental slope clinoforms commonly have a relief of several kilometers. For example, modern slope clinoforms (>1° gradient) offshore of the western margin of Africa and the eastern margins of North and South America have reliefs in excess of three kilometers (O'Grady et al., 2000). As mentioned previously, shelf-phase delta clinoforms are commonly an order of magnitude smaller than those on mature continental margins (i.e. tens-of-meters versus hundreds-of-meters to kilometer relief). At Venture and Alma, therefore, the association of marginal marine strata with the large-scale (i.e., < 0.5 km relief) clinoform reflections supports a shelf margin paleogeographic interpretation.  

5.6.3 Stratigraphic position over relatively mudstone-rich deposits

The Upper Missisauga at Alma and Glenelg and the Lower Missisauga at Venture are comparatively more sandstone-rich than underlying strata (Figures 5.11, 5.14, and 5.18). This is interpreted to reflect shelf margin progradation. On modern unglaciated shelves, most sediment is trapped within several tens-of-kilometers of the shoreline because of several factors, including: 1) the “littoral fence” caused by asymmetric shoaling, fairweather wave orbitals, which rework sand onshore during fairweather periods; 2) a low downslope gravitational force caused by low shelf gradients (<0.1°), which hinders sand-rich turbidity current ignition; 3) rapid flocculation of mud suspended in river plumes; 4) the Coriolis force, which causes offshore-flowing currents to deviate parallel to shore; and 5) flood-dominance typical of coastal tidal currents, which trap sand

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21 Assuming that shelf-slope profiles during Missisauga deposition were analogous to modern shelf-slope profiles, Missisauga shelf-phase deltas could only have grown to a maximum of ~200 m relief, assuming that the shelf edge depth acted as the limit to upward growth. All clinoform reflections discussed here have at least twice that relief; they are therefore interpreted to have formed by progradation of the entire continental slope.
in zones of bedload convergence in estuaries and tidally influenced and dominated deltas (Postma, 1967; Pantin, 1979, 1983; Parker, 1982; Swift and Niederoda, 1985; Garvine, 1999; Droppo, 2001; Dalrymple and Choi, 2003; Dalrymple and Cummings, 2004; Geyer et al., 2004). As a consequence, little new sediment (especially sand) is likely to reach the continental slope unless shorelines reach the shelf edge during regression. The occurrence of the sand-rich strata studied here above more mudstone-rich strata of the Verrill Canyon (Alma, Glenelg) and Mic Mac formations (Venture) is therefore interpreted to be a result of the shelf margin reaching those localities as it prograded incrementally basinward\textsuperscript{22}. Sandstone-rich strata studied were therefore likely deposited at or slightly landward of the shelf edge, a hypothesis that is supported by the general upward-thinning of successive upward-coarsening units (e.g., Figures 5.14 and 5.18).

5.6.4 Mass movement and gravity-flow deposits

The stratigraphic successions at Alma and Glenelg contain common mass movement and sediment gravity-flow deposits. As argued above, because continental slope clinoforms have steeper gradients (typically >2\textdegree; O'Grady et al., 2000) and greater reliefs than shelf-phase deltaic clinoforms, sediment gravity-flows (turbidity currents, debris flows, slumps) are more likely to be initiated on deltas that downlap the continental slope (Pulham, 1989; Martinsen, 1989, 1990; Collinson et al., 1991; Plink-Björklund et al., 2001; Steel et al., 2003; Mellere et al., 2003; Donovan, 2003). Lack of gravity-flow deposits in the interval investigated at Venture may suggest deposition in slightly shallower water on the outer continental shelf, an interpretation supported by the

\textsuperscript{22} Some of the sandstone bodies in the relatively mudstone-rich deposits that underlie the studied intervals are potential slope turbidite deposits
position of Venture ~5 to 20 km updip (paleolandward) of, as opposed to directly within (e.g., Alma), a package of large-scale clinoform reflections. The upward decrease in abundance of sediment gravity-flow deposits in the Upper Missisauga at Alma and Glenelg is interpreted to reflect a change from upper slope to outer shelf deposition as the shelf margin prograded to and past these locations.

5.6.5 Growth faults

Major listric growth faults that occur in Alma, Glenelg and Venture fields are interpreted to reflect a shelf margin paleogeographic setting (Figure 5.7, 5.20, and 5.21). Gravity instability and sliding of continental slope strata tends to form a strongly extensional regime at the shelf margin. Growth faults are therefore common along shelf margins, especially those supplied by a high fluvial sediment flux (Winker and Edwards, 1983).

5.6.6 Overpressure

In the intensely growth-faulted central Sable Subbasin, the top of pore-fluid overpressure occurs in monotonous mudstone several tens- to hundreds-of-meters below the sandstone-rich Upper Missisauga reservoir intervals at Alma and Glenelg. At Venture, the top of overpressure occurs just below the top of the Lower Missisauga. In contrast, pore-fluid overpressure is absent on the periphery of the Sable Subbasin where growth faults are absent (e.g., Panuke Field).

The top of overpressure in the Sable Subbasin is interpreted to be the result of unstable terrigenous clastic shelf-margin progradation. (Local anomalies in pore-fluid
overpressure below the top of overpressure ("hard overpressures") may be due to hydrocarbon generation or local variations in diagenetic processes (Nantais et al., 2004). In an accreting shelf margin, the upper slope just basinward of the shelf edge experiences the highest sedimentation rates, which in turn promotes shelf-margin progradation (Pirmez et al., 1998). If, as discussed earlier, sediment supply is sufficiently high, the shelf margin becomes gravitationally unstable and growth faults form. Early movement along shelf-margin growth faults can hydraulically isolate underlying shelf margin and slope deposits, causing pore fluids to become trapped and overpressured as deposition and burial compaction continues. The observed basinward younging of the top of overpressure in the Sable Subbasin (Wade and MacLean, 1990; MacLean and Wade, 1993; Nantais et al., 2004) is therefore consistent with unstable shelf-margin progradation (see Winker and Edwards, 1982).

5.6.7 Paleoeccological evidence of rapid shallowing

Microfossil assemblages suggest that rapid shallowing occurred ~150 m below the base of the Upper Missisauga within shales of the Verrill Canyon Formation in the Alma F-67 well (Figure 5.14; Lentin, 1988). No similar microfossil data were available for Venture or Glenelg wells. Paleoeccological evidence for significant and rapid shallowing, or what has been termed foreshortened stratigraphy (Posamentier and Morris, 2000), is commonly observed in shelf-margin delta deposits (Winn et al., 1998), likely because physical and chemical conditions change substantially at the shelf margin (e.g., substrate, energy level, food distribution, oxygenation, freshwater input) over the course of a long-distance regression that brings shorelines to the shelf edge.
5.7 Discussion

5.7.1 A tide-dominated shelf margin delta?

In passive margin basins, deltas are believed to commonly become more wave-influenced as they approach the shelf margin, and switch to a tidally-influenced state only upon transgression (Suter, 2001; Yoshida et al., 2003). In theory, this hypothesis works well because (1) waves tend to experience less bottom friction as shelf widths decrease (Swift and Thorne, 1991), (2) tidal ranges tend to be amplified on particularly wide continental shelves (Archer and Hubbard, 2003), (3) the volume of water entering and exiting the coastal plain, termed the tidal prism, tends to increase as low-lying coastal plains are progressively flooded (Dalrymple, 1992), and (4) incised river valleys can become tidally-resonant when inundated (e.g., Bay of Fundy; Dalrymple, 1992). Ancient wave-dominated shelf margin delta deposits have commonly been documented (e.g., Morton and Suter, 1996; Porebski and Steel, 2003), as have fluvially-dominated examples presumably deposited in smaller, fetch-limited basins where wave energy at the shelf margin was low (e.g., Pulham, 1989; Mellere et al., 2003). In contrast, a strong tidal control on delta facies and architecture, although commonly observed in modern shelf-phase deltas (Dalrymple et al., 2003), has not been interpreted in ancient shelf margin delta deposits.

In view of the above observations, it is tempting to interpret the tide-influenced (dominated?) ~125 m-thick upward-coarsening succession at Glenelg as something other than a shelf margin delta deposit. Tidal influence is unequivocal: rhythmically-laminated intervals are sparsely distributed throughout the upward-coarsening muddy prodelta deposits and become extremely well developed directly beneath the base of the incised
valley. A possible explanation for this is that the delta prograded into a tidally-resonant bayhead of an incised valley. However, incised valleys are typically only several tens-of-meters deep, and tend only to be deeper if formed under extreme conditions of relative sea level fall, for instance during the draining of the Mediterranean in the Messinian (e.g., Zaitlin et al., 1994). A more likely interpretation is that topography similar to an incised valley existed at the shelf margin, perhaps at the head of an incised slope canyon. Such a scenario could account for the presence of tidal rhythmites and thickness of the upward-coarsening succession located ~350 m below the top of the Missisagua at Glenelg (Figure 5.25). The tide-dominated shelf margin delta interpreted from the Glenelg Field suggests that current shelf margin delta models, just like early facies models for shelf-phase deltas (which were based almost exclusively on the Mississippi Delta), are perhaps based on too limited a dataset. It seems likely that as more data are collected and synthesized, a broader range of styles of shelf-margin deposition, perhaps similar to that currently documented for shelf-phase deltas (e.g., Galloway, 1975; Reading and Collinson, 1996), will be recognized.

5.7.2 Offset vs. vertical lobe stacking

Shelf margin deltas commonly have an offset stacking pattern (e.g., Roberts et al., 2002), presumably because lowstand fluvial-deltaic shorelines tend to prograde into topographic lows between older shelf margin sand bodies. However, Venture sandstones 8 to 5, interpreted to be shelf margin delta deposits, stack vertically with incised valleys

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23 Although more commonly associated with protected coastal plain regions (e.g., mudflats, tidally-influenced fluvial point bars; Dalrymple et al., 1991; Li et al., 2000), convincing tidal rhythmites have also been reported in both modern and ancient delta front deposits (Smith et al., 1990; Williams, 1991; Jaeger and Nittrouer, 1995; Kuehl et al., 1996; Miller and Eriksson, 1997).

24 It is useful to note that elongate topographic elements occur at the shelf margin, even in supply dominated settings (e.g., Swatch of No Ground, offshore Ganges-Brahmaputra Delta).
located consistently in the thickest part of the deltaic sandstone body. This suggests that, if loaded sufficiently, shelf margin depocenters will have sufficient growth-fault related subsidence to negate depositional topography and create topographic lows through which subsequent lowstand fluvio-deltaic systems would preferentially flow. This hypothesis is supported by observations from the Late Pleistocene shelf margin offshore of the Orinoco River, Venezuela, where high rates of deposition and significant growth-fault related subsidence has created ~45 m deep fault scarps on the seafloor at the shelf margin (Sydow et al., 2003). This observation has important implications for exploration downdip of the shelf margin; namely, that incised valleys, and thus the upper portions of any possible (downdip) slope turbidite systems, will most likely be located where shelf margin growth fault subsidence was greatest.

5.7.3 Turbidites vs. storm beds at the shelf margin

Shelf-margin delta deposits in all fields investigated are interpreted to consist, at least in part, of hummocky cross-stratified sandstone. In the Alma, Glenelg, and Venture fields hummocky cross-stratified sandstone forms the main reservoir. Although it can resemble antidune cross-stratification formed in shallow water flows or density-stratified turbidity currents (Alexander et al., 2001), hummocky cross-stratification is typically inferred to form between storm and fairweather wave base under the influence of energetic, long period storm waves (Southard et al., 1990; Arnott and Southard, 1990; Dumas, 2004). Hummocky cross-stratification has certain key features that allow it to be identified in core, including low-angle dip (<10°) of curved and planar laminae, presence of low-angle truncations within a bed, gentle upward fanning of laminae, common
upward-finining trends, and association with small, capping wave-ripples. The abundance of hummocky cross-stratified sandstone at all localities suggests that shelf margin deltas were typically wave-dominated, with the exception of the tidally-dominated shelf margin delta at Glenelg discussed above.

However, as oscillatory velocity increases or unidirectional currents strengthen, storm waves can also deposit oscillatory (and combined flow) plane bed, which arguably will be indistinguishable from planar laminated sandstone deposited from turbidity currents (i.e., Bouma T₃ turbidites; unless laminae display subtle “wavyness”; see Arnott, 1993). As planar laminated turbidites are common in shelf margin delta front deposits (Steel et al., 2003), many of the planar laminated sandstone beds observed in the Glenelg and Alma fields could be turbidity current deposits as opposed to oscillatory plane bed deposits (or perhaps a mix of both? e.g., Myrow and Southard, 1996; Wright et al., 2001). Turbidity current deposition is inferred to have occurred at Glenelg and Alma because current ripples, although rare, are present locally in prodelta and delta front deposits, either on top of planar laminated beds or isolated within mudstone. In contrast, current ripples were not observed in upward-coarsening successions in more proximally-located fields (e.g., the Naskapi Member in the Panuke Field; see Chapter 3), where planar-laminated beds were capped by small wave ripple cross sets (if any). It is possible, therefore, that the type of ripple (wave vs. current) that caps planar-laminated beds in upward-coarsening successions may provide an additional criterion useful in differentiating shelf and shelf-margin paleogeographic settings.
5.7.4 Shoreface vs. delta front

All upward-coarsening successions at Alma, and most upward-coarsening successions at Glenelg, apparently lack associated fluvial deposits. Except for transgressive lags, upward-coarsening successions are composed entirely of regressively-deposited shallow-marine sandstone and mudstone. Traditionally, these strata would be interpreted as shoreface deposits because they lack obvious fluvial feeder systems. However, lack of fluvial deposits may simply be a result of transgressive ravinement, a process that is capable of removing all evidence of fluvial feeder systems (ca. 6-15 m of Holocene ravinement in Gulf Coast of Mexico – Rodriguez et al., 2001). Furthermore, upward-coarsening successions are typically sparsely bioturbated, which might suggest deposition in a delta front setting that was stressed by fluvial discharge induced salinity fluctuations (Gingras et al., 1998). Intense bioturbation in some upward-coarsening sandstones in the Alma Field may suggest deposition down-coast of the main fluvial input in a shoreface environment (Gingras et al., 1998).

5.7.5 What is the Sable Delta?

*Sable Delta* is a colloquial term used to describe deposits of the Mic Mac and Missisauga formations accumulated during regression in the Sable Subbasin (e.g., Eliuk, 1978; Wade and MacLean, 1990; Sable Offshore Energy, 1996; Canada Nova Scotia Offshore Petroleum Board, 2000). Net regression did indeed occur, as indicated by upward-coarsening trends observed in well log and cuttings data and large-scale, progradational clinoform reflections observed locally in seismic data (Figures 5.20 to 5.22). However, this large-scale, long-term regression was not strictly “deltaic” in

nature, but was related to progradation of the entire shelf margin. Although deltaic deposits form volumetrically-important but individually-minute stratigraphic building blocks within the Missisaugan Formation, the use of the term "Sable Delta" to describe net regression during deposition of the Mic Mac and Missisaugan formations is misleading. Simply put, the Sable Delta is a prograding shelf margin.

5.9 Summary

Approximately 128 m$^3$ x 10$^6$ (4527 BCF), or 50% of the original in-place gas reserves discovered offshore Nova Scotia are interpreted to be hosted in shelf-margin delta sandstones (Alma, Glenelg, and Venture/West Venture/South Venture fields; Canada Nova Scotia Offshore Petroleum Board, 2000). Although seemingly high, it is not anomalous when compared to other passive margin basins such as the U.S. Gulf Coast, where almost all of the largest hydrocarbon discoveries (i.e., multiple Tcf) discoveries made in onshore and shelf regions over the past 30 years (e.g., Wilcox, Frio, Vicksburg) are in shelf-margin delta deposits (Meckel, 2003).

Recognition of the shelf-margin delta play type offshore Nova Scotia will not only aid production strategies employed in existing fields, but will provide a framework to guide exploration in genetically related parts of the stratigraphic section. On a production scale, it is important to consider the shelf-margin-parallel form typical of shelf-margin delta sandbodies (i.e., commonly over several tens of kilometers), which reflect subsidence along the shelf margin and alongshore wave reworking (Suter and Berryhill, 1985). On an exploration scale, identifying shelf-margin trends is important because shelf-margin deltas typically form simultaneously along a shelf margin,
producing what has been referred to as a “string of pearls” (Meckel, 2003). Shelf-margin deltas also commonly act as staging areas for sediment exiting shelf incised-valleys and entering slope and basin floor turbidite systems (Steel et al., 2003). Identifying shelf-margin depocenters is therefore an important first step when developing deepwater exploration strategies in passive margin basins like offshore Nova Scotia.
Figure 5.1  Location map of study area, showing depth to basement of passive margin basin fill, offshore Nova Scotia. Contours are in kilometers (modified from MacLean and Wade, 1992).
Figure 5.2a  Location of core data from the Missisauga Formation used in this study, Sable Subbasin, offshore Nova Scotia.
Figure 5.2b  Location of biostratigraphic data used in this study, Sable Subbasin, offshore Nova Scotia.
Figure 5.2c  Location of seismic data used in this study, Sable Subbasin, offshore Nova Scotia.
Figure 5.3  Stratigraphic frameworks, Sable Subbasin, offshore Nova Scotia.
Figure 5.4  Interpreted dip-oriented seismic cross-section, Sable Subbasin (modified from Wade and MacLean, 1990).
Figure 5.5  Isopach map, Missisauga Formation (modified from Wade, 1991a and MacLean and Wade, 1992).
Figure 5.6  Time-structure map of the O Marker reflection, Sable Subbasin.

Reconstructed from seismic data (see Figure 5.2c for seismic line locations).
Figure 5.7 Uninterpreted and interpreted dip-oblique seismic form line traces, Onondaga and Glenelg fields, central Sable Subbasin (GSI-GSI-S98-217A and PRX-GSI-83-926 lines). Note: 1) the lack of obvious onlap/offlap cycles in the Missisauga Formation, 2) the absence(?) of the O Marker reflection basinward of the Onondaga master growth fault, and 3) the anticlinal form of the Glenelg structure. Seismic picks used are the same as in MacLean and Wade (1993).
Figure 5.8 Structure map, top of Venture sandstone 6, Venture Field region (modified from Sable Offshore Energy, 1996).
Figure 5.9  Stratigraphy of sandstone reservoirs, Venture and West Venture fields (modified in part from Wade and MacLean, 1990, and in part from Sable Offshore Energy, 1996).
Figure 5.10  Pressure data for wells in the (a) Glenelg, (b) Alma, (c) Venture, and (d) Panuke fields. Note that overpressured conditions exist in all cases except (d), and that the top of overpressure is located in older, deeper strata in the Venture Field and in younger, shallower strata in the more basinward Alma and Glenelg fields (i.e., the top of overpressure rises stratigraphically in a basinward direction).
Figure 5.11a  Interpreted strike-oriented well log cross-section, Venture and West Venture fields. See Figure 5.8 for cross-section location.
Figure 5.11b  Interpreted dip-oriented well log cross-section, Venture Field. See Figure 5.8 for cross-section location.
Figure 5.12  Selected core photos and sedimentological logs from Venture sandstones 8 to 5, Lower Member of the Missisauga Formation, Venture and West Venture fields. (a) sedimentological log of part of an upward-coarsening unit (interpretation – storm-dominated delta-front deposits; West Venture C-62, core 9, boxes 20 to 17, 5186.2-5181.99 m (measured depth)), (b) low-angle (<10°) cross-stratified sandstone common in upward-coarsening units (Facies V3; interpretation – hummocky cross-stratified sandstone; West Venture C-62, core 9, box 19, 5184.64 m (measured depth)), (c) a portion of a heterolithic channel-form unit (Facies V5; interpretation – tide-influenced fluvial deposits; West Venture C-62, core 5, boxes 25 to 18, 5099.6-5092 m (measured depth)), and (d) rhythmic stratification, which is rarely observed in the heterolithic channel-form units (Facies V7; Venture H-22, core 2, box 1, 4895 m (measured depth)).
Figure 5.13  Structure map, top of the Missisauga Formation (Alma A "sand"), Alma Field (modified from Sable Offshore Energy, 1996 and Mobil Oil, 1998a).
Figure 5.14  Interpreted strike-oblique well log cross-section, Alma Field. Transgressive surface of erosion (TSE) and sequence boundary (SB). For details on individual facies, see Table 5.2.
Figure 5.15  Part of an upward-coarsening succession, Alma C "sand", Upper Mississauga, Alma Field (Alma K-85, core 6, boxes 6 to 3, 3030.84-3025.58 m (measured depth)).
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3025.58 m (MD)</td>
<td>3 to 5 degrees east dip.</td>
<td>Facies A2</td>
<td>Alma C-Sand*</td>
<td>Upper Member Mississauga Fm</td>
</tr>
<tr>
<td>3030.84 m (MD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.16  Structure map, top of the Glenelg B pool, Upper Missisauga, Glenelg Field (modified from Sable Offshore Energy, 1996).
Figure 5.17  Gas pools, Glenelg Field (from Sable Offshore Energy, 1996; MacLean and Wade, 1993). Biostratigraphic data is not available for the Glenelg N-49 well; however, biostratigraphy from the nearby Glenelg J-48 well suggests the Glenelg B and C1 pools were deposited between the Hauterivian and Barremian (see Ascoli, 1990).
Figure 5.18  Interpreted strike-oblique(?) well log cross-section, Glenelg Field.

Lithostratigraphic picks are from MacLean and Wade (1993), except for Glenelg H-38.

Biostratigraphic picks for the Glenelg J-48 well are from Ascoli (1990).
SURFACES
- wave ravinement surface
- sequence boundary

FACIES (see Table 5.3)
- G1 tide- and storm-influenced prodelta
- G2 tidal rhythmites (delta front deposit?)
- G3 tidally influenced fluvial deposits
- G6 storm-dominated shoreface/offshore

INTERPRETATIONS

stacked, storm-dominated shoreface deposits (outer shelf?)

tide-influenced fluvial deposits

storm- and tide-influenced slope and shelf margin deposits

top of compressive (Glenelg J-48)

slope turbidites

upper slope detritus
**Figure 5.19a** Facies G1 (interpretation – tide- and storm-influenced prodelta deposits), Upper Missisauga, Glenelg Field:  
(a) *Teichichnus* burrow cross-cutting a thin, small-scale wave ripple cross-stratified sandstone bed (Glenelg E-58, core 2, 3450.10 m (measured depth));  
(b) normally graded, horizontally laminated very fine sandstone bed (Glenelg E-58, core 3, 3534.10 m (measured depth));  
(c) normally graded, low-angle cross-stratified very fine sandstone bed (Glenelg E-58, core 4, 3545.38 m (measured depth));  
(d) soft sediment deformation (Glenelg E-58, core 5, 3730.97 m (measured depth));  
(e) sheared layer (Glenelg E-58, core 5, 3727.2 m (measured depth));  
(f) small "domino-style" normal faults (Genelg E-58 well, core 5, 3729.4 m (measured depth));  
(g) rhythmically laminated sandstone bed (tidal rhythmites; Glenelg E-58A, core 7, box 3);  
(h) rhythmically laminated sandstone beds (tidal rhythmites; Glenelg E-58, core 5, 3709.36 m (measured depth)).
Figure 5.19b  Facies G3 (tidally influenced fluvial deposits), Upper Missisauga, Glenelg Field. Core photos are from Glenelg N-49 well, cores 6 and 5 (3666.16 to 3628.8 m measured depth). These show (a) rhythmically laminated intervals (tidal rhythmites; white arrows) and thick mudstone interbeds, (b) bipolar cross-stratification, (c) angular mudstone interclasts, (d) a thick double mudstone drape, (e) a large *Diplocraterion* burrow, and (f) the upward-fining nature of a Facies G3 channel fill.
Figure 5.19c  An interpreted section of Upper Missisauga core from the Glenelg N-49 well, showing an upward transition from tidally influenced fluvial to storm-dominated marine deposits.
**Figure 5.20**  Uninterpreted and interpreted dip-oriented seismic cross-section, Venture Field, Sable Subbasin (PRX-GSI-83-1042 seismic line). Note large-scale (>1 km relief) accretionary clinoform reflectors downdip of the Venture Field interpreted to be Mic Mac and Lower Missisauga continental slope clinoforms. Well-to-seismic ties are the same as those outlined in MacLean and Wade (1993) and Mobil Oil Canada (1997b)
Figure 5.21  Uninterpreted and interpreted dip-oblique seismic cross-section, Alma Field, Sable Subbasin (PRX-GSI-83-846C seismic line). Note the apparent increase in dip of the O Marker basinward of the master Alma growth fault.
Figure 5.22  Uninterpreted and interpreted dip-oblique seismic cross-section, Panuke Field, western edge of the Sable Subbasin (GSI-GSI-PA99-110 seismic line). Relief of the Barremian (i.e., Upper Missisauga) continental slope clinoform in this low accommodation part of the subbasin is approximately 400 m, and slope run-out distance is approximately 13 km. Note the progradational nature of the Missisauga slope clinoforms, lack of growth faults, and the relaxation of slope clinoform gradient at the contact between the Upper Missisauga and the overlying Naskapi shales.
Figure 5.23  Tithonian (Lower Missisauga) and Barremian (Upper Missisauga) shelf-margin trends interpreted from subsurface data, Sable Subbasin. Solid grey zones indicate seismically resolvable shelf-margins; hatched zones indicate shelf-margin positions inferred from well log, sedimentological, and biostratigraphic data.
Figure 5.24  Features common to the shelf-margin delta play-type, Missisaug Formation, offshore Nova Scotia.
deeply penetrating listric growth faults

rapid pinchout of sandstone

association with large-scale cliniform reflectors
(i.e., more than one hundred meters relief)

GR log

stratigraphic evidence of gravity flow deposition and slope instability (turbidites, debrises, slumps/slides)

100 m

thick upward-coarsening units (i.e., more than one hundred meters thick) overlain by progressively thinner, sandier upward-coarsening units

carbonate evidence of rapid shallowing

overpressured strata

potential slope turbidites?
Figure 5.25  Depositional model for the Upper Member of the Missisauga Formation, Glenelg Field. (a) irregular, funnel-shaped antecedent topography at shelf margin (e.g., Swatch of No Ground, offshore Ganges-Brahmaputra); (b) initial shallow marine sedimentation is tide-influenced; (c) further relative sea level fall causes incision of delta plain; (d) estuarine sedimentation in incised valley during initial transgression is tide-dominated; (e) as valley fills, it becomes tidally dissonant, and a wave-formed barrier-inlet forms at the estuary mouth; (f) all subsequent shallow marine sedimentation is storm-wave dominated (main Glenelg reservoirs are storm-dominated shallow marine sandstones).
(a) pre-existing funnel-shaped topographic depression at shelf margin (head of a slope canyon?)

(b) tide-dominated delta

(c) relative sea level fall and valley incision

(d) tide-dominated estuarine infill

(e) valley fills and becomes tidally dissonant; waves start to control estuarine geomorphology

(f) all subsequent Upper Mississippian deposits at Glenelg are storm-dominated
Chapter 6. Conclusions

1) High terrigenous sediment influx and high frequency, small amplitude relative sea level falls transferred abundant fluvial sediment to the shelf margin during deposition of the Missisauga Formation (Tithonian-Barremian). Because of limited well control, it is unclear whether the high-frequency relative sea level cycles affected the entire basin or were only local in extent. These high frequency relative sea level falls caused the shelf margin to prograde despite net low frequency, large amplitude relative sea level rise. High sediment supply caused gravity sliding of shelf margin and slope deposits, which resulted in the formation of large listric shelf-margin growth faults in the central Sable Subbasin. The Tithonian (Lower Missisauga) shelf margin was located several kilometers basinward of the Venture Field, and trended approximately E-W. Between the Tithonian and the Barremian, the Missisauga shelf margin prograded approximately ~40 km south to a position just basinward of the Alma and Glenelg fields.

2) Missisauga shelf margins are typically poorly resolved in seismic data in the Sable Subbasin. However, their location can be inferred based on a combination of the following criteria (in approximate order of decreasing importance):

- large relief (*i.e.*, several hundred meters plus) clinoform reflections
- thick (*i.e.*, one hundred meters or more) upward-coarsening successions
- common gravity-flow deposits
- superposition of sandstone-rich over mudstone-rich strata
- large, listric growth faults
- paleoecological evidence indicating rapid shallowing
- the top of overpressure
3) Growth-faulted shelf-margin deltas in the Missisauga Formation constitute an important but previously unrecognized play type that host at least half of the currently discovered in-place gas reserves offshore Nova Scotia. Upward-coarsening shelf margin delta successions typically contain abundant hummocky cross-stratified sandstone, suggesting that storm waves commonly controlled shelf margin delta morphology and facies distribution. Amalgamated, hummocky cross-stratified sandstone is the main reservoir type at Alma, Glenelg, and Venture/West Venture/South Venture fields. However, shelf-margin delta successions locally contain abundant tidal rhythmites, suggesting that, at least locally, tide-dominated shelf margin deltas formed. Estuarine incised valley fills, where cored (e.g., Venture/West Venture and Glenelg fields), are composed primarily of very muddy, tidally influenced fluvial deposits, suggesting that incised valleys commonly became tidally resonant during transgression.

4) In contrast to coeval upward-coarsening deltaic units located downdip in the Glenelg and Alma fields, the Upper Member of the Missisauga Formation in the Panuke Field is characterized by two sharp-based, upward-fining units. 3-D seismic data suggest the base of the lowermost upward-fining unit is a fluvially eroded incised valley at the top of the O Marker. Seismic data show the incised valley to correlate downdip to progradational slope clinoforms, suggesting that it formed during relative sea level fall below the shelf edge. The uppermost sharp-based unit passes upward from a 50 m thick braided fluvial sandstone into a 50 m thick heterolithic coastal plain unit, which in turn is overlain by ~150 m of offshore mudstone. The base of the uppermost sharp-based unit is interpreted to be a wide (>20 km) incised valley formed during a slow relative sea level fall in the Barremian. However, shelf-margin progradation occurred until the end of
coastal plain deposition in the Panuke Field (i.e., the Missisauga-Naskapi boundary), suggesting that although net transgression was occurring, high frequency relative sea level falls episodically caused fluvial systems to bypass the shelf and deliver sediment to the shelf margin. The main Panuke reservoir is a sharp-based, transgressively deposited shallow marine sand-body located between heterolithic coastal plain deposits of the Missisauga Formation and offshore mudstone of the Naskapi Member of the Logan Canyon Formation.
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APPENDIX 1: DETAILED CORE LOGS
## Appendix 1, table 1 Facies descriptions and interpretations, Alma Field (Upper Missisauga)*

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<th>Lithology and Texture</th>
<th>Physical Sedimentary Structures</th>
<th>Biogenic Features</th>
<th>Gamma Ray Log Character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>mudstone</td>
<td>microfaults are present locally, and thin (&lt;1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical “streaks” barren of organic particles are also observed locally (interpretation = pillar (dewatering) structures)</td>
<td>Bioturbation is absent or very minimal, and includes <em>Teichichnus</em>, <em>Planolites</em>, <em>Asterosoma</em>, <em>Helminthopsis</em>, <em>Chondrites</em>, <em>Zoophycos</em>, <em>?Arenicolites</em>, <em>Palaeophycus</em>, <em>Terebellina</em>; shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on bedding surfaces</td>
<td>upward-coarsening</td>
<td>prodelta mudstone with evidence of mass movement and gravity flow deposition</td>
</tr>
<tr>
<td>A2</td>
<td>Inter-stratified mudstone and thin beds of (&lt;10 cm), very fine sandstone</td>
<td>thin sandstone beds are typically planar to low-angle (&lt;10°) cross-stratified, or rarely small-scale (&lt;5 cm) high-angle (&gt;15°) cross-stratified</td>
<td>Bioturbation in mudstone is generally low, and includes <em>Asterosoma</em>, <em>Planolites</em>, <em>Teichichnus</em>, <em>Zoophycos</em>, and <em>?Cylindrichnus</em>; rare escape traces and and <em>Opomorpha</em> in sandstone</td>
<td>upward-coarsening</td>
<td>storm-influenced delta front and prodelta heterolithics</td>
</tr>
<tr>
<td>A3</td>
<td>very fine to medium sandstone</td>
<td>where not obscured by bioturbation, sandstone is either planar laminated, low-angle (&lt;10°) cross-stratified, or medium-scale (10-20 cm) high-angle cross-stratified</td>
<td>bioturbation is commonly intense, with <em>Opomorpha</em>, <em>Palaeophycus</em>, <em>Helminthopsis</em>, <em>Planolites</em>, <em>Skolithos</em>, <em>Teichichnus</em>, <em>Zoophycos</em>, <em>Asterosoma</em>, <em>?Thalassinoidea</em>, <em>?Conichnus</em> and <em>?Diplocraterion</em>.</td>
<td>upward-coarsening</td>
<td>unstressed shoreface deposits</td>
</tr>
<tr>
<td>A4</td>
<td>Poorly-sorted, carbonate cemented sandstone with “paint-speckled” appearance</td>
<td>Sedimentary structures are rarely preserved due to bioturbation</td>
<td>Bioturbation is typically intense, and includes <em>Opomorpha</em>, <em>Planolites</em>, <em>?Asterosoma</em>, <em>?Thalassinoidea</em>, and <em>Helminthopsis</em>; bivalve, scaphopod, and gastropod shell fragments are common</td>
<td>usually thin bed (&lt;1 m thick) with low API values</td>
<td>transgressive lag</td>
</tr>
<tr>
<td>A5</td>
<td>Poorly-sorted, muddy coarse to very fine sandstone</td>
<td>typically not visible due to intense bioturbation</td>
<td>bioturbation is intense, with large <em>Opomorpha</em> and <em>Palaeophycus</em> (trace fossils hard to ID due to intense bioturbation)</td>
<td>sharp-based, upward fining</td>
<td>transgressive shelf sandstone</td>
</tr>
</tbody>
</table>

*An extended facies analysis for the Alma Field is presented in Appendix 2.
### Appendix 1, table 2 Facies descriptions and interpretations, Glenelg Field (Upper Mississauga)*

<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology and texture</th>
<th>Physical sedimentary structures</th>
<th>Biogenic features</th>
<th>Gamma ray log character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>mudstone with thin, very fine sandstone interbeds</td>
<td>sandstone beds are horizontally to low-angle (&lt;10°) cross stratified; sandstone beds are rarely normally graded; some rhythmically laminated intervals in both mudstone and sandstone interbeds; deformed muddy sandstone beds common</td>
<td>bioturbation in mudstone is typically very low, with Planolites, Tetrichnus, Terebellina, and Asterosoma; rare Ophiomorpha in sandstone beds; disseminated organic flecks are common</td>
<td>upward-coarsening</td>
<td>Storm- and tide-influenced prodelta deposits</td>
</tr>
<tr>
<td>G2</td>
<td>Interlaminated mudstone and very fine sandstone</td>
<td>rhythmically alternating mudstone and sandstone laminae; rhythmites typically form successions that progressively thicken and thin (interpretation – tidal rhythmites); contacts between sandstone and mudstone laminae in rhythmites are typically gradational</td>
<td>no bioturbation observed; disseminated coal flecks abundant throughout</td>
<td>Slightly serrated</td>
<td>tide-dominated delta front deposits (delta front interpretation based on stratigraphic position overlying Facies G1 and underlying Facies G3)</td>
</tr>
<tr>
<td>G3</td>
<td>medium to very coarse sandstone with thick mudstone interbeds</td>
<td>sandstone beds (~20 cm ave.) are commonly high-angle (&gt;15°) cross-stratified; bipolar cross-sets and double mud drapes observed; mud intraclasts present; rare rhythmically laminated intervals (like Facies G2) present</td>
<td>bioturbation very sparse, and includes Skolithos, Diplorotarian and Ophiomorpha in sandstone, and small Planolites in mudstone; pebble-sized coal clasts and disseminated coal flecks abundant throughout</td>
<td>serrated, sharp-based upward-fining</td>
<td>tide-influenced fluvial channel fill deposits</td>
</tr>
<tr>
<td>G4</td>
<td>organic-rich mudstone with thin rooted coal beds</td>
<td>stratification is typically not visible, although rare, high-angle (&gt;15°) cross-sets (~15 cm thick) are visible locally</td>
<td>bioturbation increases upward; trace fossils were hard to ID, but rare Tetrichnus burrows observed locally</td>
<td>upward-fining</td>
<td>transgressive abandonment deposits (grades up from Facies G3 or G5)</td>
</tr>
<tr>
<td>G5</td>
<td>Coarse sandstone</td>
<td>bioturbation sparse throughout (Ophiomorpha); rare pebble-sized coal clasts</td>
<td></td>
<td>sharp-based blocky</td>
<td>Tidal inlet fill (occurs over coastal plain (Facies G3 and G3) and under marine (Facies G6 and G7) deposits)</td>
</tr>
<tr>
<td>G6</td>
<td>mudstone with thin, very fine sandstone interbeds</td>
<td>sandstone beds are horizontally laminated to low-angle (&lt;10°) cross stratified</td>
<td>bioturbation in mudstone is typically low, with Planolites, Asterosoma, Zoophycos, Tetrichnus, Terebellina, and Rosselia; rare Ophiomorpha, Cylindrichnus Chondrites and Paleaeophycus burrows are present in sandstone</td>
<td>upward-coarsening</td>
<td>storm-dominated delta front and offshore deposits (main Glenelg reservoirs)</td>
</tr>
<tr>
<td>G7</td>
<td>Poorly sorted sandstone</td>
<td>typically not visible</td>
<td>bioturbation is locally intense, and Ophiomorpha burrows are typically predominant; unlined, sandstone-filled Thalassinoides commonly penetrate down from Facies G7 into underlying mudstone</td>
<td>usually thin bed (&lt;1 m thick) with low API values</td>
<td>transgressive lag</td>
</tr>
</tbody>
</table>

*An extended facies analysis for the Glenelg Field is presented in Appendix 2.*
## Appendix 1, table 3 Facies descriptions and interpretations, Panuke/Cohasset field region (Upper Mississauga)*

<table>
<thead>
<tr>
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<th>Lithology and texture</th>
<th>Physical sedimentary structures</th>
<th>Biogenic features</th>
<th>Gamma ray log character</th>
<th>Facies in Venture, Glenelg, and Alma fields with similar aspect</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>medium to coarse sandstone</td>
<td>beds are typically high-angle (&gt;15°) cross-stratified or planar laminated; cross-sets are 10-100 cm thick; mud intraclasts and coal fragments are common</td>
<td>no trace fossils observed</td>
<td>Blocky</td>
<td>braided fluvial channel fills (braided channel pattern inferred based on a braid-bar like feature observed in 3-D seismic data)</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>medium to coarse sandstone</td>
<td>beds are typically high-angle (&gt;15°) cross-stratified or planar laminated; cross-sets are 10-100 cm thick; mud intraclasts and coal fragments are common; rare double mud drapes</td>
<td>several <em>Skolithos</em> burrows observed</td>
<td>Blocky</td>
<td>tide- and marine-influenced braided fluvial channel fills</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>mudstone with oyster shells</td>
<td>siltstone interbeds are planar laminated to low-angle (&lt;10°) cross-stratified</td>
<td>Bioturbation is generally absent, but is locally intense. Trace fossils include small <em>Planolites, Teichichnus, Asterozoan, Zoophycos, ?Cylindrical and Rosselia.</em></td>
<td>Muddy</td>
<td>lagoonal deposits</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>mudstone with fine sandstone laminae</td>
<td>sandstone laminae are lenticular (pod-shaped), wavy (undulating top and bottom contacts), or pinprone shaped (mm-thick, flat, and discontinuous across the core; synaeresis cracks, small-scale concave normal faults, and microfaults are present; decimeter-thick, rhythmically-interstratified mudstone and fine sandstone also occur rarely</td>
<td>Bioturbation is generally low, but locally intense. Trace fossils include small <em>Planolites, Arenicolites, Teichichnus, Chondrites, Diplocraterion, ?Skolithos, ?Thalassinoides,</em> and ?<em>Rosselia:</em> coal fragments and flakes are common</td>
<td>Serrated</td>
<td>tidal flat deposits</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>fine sandstone</td>
<td>sandstone beds are planar laminated, small-scale (&lt;5 cm) to large-scale (5-20 cm) high-angle (&gt;15°) cross-stratified</td>
<td>Trace fossils are rare, and include <em>Skolithos, Ophiomorpha,</em> small <em>Planolites</em> and escape traces; rare, unlined, passively-filled <em>Thalassinoides</em> burrows subend from sharp-basal contact; roots, carbonaceous mudstone, and a thin cm-thick coal bed are observed at the top of one of the sharp-based units</td>
<td>blocky to upward-finining</td>
<td>small tidal channel deposits</td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>very fine to fine sandstone</td>
<td>sandstone is either planar laminated or small- (&lt;5 cm) to</td>
<td>bioturbation is generally absent, but small <em>Planolites</em> burrows occur in thin</td>
<td>Upward-coarsening</td>
<td>bayhead delta deposits</td>
<td></td>
</tr>
</tbody>
</table>

*Appendix 1, table 3 Facies descriptions and interpretations, Panuke/Cohasset field region (Upper Mississauga)*

<table>
<thead>
<tr>
<th>Appendix 1, table 3 Facies descriptions and interpretations, Panuke/Cohasset field region (Upper Mississauga)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>P1</td>
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<tr>
<td>P2</td>
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<td>P4</td>
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<tr>
<td>P7</td>
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<tr>
<td>P8</td>
</tr>
<tr>
<td>P9</td>
</tr>
<tr>
<td>P10</td>
</tr>
</tbody>
</table>

*An extended facies analysis for the Panuke/Cohasset region is presented in Chapter 3.*
### Appendix 1, table 4 Facies descriptions and interpretations, Venture sandstones 8 to 5, Venture and West Venture fields (Lower Missisauga)*

<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology and texture</th>
<th>Physical sedimentary structures</th>
<th>Biogenic features</th>
<th>Gamma ray log character</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>light blue-gray carbonate mudstone</td>
<td>massive to faintly laminated</td>
<td>brachiopod, bryozoa, and foraminifera bioclasts</td>
<td>blocky</td>
<td>shelf carbonate deposits</td>
</tr>
<tr>
<td>V2</td>
<td>mudstone with rare to common thin (&lt;10 cm) siltstone and very fine sandstone beds</td>
<td>Siltstone and sandstone beds are typically planar to low-angle (&lt;10°) cross-stratified</td>
<td>sparse to intense bioturbation, with Planolites, Palaeophycus, Asterosoma, Helminthopsis, Chondrites, Zoophycos, Terebellina, Teichichmus, and Rosselia; several specimens of a Circulodium-like dinoflagellate and one Subtisphaera-like specimen observed (Rob Fensome, personal communication, 2002)</td>
<td>upward-coarsening</td>
<td>offshore/distal storm-dominated delta front deposits</td>
</tr>
<tr>
<td>V3</td>
<td>well-sorted, very fine to fine buff-coloured sandstone</td>
<td>sandstone is horizontally laminated to low-angle (&lt;10°) cross-stratified</td>
<td>bioturbation is sparse, with Ophiomorpha, Rosselia, and ?Cylindrichmus in sandstone, and Teichichmus, Paleophycus, Terebellina, Chondrites, Ophiomorpha, Cylindrichmus, Asterosoma, and ?Rosselia in rare mudstone beds</td>
<td>upward-coarsening to blocky</td>
<td>storm-dominated delta-fan deposits</td>
</tr>
<tr>
<td>V4</td>
<td>moderately to well-sorted medium sandstone</td>
<td>sandstone beds (1-25 cm thick) are high-angle (&gt;15°) to low-angle (&lt;10°) cross-stratified</td>
<td>bioturbation is sparse, with rare Ophiomorpha burrows; rare layers of sparsely disseminated organic flecks in sandstone</td>
<td>blocky to upward-coarsening</td>
<td>storm-dominated upper delta-front deposits</td>
</tr>
<tr>
<td>V5</td>
<td>mudstone with common fine to coarse sandstone interbeds (10-75 cm thick)</td>
<td>sandstone is high-angle (&gt;15°) cross-stratified; rare synaeresis cracks, load structures, double mud drapes, and rhythmically laminated intervals</td>
<td>bioturbation typically absent, but rare Ophiomorpha and Diplocraterion present in sandstone; also rare Ophiomorpha and Diplocraterion present in sandstone; mudstone contains rare Teichichmus, Thalassinoideas, ?Rhychoconarium and small Planolites pebble-sized abundant coal clasts and disseminated organic flecks; one possible dinoflagellate observed (Rob Fensome, personal communication, 2002)</td>
<td>sharp-based and serrated, units commonly fine upward slightly</td>
<td>tide-influenced fluvial deposits</td>
</tr>
<tr>
<td>V6</td>
<td>mudstone with pin stripes, wavy, and lenticular laminated very fine sandstone</td>
<td>sandstone laminae are typically high-angle (&gt;15°) cross-stratified and have flat to scoop-shaped bases; rare synaeresis cracks present</td>
<td>typically unbioturbated, although rare small Planolites burrows observed; root traces observed once</td>
<td>serrated</td>
<td>tidal flat deposits</td>
</tr>
<tr>
<td>V7</td>
<td>well-sorted medium to coarse sandstone</td>
<td>beds are typically high-angle (&gt;15°) cross-stratified; cross sets are a maximum of ~1 m thick</td>
<td>no trace fossils observed; coal fragments present locally</td>
<td>blocky</td>
<td>fluvial deposits</td>
</tr>
<tr>
<td>V8</td>
<td>coal and pyrite-rich black mudstone</td>
<td></td>
<td>no trace fossils observed</td>
<td>usually thin bed (&lt;1 m thick) with higher API values</td>
<td>marsh deposits</td>
</tr>
<tr>
<td>V9</td>
<td>poorly sorted, carbonate cemented sandstone with a &quot;paine-speckled&quot; appearance</td>
<td>typically not visible due to intense bioturbation</td>
<td>bioturbation is commonly intense, with Ophiomorpha, Chondrites, Skolihos, Palaeophycus, ?Teichichmus, and ?Rosselia/Cylindrichmus; pebble-size coal fragments, coal flake, and mm-thick coal partings are common</td>
<td>usually thin bed (&lt;1 m thick) with low API values</td>
<td>transgressive lag</td>
</tr>
</tbody>
</table>

*An extended facies analysis for the Venture and West Venture fields is presented in Chapter 4.*
SYMBOLS USED IN CORE LOGS

- mudstone
- sandstone
- limestone
- muddy sandstone
- sandstone with pebbles and/or granules
- shells and/or shell fragments
- mudstone intraclast
- coal fragment
- intensely bioturbated interval
- synaeresis cracks
- small-scale wave-ripple cross-stratification (estimated ripple wavelengths <30 cm)
- current-ripple cross-stratification
- horizontal lamination
- low-angle, concave-up truncation within a sandstone bed
- cross-stratification
- fault

NOTE: cross-strata dip angle depicted in core logs are the same as that measured in core unless well is deviated (e.g., West Venture C-62), whereinupon dip angle depicted should only be taken as a rough estimate of the true value.
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clean, well-sorted lower very fine sandstone; bioturbation is low and is associated with thin cross-beded sandstone laminae that occur sporadically throughout parts of the unit and are characterized by shell fragments (mostly Q2); these tend to be more &quot;flat&quot;-shaped, indicating the presence of Ophiomorpha, Planostratus, and Planolites; the lower part of the unit is characterized by sandstone laminae, and the upper part is characterized by cross-lamination; the shell fragments are present along with a few quartz grains (less than 0.5 mm); some of the structures are vertical; others are horizontal; in some areas, 2D sheet-like structures are present</td>
<td>1 m</td>
<td>Lower fine sandstone; bioturbation is low and is associated with thin cross-beded sandstone laminae that occur sporadically throughout parts of the unit and are characterized by shell fragments (mostly Q2); these tend to be more &quot;flat&quot;-shaped, indicating the presence of Ophiomorpha, Planostratus, and Planolites; the lower part of the unit is characterized by sandstone laminae, and the upper part is characterized by cross-lamination; the shell fragments are present along with a few quartz grains (less than 0.5 mm); some of the structures are vertical; others are horizontal; in some areas, 2D sheet-like structures are present</td>
<td>Alma A pool</td>
</tr>
</tbody>
</table>

Alma F67 core 3
boxes 15/15 to 8/15

INTENSIVELY BIOTURBATED, CARBONATE-CEMENTED, VERY FINE SANDSTONE
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palleophyllum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skolithos</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nematognathus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2,845.0 m (8,000 ft)

- Mud wavy group dips at 10 degrees
- Mud wavy group dips at 15 degrees

1 m

Alma F67
core 3
boxes 7/15 to 1/15

dm scale patches or pore-filling carbonate cement

gently dipping mud wrigs

CLean, well sorted, finer very fine sandstone, ripples are low and lenticular; thin cross laminations that occur sporadically throughout; parts of the unit react with HCl — these tend to be more "blasted" trace fossils include Palleophyllum, Ophiomorpha, Skolithos, Nematognathus. Mudstone laminae are always thin (always <0.3 cm) and are always "velvety".

...They are close to horizontal near the base of the unit, and their dip increases up to 20 degrees near the top; mudstone laminae often occur in small welts groupings and are commonly "buried" (Palleophyllum)... Mud wavy wrigs groups indicate tidal influence?

...Some kind of "double mud diapir" thing going on; lacunes within the mudstone itself are Ophiomorpha, unit coarsens upwards slightly. Very hard to distinguish without microscope; flat low angle laminae present as is dense cross stratification, but only in a few places... otherwise unit appears structureless.
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
</table>
| Ophiomorpha  | Poorly sorted, muddy, upper sandstone with fine to upper coarse sand grains (they look like plant spores); fully bioturbated with muddy marls and sandier burrows | Asterosoma, *Ophiomorpha*, *Polycraterina*, *Polymorphus* | Clean, well-sorted, lower very fine sandstone to lowest fine sandstone; North Horn is low and is associated with thin, cross-bedded multidune interbedded that occur sporadically throughout; parts of the unit react with HCl; these tend to be more "blistery" |"

**Alma F67**
core 2
boxes 27/27 to 20/27
vertical well

**Ophiomorpha burrow mimicking double mud drapes**

**Upper Member, Mississippian Fm.**
Facies A5: Transgressive shelf sandstone

Alma A pool

Upper Member, Missisauga Fm
Facies A5: Transgressive shelf sandstone

Alma A pool

Upper Member, Mississauga Fm

Note high level of bioturbation and isolated white-coloured quartz sand grains ("paint"-species)
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossiliferous sandstone with minor trace fossils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trace fossils include Rhabdophycus and ?Habasphycus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alma F67 core 1 boxes 27/27 to 20/27

Upper Member, Mississippian

Note high level of bioturbation
Alma F67
core 1
boxes 19/27 to 12/27

Facies A: Transgressive shelf sandstone

well-sorted, massive to planar laminated lower very fine sandstone; very low bioturbation (exceptional Ophiomorpha burrows; one small mudstone intraclast -1 on above base of planar laminated bed in box 19/27

upward-fining unit in core 1, the unit has transition to a muddy fine sandstone, and continues to grade upward into a muddy lower very fine sandstone; fully bioturbated texture throughout except for a few planar laminated beds that start peaking through bioturbation near top of the unit - these are well-sorted with low-moderate bioturbation (Ophiomorpha predominates), some thin micritic iron-bearing carbonate cement in box 19/27

note high level of bioturbation (Ophiomorpha burrows predominate)
Facies A2: Storm-dominated prodelta/delta front

Alma A pool

Upper Member, Missisauga Fm
<table>
<thead>
<tr>
<th>Trace</th>
<th>Fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Facies A5:** Transgressive shelf sandstone

**Alma A pool**

**Upper Member, Missisauga Fm**
<table>
<thead>
<tr>
<th>INTERPRETATION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slumped contact</td>
<td>FACIES A2: Storm-dominated prodelta/delta front (slump block)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FACIES A1: Prodelta deposits</th>
<th>FACIES A2: Storm-dominated prodelta/delta front (slump block)</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-reservoir</td>
<td>Alma C pool</td>
</tr>
<tr>
<td>Verrill Canyon Fm</td>
<td>Upper Member, Missisauga Fm</td>
</tr>
</tbody>
</table>
Facies A2: Storm-dominated prodelta/delta front (slump block)

Facies A1: Prodelta deposits

Alma C pool

Upper Member, Missisauga Fm
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Litho-strat</th>
</tr>
</thead>
<tbody>
<tr>
<td>3076.21 m (MD)</td>
<td>Phylloid mucrostone (intercalated)</td>
<td>Fishmudstone: some fish bones, very fine sandstone interbeds. Lower contacts are erosional; upper contacts are planar to low angle.</td>
<td>Alma C pool</td>
<td>Alma Member, Mississauga Fm</td>
</tr>
<tr>
<td>Planolites (very small and new)</td>
<td>Interbedded mudstone and lower very fine sandstone.</td>
<td>Several rounded, isolated, inclined mudstone intercalations; one thin mudstone interbed is completely isolated.</td>
<td>Alma C pool</td>
<td>Alma Member, Mississauga Fm</td>
</tr>
<tr>
<td>3079.30 m (MD)</td>
<td>Asterozoan Planolites</td>
<td>Interbedded mudstone with some moderately thick, lower very fine sandstone interbeds. Asterozoan Planolites include: Asterozoan Planolites, Phylloid mucrostone, (intercalated).</td>
<td>Alma C pool</td>
<td>Alma Member, Mississauga Fm</td>
</tr>
</tbody>
</table>

Interpretation:
- Dermalite: deposit of fine-grained, ferruginous sandstone, typically less than 1 mm thick.
- Bioclastic: deposit of bioclastic, often peloidal, sandstone, typically less than 1 mm thick.
- Organic: deposit of organic, typically less than 1 mm thick.
- Clayey: deposit of clayey, typically less than 1 mm thick.

Boxes 22/22 to 16/22
<table>
<thead>
<tr>
<th>Trace</th>
<th>Fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Description

<table>
<thead>
<tr>
<th>Faces</th>
<th>1.5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prodelta deposits</td>
<td></td>
</tr>
</tbody>
</table>

**Facies A2:** Storm-dominated prodelta/delta front

**Facies A1:** Prodelta deposits

**Alma C pool**

**Upper Member, Missisauga Fm**
Facies A2: Storm-dominated prodelta/delta front

Alma C pool

Upper Member, Missisauga Fm
Alma K85
core 7
boxes 3/22 to 1/22

3650.75 m (NAD)

1 m

Zoophycos
Paleofauna
Benthic forams
(Biostromatolite level is high)

3654.57 m (NAD)

FACIES A2: Storm-dominated prodelta/delta front
Alma C pool
Upper Member, Mississauga Fm

Coarsening-upward mudstone; lower very fine sandstone beds occur above and thickness increases upward, the level of bioturbation also increases upward. Black flake mudstone base, lowest 1 m is crumbly; siderite ooliths common, silicified interlamination that are present tend to be wavy and parallel. Lower very fine sandstone beds start to come in in box 9/22, these are wavy parallel to low angle (<10 degrees) long wavelength flat cross-stratified (HCS) to low angle (<10 degrees) short wavelength with low angle (slope-shaped) tractional (small wave ripples) trace fossils include Planolites, Areolites, Micritoids, Ophiomorpha in sands

DESCRIPTION FACIES RESERVOIR LITHOSTRAT

growth lower very fine sandy mudstone; lower contact of unit is sharp and non-wrinkled; organic flakes present locally in moderate abundance; grades up into a bioclast-supported sandy mudstone with bioliths, Atrichosoma and Planolites, which in turn overlies (non-erosionally) by low, very fine sandy mudstone that grades into underlying mudstone
Alma K85
core 6
boxes 22/22 to 19/22

dewatering (pillar) structures (arrows)?
(elsewhere, I've also called these "knife-scratches")
### Alma K85

Core 6

Boxes 18/22 to 15/22

#### Trace Fossils

<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Litho-Strat</th>
</tr>
</thead>
<tbody>
<tr>
<td>3041.16 m (MD)</td>
<td>current Todos isolated</td>
<td>FACES A1: Product deposits</td>
<td>Alma C pool</td>
<td>Upper Member Mississauga Fm</td>
</tr>
<tr>
<td></td>
<td>pelagic isolated</td>
<td>FACES A2: Storm-dominated prodelta/delta front</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 m
FACIES A1: Prodelta deposits

Facies A2: Storm-influenced delta front deposits

Pool C

Upper Member, Mississauga Fm
Alma K85
core 6
boxes 2/22 to 1/22

planar laminated bed with starved ripple at top
thin, small-scale wave rippled bed
massive(?l bed; top ~2 cm is ripple cross-laminated
### TRACCE FOSSILI

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully bioturbated, very fine sandstone, mostly Ophiomorpha burrows; rare shell fragments at base of unit; lower contact is sawed, but is a candidate regressive surface of maximum erosion (i.e., it may have formed during forced regression)</td>
<td>Facies A3: Unstrained shelf face deposits</td>
<td>Alma B pool</td>
<td>Upper Member, Mistissina Fm</td>
</tr>
<tr>
<td>Mudsponge with thin, very fine sandstone interbeds; bioturbation is low to moderate; trace fossils include Planolites, Heteromorphus, Pseudolithifer in mudstone and Ophiomorpha in sandstone beds</td>
<td>Alma B pool</td>
<td>Alma B pool</td>
<td>Upper Member, Mistissina Fm</td>
</tr>
</tbody>
</table>

Alma K85
core 5
boxes 21/21 to 18/21

1 m
Alma K85
core 5
boxes 17/21 to 14/21

ammonite (plan view)

irregular, oxidized contact
Alma K85
core 5
boxes 13/21 to 10/21
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2915.04 m (NQ)</td>
<td>very fossiliferous in lower 1 m (echinoid gastropod, bivalves); very few sandstone interbeds</td>
<td>Alma A pool</td>
<td>Upper Member, Mississippian Fm.</td>
<td></td>
</tr>
</tbody>
</table>

**Alma K85**
core 5
boxes 5/21 to 2/21
<table>
<thead>
<tr>
<th>Face A1: Prodelta deposits</th>
<th>Alma A pool</th>
</tr>
</thead>
</table>
| Upper Member, Mississauga Fm | }
Alma K85
core 4
boxes 22/22 to 19/22
Facies A1: Prodelta deposits
Facies A4: Transgr. lag
Facies A1: Prodelta deposits

Alma A pool

Upper Member, Mississauga Fm
Facies A2: Storm-influenced delta front and prodelta deposits

Upper Member, Missisauga Fm

Alma A pool
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2895.42 m (602)</td>
<td>Convex up cross-stratified sand &lt; 0.7° dip at base and 10° at top</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In mudstone...
- Astropecten
- ?Patellochirus
- ?Planorbinoceras

In sandstone...
- ?Ophiomorpha
- ?Phlechothyris

---

**Alma K85**
core 4
boxes 10/22 to 7/22

---

**Upper Member, Mississauga Fm**

**Facies A1: Prodelta deposits**

**Alma A pool**

---

large ?Asterosoma/Telchichnus
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2888.26 m (445)</td>
<td>mudstone</td>
<td>A2</td>
<td>Alma pool</td>
<td>Upper Member Missauga Fm</td>
</tr>
<tr>
<td>2893.42 m (445)</td>
<td>massive (?)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Alma K85**
core 4
boxes 6/22 to 3/22
Facies A1: Storm-influenced delta front and prodelta

Facies A4: Transgressive lag

Facies A1: Storm-influenced delta front and prodelta

Alma A pool

Upper Member, Mississauga Fm
## Alma K85
core 3
boxes 17/21 to 14/21

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2873.38 m DMDT</td>
<td>muddy bioturbated lower very fine sandstone</td>
<td>Facies A3, Unstressed shoreface deposits</td>
<td>Alma A pool</td>
<td>Upper Member, Mississauga Fm</td>
</tr>
</tbody>
</table>

- Zoophycos
- Ancoracme
- Scaphopoda
- Pleurotomarina
- Planolites
- Patellophyton
- Taphonodale (High)

- Upward-coarsening block mudstone: distortion is very low to low; rare, thin lower very fine sandstone interbed - these are either low-angle cross-stratified or parallel laminated.
Alma K85
core 3
boxes 13/21 to 10/21

Trace fossils

2869.37 m (MD)
Zoea phycus
A. perrotia
A. tenuifascia
Teichichnus
Norimbergopsis
Planolites
Pelecypodites
Ophiactites
(likely)

1 m

Facies A3: Unstressed shoreface deposits
Alma A pool
Upper Member Mississauga Fm

Muddy bioturbated lower very fine sandstone

large Teichichnus burrow (arrow)
TRACe FOSSILS

DESCRIPTION FACIES RESERVOIR LITHOSTRAT

2864.58 m (WE)

Fully bioturbated muddy lower very fine sandstone; some "pockets" of quartz coarse sandstone in most places these "pockets" are obviously burrow minals (Thalassinoides) but occasionally not so convincingly burrows in Coarse sands include large Arctosaeae (up to 5 cm diameter), Textularia, Paleonothophora, Ophiomorpha, Monocorona, Thalassinoides

2860.27 m (WE)

muddy bioturbated lower very fine sandstone

Alma K85
core 3
boxes 9/21 to 6/21

Facies A3: Unstressed shelfface

Alma A pool

Upper Member, Mississauga Fin

"Streaky" mudstone
note complete lack of burrows
This stuff occurs elsewhere (e.g., in Glenady Est.

I've sometimes described it as "amphibole-look" mudstone

LOADED CONTACT sandstone outcrops mudstone with "streaky" look
- pillar structure, where present, are always associated with this "streaky" mudstone
- interpretations the "streaky" mudstone was deposited rapidly from suspension
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
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<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>2858.80 m (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asteroceras</td>
</tr>
<tr>
<td>Planolites</td>
</tr>
<tr>
<td>Suberetites</td>
</tr>
<tr>
<td>Oxytomopora</td>
</tr>
<tr>
<td>Chondrites</td>
</tr>
<tr>
<td>one Skolithos (high)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2859.55 m (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

**Alma K85**

**core 3**

**box 1/21**
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies P4:</td>
<td>Tidal flat deposits</td>
</tr>
<tr>
<td>Facies P6:</td>
<td>Bayhead delta deposits</td>
</tr>
<tr>
<td>Facies P7:</td>
<td>Lagoonal deposits</td>
</tr>
</tbody>
</table>

**Upper Member, Mississauga Fm**

**Como P21**

core 1, boxes 25/25 to 18/25

**Gradational lower contact of Facies P6**

**Base**

**Top**
Glenelg E58
core 6
boxes 22/22 to 15/22

Facies G1: Storm- and tide-influenced prodelta deposits

Upper Member, Mountsberg Fm

non-reservoir

mudstone; occasional fine sandstone laminae with thin interbeds; typically no bioturbation (a few Planolites, one Schizolithus, one Terebellina observed); bioturbation decreases up-core and deformation increases up-core; some planar cross-laminae upwards into overlying units; siderite bands and nodules common throughout; some small carbonate nodules in lower 3-10 m
Glenelg E58
core 6
boxes 14/22 to 7/22

Facies G1: Storm- and tide-influenced prodelta deposits

Upper Member, Musisauga Fm.

Teichichnus burrow (arrow)
Facies G1: Storm- and tide-influenced prodelta deposits

non-reservoir

Upper Member, Missisauga Fm
**Trace Fossils**

<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostrat</th>
</tr>
</thead>
</table>

**Glenelg E58**

Core 5

Boxes 21/23 to 14/23

**Extensively Sheared Layer**

**Facies G1: Storm- and tide-influenced prodelta deposits**

- Mudstone, occasional fine sandstone, laminated in interbeds, typically no biostromes, 1-2 stromatolites, one Tithonian, one non-calcareous bivalve, bioturbation decreases up core and deformation increases up core; unit consists upwards into overlying unit; distal bands and nodules common throughout, some small carbonate nodules in lower 5-10 cm; microfaults and sheared intervals are common throughout.
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3712.5 m (MD)</td>
<td>Mustard and occasional fine sandstone (continuous with intervals of fine pelitic mudstone); typically no bioturbation. A few Horvathina, one Schlichters, one Terebellina, two Neopallium. Bioturbation decreases up-core and deformation increases up-core with coarsening upwards into reworking with calcite bands and nodules; common throughout. Some small carbonate nodules in lower ~5-10 m microfacies, and sheared intervals are common throughout.</td>
<td>Facies G1: Storm- and tide-influenced prodelta deposits</td>
<td>non-reservoir</td>
<td>Upper Member, Missisauga Fm</td>
</tr>
</tbody>
</table>

Glenelg E58
core 5
boxes 13/23 to 6/23
Facies G1: Storm- and tide-influenced prodelta deposits

non-reservoir

Upper Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3545.00 m (RSG)</td>
<td>amphibole-look</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>amphibole-look</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>deformed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>combined flow ripples</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interbedded very fine sandstone (low angle, long to small wavelength) in cross-stratified beds. Vugs and large truncations.

- Amphibole boredom
- Low angle truncations
- Opaline microfossils
- Gradational top contacts
- Organic partings and mudstone streaks
- Amphibole look (unlaminated, non-symmetrical), typically no to very low bioturbation
- Planarities, some rare Anomalissa
- No as much loading or faulting as in core 5 & 6. Carbonate nodules common, no obvious rhythmity.
- Occasional current ripple, no microfaulting.
- Rare synepigenetic calcite

Facies G6: Storm-dominated delta front and offshore deposits

C1 pool

Upper Member, Missisauga Fm

---

**Glenelg E58 core 4**

boxes 14/14 to 7/14

---

**Glenelg E58 core 4**

3549.9 m

---

current-ripple cross-stratification?

...is this a Bouma Tc turbidite?
Facies G6: Storm-dominated delta front and offshore deposits
Facies G6: Storm-dominated delta front and offshore deposits

C1 pool

Upper Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interbedded very fine sandstone and mudstone, unit occurs as upward slight</td>
<td></td>
<td>B Pool</td>
<td>Upper Member, Musquaba Fm</td>
</tr>
<tr>
<td></td>
<td>very fine sandstone beds commonly mudby, typically no bioturbation, hummocky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>cross-stratified; can contain <em>Ophiomorpha, Teichichnus</em> (low); top few cm of sandstone beds often contain apple-looking (combined flow ripple) beds can be folded and deformed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>typically no bioturbation, but rare intervals with very low density bioturbation present (Planolites); dente nodules/fan beds common</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

?Teichichnus burrow (arrow) cross-cutting a small-scale wave-ripple cross-stratified sandstone bed
Facies G6: Storm-dominated delta front and offshore deposits

B Pool

Upper Member, Misissauga Fm
Facies G6: Storm-dominated delta front and offshore deposits

Facies G7: Transgressive lag

Facies G6: Storm-dominated delta front and offshore deposits

? (see Sable Offshore Energy (1996) for further details)
Facies G6: Storm-dominated delta front and offshore deposits

? (see Sable Offshore Energy (1996) for further details)

Upper Member, Missisauga Fm
bioturbated mudstone with very fine sandstone interbeds.

mudstone

fully bioturbated (kind of a very faint paint spotty throughout) trace fossils generally hard to identify. some rare glimpses of Planolites, Scolicia, Asaphid; I think there are lots of these, hard to see (uniquely) Trybella, Holothuriformes into Tachichnus; Molenorms bioturbate increases upward; siderite nodules common

very fine sandstone interbeds

typically very low levels of bioturbation (Scolicia, Asaphid); all very faint or invisible; Gylisichnus and are typically low angle long wavelength cross-laminated; some low angle small wavelength wave ripples present

Facies G6: Storm-dominated delta front and offshore deposits

? (see Sable Offshore Energy (1996) for further details)

Glenelg H38
core 1
boxes 6/22 to 1/22

Upper Member, Mississauga Fm
**Trace Fossils**

**Description**
- Rhythmically interbedded mudstone and sandstone composed predominantly of thin (0.1 cm to 1 cm) rhythmites.
- Rhythmically alternating layers of mudstone and siltstone to lower fine sandstone. Basal lamination is absent. Dissolution coal flakes are abundant.
- Contacts between sandstone and mudstone laminae are typically gradational, although sides of the base of sandstone laminae are faceted.
- Rhythmites typically form successions that progressively thin and thin. Also, although flat, rhythmites commonly dip between 1 to 15 degrees. Rhythmically layered intervals are sporadically disturbed throughout and grade in and out of mudstone. Although the base of the unit is not sampled in core, log data suggests that the unit genetically overlies mudstone interpreted to be progradational in origin (Facies G7).

**Facies C2**: Tidal-dominated delta front deposits

**Tidal Rhythmites**

**Glenelg N49**
- Core 6
- Boxes 22/22 to 19/22
Facies G2: Tide-dominated delta front deposits

below Glenelg B and C1 pools

NOTE: delta front interpretation is based mainly on stratigraphic position

Upper Member, Mississauga Fm
### TRACED FOSSILS

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRATAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composed of two distinct facies (see below)</td>
<td></td>
<td>below Glenelg B and C1 pools</td>
<td>Upper Member, Messapian Fm</td>
</tr>
<tr>
<td>(A) honey brown coarse sandstone well sorted and always with organic debris with respect to underlying unit occasional mud cracks occasional small plant and small cavities enclosed throughout obliquely high-angle current ripples but otherwise low angle to bedding when high angle to bedding all features lead to negligible linear scale growth up to three thickly parallel thin mud bands (see photo base 3/10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B) medium sandstone with cross-stratification in erosive or discordant fluvial-braided braided channel deposits with small grains and small mud cracks and small plant impressions in some cases prior to pebbly and sand size mud cracks and small mud cracks in red muds some plant impressions in red muds with some plant impressions in red muds with some plant impressions in red muds</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TIDALLY-INFLUENCED FLUVIAL DEPOSITS

Interpreted channel base (black arrow) potential fluid mud deposits? (white arrow)

---

**Legend**

- **A**: Honey brown coarse sandstone
- **B**: Medium sandstone
- **C**: Mudstone
- **D**: Mudstone
- **E**: Mudstone
- **F**: Mudstone
- **G**: Mudstone
- **H**: Mudstone
- **I**: Mudstone
- **J**: Mudstone
- **K**: Mudstone
- **L**: Mudstone
- **M**: Mudstone
- **N**: Mudstone
- **O**: Mudstone
- **P**: Mudstone
- **Q**: Mudstone
- **R**: Mudstone
- **S**: Mudstone
- **T**: Mudstone
- **U**: Mudstone
- **V**: Mudstone
- **W**: Mudstone
- **X**: Mudstone
- **Y**: Mudstone
- **Z**: Mudstone

---

**Note:** The image contains a table, a diagram, and a page number (400) at the top right corner.
Facies G3: Tide-influenced fluvial deposits

below Glenelg B and C1 pools

Upper Member, Missisauga Fm
Facies G3: Tide-influenced fluvial deposits

below Glenelg B and C1 pools

Upper Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>FACIES</td>
</tr>
<tr>
<td>RESERVOIR</td>
</tr>
<tr>
<td>LITHOSTRAT</td>
</tr>
</tbody>
</table>

Glenelg N49  
core 5  
boxes 20/22 to 17/22

---

Facies G3: Tidally-influenced fluvial deposits

1m

below Glenelg B and C1 pools

TIDALLY INFLUENCED FLUVIAL DEPOSITS
Facies G3: Tide-influenced fluvial deposits

below Glenelg B and C1 pools

Upper Member, Missisauga Fm
Glenelg N49
core 5
boxes 12/22 to 9/22
Facies G3: Tide-influenced fluvial deposits

below Glenelg B and C1 pools

Upper Member, Missisauga Fm

general Diplocraterion burrow (arrow)
Facies G3: Tide-influenced fluvial deposits

below Glenelg B and C1 pools

Upper Member, Mississauga Fm

note large mudstone intraclasts (white arrow) and coal fragment (black arrow)
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Litho-Strat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3618.20 m (MSL)</strong></td>
<td>11° dip up</td>
<td>11° dip up</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interbedded...

(A) Moderately well sorted brownish/belger coarse sandstone

horizontally bedded (11° dip up) near top contact, with a very common low angle to horizontal, whereas near base, it is more typical. Generally, beds are conglomerate rich-on-
highs and give a set of thicknesses of 0.2 m. One bed is a very coarse sandstone with a white fine up-slope; some dark grey-brown silt and there is a small cloudbase here and there.

and

(B) Poorly sorted sandstone

(q) Poorly sorted sandstone

show thin, low angle, when observed after small strain. Helicale are net-rolled; the lower part of the rhythmic laminations are evident in the middle section. Some bioturbation is common. The sediments are commonly loaded.

 interpretations between (A) & (B) are difficult; some interbeds are present in the middle section. They exhibit a slope-up at the base of (A) and typically a slope-up at the base of (B).

---

**Glenelg N49**

core 4

boxes 21/21 to 18/21

---

**Faces G3: Tide-influenced Fluvial deposits**

below B and C1 pools

---

**Upper Member, Mississauga Fm**

---

---
\textbf{Gleneag N49}  
core 4  
bases 10/21 to 6/21

\begin{tabular}{|c|c|c|c|}
\hline
\textbf{TRACE} & \textbf{FOSSILS} & \textbf{DESCRIPTION} & \textbf{FACIES} & \textbf{RESERVOIR} & \textbf{LITHOSTRAT} \\
\hline
3668.44 m (HC) & & & & & \\
\hline
1 m & & & & & \\
\hline

Facies GS: Storm-dominated delta front and offshore deposits  
white alkaline calcarenite (lightly bioturbated, \textit{Ophiomorpha}-rafted) mixed with HC and in some cases fossiliferous  
upper rocky surface  

Facies G7: Transgressive lag  
brownish coarse calcarenite moderately to moderately well sorted occasional \textit{Ophiomorpha} burrows and bioturbation moderate and fossiliferous hard to interbedded massive ripples (locally) small sand waves (locally) wavy lamination in sand and silt (thinly) cross-bedding upward trend, low angle, no ripple marks  

Facies GS: Tidal inlet fill (7)  
 regular, sometimes high, on northwest portion

\end{tabular}
Facies G6: Storm-dominated delta front and offshore deposits

below B and C1 pools

Upper Member, Missisauga Fm
### Glenelg N49

- **core 4, box 2/21 to core 3, box 21/22**

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zoophycos Setchelnnae (mod., 1st burrowing phase)</td>
<td></td>
<td>Facies G6: Storm-dominated delta front and offshore deposits</td>
<td>below B and C1 pools</td>
<td>Upper Member, Mississauga Fm</td>
</tr>
<tr>
<td>Ophiomorpha (light)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha (one)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha (one)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha (two)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coal clutch</td>
<td>Well sorted/light brownish medium sandstone</td>
<td>Facies G6: Storm-dominated delta front and offshore deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 m</td>
<td>Typically horizontal to low-angle cross-stratified to bedded</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3596.24 m (ME)</td>
<td>some high-angle to chaotic foresets, inner soc-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tectonic slip =</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>grading top = 1/2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of unit consists Ophi-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>morpha busconica (two),</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>bioclastic and organic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Facies G4:** Transgressive abandonment deposits

**Facies G7:** Transgressive lag

**Facies G7:** Transgressive lag

**Facies G6:** Storm-dominated delta front and offshore deposits

Below B and C1 pools

**Upper Member, Missisauca Fm**
TRACE FOSSILS

DESCRIPTION

FAUCES

RESERVOIR

LITHOSTRAT

Glenelg N49

core 3

boxes 16/22 to 13/22

below B and C1 pools

Upper Member, Missisaugua Fm

delta front and offshore deposits

Facies G6: Storm-dominated

1 m

HCS, mm

Planarities

(x/low)

+smoothwater facets

(x/low)

planes due to tides, but with disarranged bedding

3584.23 m NED

deposit

slump block?

upward-courveting ripples

that consists of interbedded

(1) low sinuosity cross strata;

and (2) laminated muds

UK cleaner silt sandstone

sloae angle spiral s-stra,

often erosive or gentle tran- 
sctions (HCS) one bed is set-

able drift (say 0.1 cm)

abundant tools are common-

broad and broad-typically so

blocky, wishtone beds have

thin boken contacts, top con-

trasts are often gradational

00 micarates

very high concentration of org

nocks and clasts and beds

commonly blocked cyclical

onset, bars and these thin

layers of "Planktonic" bioclasts

in alternate rhythmically inter-

bedded (see below and oppo-

site page)

accumulation

-> HCS/brackish suggest storm

water in facies

- clinoforms and ripple drift

- very high sand fraction, and

- slump suggests offshore influence

Planolites

(x/low)

3569.36 m NAD

-
Glenelg N49
core 3
boxes 12/22 to 9/22

TRACE FOSSILS

DESCRIPTION

3579.02 m (M.D.)
upward-coarsening unit that consists of interbedded:
(A) fine angle-sorted sands and (B) laminated muds
(B) low-angle cross-stratification
sandstone is low-angle cross-stratified, with rare, thin, single-fan
currents (AC); one bed is a unit of small, tube burrows (well
absent; beds are commonly isolated and indistinct; typically no
bioturbation present); these have sharp, low contacts, sloping
contacts on otherwise gradational
bilaminar
very high concentration of spicules, particularly in outer shelf and tidal;
common burrows (bottom typically absent; zone 3 and 4 seas farther
from outlet of Halibuton basin); include artificially stranded
3584.23 m (M.D.)
hyaline bodies
Plankites (zone)

FACIES

RESERVOIR

LITHO-STRAT

delta front and offshore deposits
delta front and offshore deposits
below B and C pools
Upper Member, Mississauga Fm.
Facies G6: Storm-dominated delta front and offshore deposits

below B and C1 pools

Upper Member, Mississauga Fm
Facies G6: Storm-dominated delta front and offshore deposits

below B and C1 pools

Upper Member, Mississauga Fm
Panuke B-90
core 11, boxes 17/17 to 13/17

-~1 m break

Panuke B-90
core 12, boxes 3/23 to 1/23
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
</table>

**Panuke B-90**  
core 11, boxes 12/17 to 5/17

Facies P1: Braided fluvial deposits  
below main hydrocarbon-bearing sandstones  
Upper Member, Missisauga Fm

---

1 m

- Mudstone
- Calcareous gravel
- Gravel 1 cm
- Conglomerate 3 cm
- Sandstone
Panuke B-90

core 11 box 4/17 to
core 10 box 25/28

Facies P1: Braided fluvial deposits
below main hydrocarbon-bearing sandstones

Upper Member, Missisauga Fm

Facies P1: Braided fluvial deposits
note ubiquitous high-angle (dune) cross-stratification,
plus lack of mudstone and bioturbation
TRACE FOSSILS | DESCRIPTION | FACIES | RESERVOIR | LITHOSTRAT
---|---|---|---|---
escape trace — | Facies P1: Braided fluvial deposits | below main hydrocarbon-bearing sandstones | Upper Member, Mississauga Fm

Panuke B-90
core 10, boxes 24/28 to 17/28

1 m
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir Strata</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>deformed mudstone; very low bioturbation (Planolites); mudstone bedding planes are dipping and deformed, and the mudstone is cut by one normal fault; overlying is sandstone bed which is subhorizontal triple cross-laminated; lower contact is layer of clay and some oyster fragments.</td>
<td>Facies P1: Braided fluvial deposits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>looks like poorly sorted unit below oyster shell rich mudstone except more mud clasts. Top 'clean' up - i.e. loose shell beds, mud clasts, HCS, and poor sorting. Top of bed is low angle long wavelength cross-laminated (not folding - not HCS).</td>
<td>Facies P3: Lenticular deposits</td>
<td>below main hydrocarbon-bearing sandstones</td>
</tr>
<tr>
<td></td>
<td>some shell clasts in this clast bed.</td>
<td></td>
<td>Upper Member, Mississippian Fm.</td>
</tr>
<tr>
<td></td>
<td>very poorly sorted oyster is debris; thick interlaminated sandstone, mainly with HCS, some mud (LS)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 m
Facies P1: Braided fluvial deposits

below main hydrocarbon-bearing sandstones

Upper Member, Missisauga Fm
Panuke B-90
core 9, boxes 40/40 to 33/40

below main hydrocarbon-bearing sandstones

Upper Member, Mississauga Fm

1 m

2371 m

mudstone

conglomerate

sandstone

Facies: P1: Braided fluvial deposits
Facies P1: Braided fluvial deposits

Facies P2: Tide- & marine-influenced braided fluvial deposits

below main hydrocarbon-bearing sandstones

Upper Member, Mississauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mudstones</strong></td>
<td><em>Brown sugar</em> brown to light brown coarse to fine sandstone; typically high angle cross-bedded, not usually well sorted, typically moderately sorted, occasional mud drapes, this unit can be broken into separate units which exhibit cyclic flooding-upward trends (maximum = 7.5 m thick); maximum cross-set is ~1 m thick; rare shell/s burrows; several double mud drapes on dune foresets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Foraminifera</strong></td>
<td><em>below main hydrocarbon bearing sandstones</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Panuke B-90
core 9
boxes 24/40 to 17/40
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thalassioskler (quartz pebble filled) (mod)</td>
<td>Substratified, very sandy mudstone; composed of fine sand separated by thin silt laminae.</td>
<td>Facies P4: tidal flat deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylindrichnus (bright), Stelichnus (dull), Planolites (dull)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thalassioskler (quartz pebble filled) (mod)</td>
<td>Substratified, very sandy mudstone; composed of fine sand separated by thin silt laminae.</td>
<td>Facies P4: tidal flat deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cylindrichnus (bright), Stelichnus (dull), Planolites (dull)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mudstone</td>
<td></td>
<td>Facies P2: Tide- and marine-influenced braided fluvial deposits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Panuke B-90
core 9, boxes 16/40 to 9/40

**Upper Member, Mississippian Fm.**

**Facies Association 2**

**Facies Association 1**

**Thalassioskler Burrows**

**Below main hydrocarbon-bearing sandstones**

**Unlined**
Facies P4: Tidal flat deposits
Facies P5: Tidal channel deposits
Facies P4: Tidal flat deposits
below main hydrocarbon-bearing sandstones

Upper Member, Mississauga Fm
Panuke B-90
core B, boxes 37/37 to 30/37

TRACE FOSSILS

DESCRIPTION

FACIES

RESERVOIR

LITHOSTRAT

s. small
Planolites
(lime low)
Rosaceatella
Clitoceras

nant pisitake

--

oyster shell fragments

black unbioturbated mudstone with oyster shells and rare thin small-scale wave ripple cross-stratified beds

Facies P4c: Tidal flat deposits

below main hydrocarbon-bearing sandstones

Upper Member, Missisauga Fm

Diplodoceras
Rhabdopleurina
Plesioceras
Chonetes
(lime high)

Facies P3: Lagoon deposits

\begin{tabular}{|l|}
\hline
intergradations of 1) inter-laminated to thinly interbedded pisitake to lenticular fine sandstone and angular to sub-rounded quartz arenites are commonly  very small wave ripple (rippled and 2) thin fine sandstone beds (10 cm) with small to medium scale wave ripple cross-stratification (combined flow); some synaeresis crackle/crackle very low bioturbation laminae. Plesioceras, Diplodoceras, Pelecypods, Chonetes, Chonetes, Diplodoceras, Bivalves, Fish sp., and ?Maiasaura?
\hline
\end{tabular}

WAVY AND PISTRIPE LAMINATION
Facies P4: Tidal flat deposits

? Facies P3: Lagoonal deposits?

Facies P4: Tidal flat deposits

below main hydrocarbon-bearing sandstones

Upper Member, Mississauga Fm
### Table: Trace Fossils Description

<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostrat</th>
</tr>
</thead>
<tbody>
<tr>
<td>? Facies P.4: Tidal flat deposits</td>
<td>?</td>
<td>Facies P.4: Tidal flat deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>? Facies P.3: Laggonal deposits</td>
<td></td>
<td>Facies P.3: Laggonal deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>? Facies P.2: Tidal channel deposits</td>
<td>?</td>
<td>Facies P.2: Tidal channel deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>? Facies P.1: Tidal flat deposits</td>
<td>?</td>
<td>Facies P.1: Tidal flat deposits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Panuke B-90**
core 8, boxes 21/37 to 14/3

**Small-Scale Slump**

- Mudstone with common thin very fine pinites to lenticular siltstone interbeds (layered, some current ripples)
- Very sparse bioclasts (small Ps, one Ps set, slumped synesesis crinkles, top contact is bioturbated, lower contact is gradational)
- Oyster shell fragments
- Ostracod and rare fish fossils
- Upward-coarsening unit; uninflated Thalassiodora burrows extend from lower contact; trace fossils include Ophiomorpha, Planolites, and Diplocraterion
- Mudstone with rare and scattered marine fauna; smooth, thin section with rare trace fossils
- Mudstone with rare and scattered marine fauna; smooth, thin section with rare trace fossils

**Diagram:**
-Upper Member, Misissauga Fm
-Below main hydrocarbon-bearing sandstones

**Scale:** 1 m
**Panuke B-90**
core 8, boxes 13/37 to 6/37

**TRACE FOSSILS**

<table>
<thead>
<tr>
<th>Description</th>
<th>Facies P3: Lagoonal deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black mudstone; no relict; very fossil-laden layer of peeper-speckled</td>
<td></td>
</tr>
<tr>
<td>Siltstone-mudstone sandstone with abundant shell tact (mop, oyster, and other)</td>
<td></td>
</tr>
</tbody>
</table>

**RESERVOIR**

- Fully bioturbated cross-bedding; and cleaning-up unit: trace fossils near base — Bm, Thacher (at base), Diplod.  "Dich" trace fossils near top — Opb, Rnt "garnet" shells: occasional and some oyster shells

**LITHO-STRAT**

- Mudstone; no sand beds; very low bioturbation (two or two Thacher); lower contact is gradual; top contact is sharp — untitled Thacher

**Facies P4: Tidal flat deposits**

- Upward-fining, moderately high to fully bioturbated very fine sandstone to sandy mudstone bioturbation increases up section from moderate-high to full trace fossils (near sandy base) — small Diplod; Rnt; Thacher; trace fossils (near muddy top) — Rnt, Thacher; some large oyster shells near top

---

**Upper Member, Mississauga Fm**

**1 m**

**Opb, Ro? (right)**

**Rnt, Door, Teich? (right)**

**Ro? (right)**

**small Diplod, Rnt, Teich? (right)**

---

**core 8, boxes 13/37 to 6/37**

---

**top**

**base**
Panuks B-90
core 8, box 5/37 to
core 7, box 37/39
Facies P6: Bayhead delta deposits
Facies P3: Lagoonal deposits
Facies P4: Tidal channel deposits
below main hydrocarbon-bearing sandstones

Upper Member, Missisauca Fm
below main hydrocarbon-bearing sandstones
**Panuke B-90**
core 7, boxes 20/39 to 13/39

<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostrat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>as below, but with thin pelecypod to lenticular very fine sandstone laminae</td>
<td>Facies P4: Tidal flat deposits</td>
<td>non-reservoir</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mudstone with thin siltstone beds and laminae; siltstone beds are typically normally graded and parallel laminated to low angle cross-stratified... (see photo)</td>
<td>Facies P3: Lagoonal deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine sandstone; bioturbation is very low to non-existent (small P)</td>
<td>Facies P1: Transitional shallow marine sandstone</td>
<td>Panuke P3 sandstone</td>
<td>Upper Member, Mississauga Frm</td>
</tr>
<tr>
<td></td>
<td>Fully bioturbated, poorly sorted mudstone; shallow marine sandstone, siltstone, and skeletal debris; trace fossils abundant; occasional burrows, typically aligned vertically, with well-sorted coarse sandstone fills</td>
<td>Facies P3: Lagoonal deposits</td>
<td>below main reservoir</td>
<td></td>
</tr>
</tbody>
</table>

**PAINT-SPECKLE TEXTURE**

'Paint speckle' are the white mottled spots on a clay matrix that occur throughout.
Panu3e B90
core 7, boxes 12/39 to 5/39
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha, Cylindrichnus</td>
<td>very poorly sorted sandstone: basal layer is full of sandstone pebbles, shell bits, coal fragments, and unidentified mud slates; sandstone pebbles often have diagenetic rings (see photo); lower contact tight at a high angle; HC reaction throughout; lots of small green grains (glauconite); a few large, thick-walled Ophiomorpha borings with reddish borings</td>
<td>P9: Offshore mudstone</td>
<td>non-reservoir</td>
<td>Nokomis Mb, Logan Canyon Fm</td>
</tr>
<tr>
<td>Cylindrichnus, Skolithos (very fine)</td>
<td>fine sandstone: physical and redolent structures are typically hard to ID; only a few (10 or so high-angle cross-stratified beds) are observed; these are oriented 0/90 degrees to each other, and are separated by a non-horizontal contact (see photo); locally fully bioturbated and slightly muddy; otherwise bioturbation is moderate throughout (cook, 1986), trace fossils are reddish in color; a few minor mud interbeds; coal flakes present near top contact and lower contact in low concentrations; lower contact is a coarse sandstone, paint-splatter layer; top contact dips at a high angle, and is overlain by a well-developed lag (see photo)</td>
<td>P8: Transgressive shallow marine sandstone</td>
<td></td>
<td>Upper Member, Missoula Fm</td>
</tr>
</tbody>
</table>

**Panuke B90**
core 7 box 4/39 to core 8, box 24/27
Panuke F-99
core 3, boxes 40/40 to 32/40

**TRACE FOSSILS**

<table>
<thead>
<tr>
<th>FACIES</th>
<th>DESCRIPTION</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies P4: Tidal flat deposits</td>
<td>Intensely interlaminated mudstone and very fine sandstone; locally fully bioturbated; locally low bioturbated (Tich, small PI, Rod, Ch, Anti), swelling days locally vice oyster frag. matrix; PI = intercalated; lots of oysters (chunks and flecks); very fine sandstone laminates are noisy parallel laminites to low angle long wavelength to low angle short wavelength wave ripples</td>
<td>non-reservoir</td>
<td>Upper Member, Mississauga Fm</td>
</tr>
<tr>
<td>Facies PS: Tidal channel deposits</td>
<td>Dark beige fine sandstones; low angle (~10 degrees) to high angle (~20 degrees); small scale, a few trace fossils (Lo in muds); some vertical burrows near to (small) SAL, top ~10 cm under top contact is laminated; top contact = irregular; low organic content</td>
<td>non-reservoir</td>
<td>Upper Member, Mississauga Fm</td>
</tr>
<tr>
<td>Facies P4: Tidal flat deposits</td>
<td>Paint speckle mudstone occurs up into paint speckle very fine sandstones; typically fully bioturbated; HCl-methane in sands; oyster shell fragments common; lower contact is sharp and highly irregular; top contact = shell beds; local siltstone patches</td>
<td>non-reservoir</td>
<td>Upper Member, Mississauga Fm</td>
</tr>
</tbody>
</table>

**TALLAHASSEAN**

- Small Planolites (low mud)
- Nodosites (1)

**2327.8 m (MC)**

- Sandstone
- Conglomerate
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chondrites</td>
<td>Mudstone with &quot;paint-speckled&quot; look coarsening upwards into very fine sandstone with &quot;paint-speckled&quot; look; typically fully bioturbated sandstone reacts with HCl; oyster and gastropod shell fragments common; local oolite patches; lowest contact = highly irregular.</td>
<td>Facies P3: Tidal channel deposits</td>
<td>IX</td>
<td>X</td>
</tr>
<tr>
<td>Alloephanus</td>
<td>Mudstone, brownish gray to dark gray, bioturbated, some burrows, casts, and molds; locally bioturbated sandstone with oolitic fabric</td>
<td>Facies P3: Lagoonal deposits</td>
<td>IX</td>
<td>X</td>
</tr>
<tr>
<td>Thalassinoidea (highest)</td>
<td>Very well sorted fine sandstone, some bioturbation, some burrows, casts, and molds; locally bioturbated sandstone with oolitic fabric</td>
<td>IX</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>Local oolite patches</td>
<td>IX</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Panuke F-99
core 3, boxes 31/40 to 24/40
Facies P3: Lagoonal deposits
Facies P6: Bayhead delta deposits
Facies P7: Transgressive lag
Facies P3: Lagoonal deposits

below main hydrocarbon-bearing
Panuke sandstone reservoirs

Upper Member, Missisauga Fm

Panuke F99
core 3, bottom 2340 to 1640
<table>
<thead>
<tr>
<th>Facies P3: Lagoonal deposits</th>
<th>Facies P8: Transgressive shallow marine sandstone</th>
<th>Facies P3: Lagoonal deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panuke P3 sandstone</td>
<td></td>
<td>Upper Member, Missisauga Fm</td>
</tr>
</tbody>
</table>

**Trace Fossils**

**Facies**

**Description**

**Lithostratigraphic units**

- Burrowed thinning-out surface

**Panuke 399 PP Z**

core 1, boxes 2.5/25 to 18/25
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>paint-speckle brecciated mucky unit; &quot;paint-speckle&quot; are individual rounded quartz grains.. these get up to small pebble sized near top contact/lower contact =&gt; Glossifungites surface. Just above this is an oxidized layer, unit is bioturbated throughout; trace fossils include Ch. Telkh, Th, C. sp.</td>
<td>P7; Transgressive lag</td>
<td>Panuke P2 sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ciertazid</td>
<td>P3: Lagoonal deposits</td>
<td>non-reservoir</td>
<td></td>
</tr>
<tr>
<td>Taphrosomides</td>
<td>very thinly interbedded mudstone and lower very fine sandstone. Biostratigraphy seen at base. This grades to fully bioturbated near top; lower very fine sandstone beds are usually low angle small wavelength wavy ripple cross strati; with low angle truncations to very parallel laminated. Littoral beds pinch and swell across core trace fossils near base =&gt; Art... near top =&gt; Ophi., others hard to tell. A layer of lag oyster shell occurs near the top contact... these are in similar stratigraphic position as oyster shell layers in other Panuke cores (e.g. PP9, BK1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P4: Tidal flat deposits</td>
<td>P3: Lagoonal deposits</td>
<td>Oyster shells</td>
<td></td>
</tr>
<tr>
<td></td>
<td>small scale wave ripple cross strati; friable sandstone with muskegon intercalate</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>slight loading along basal contacts of fine silt laminae</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FACIES</td>
<td>DESCRIPTION</td>
<td></td>
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<td>---------------</td>
<td>----------------------------------------------------------------------------</td>
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<td></td>
<td></td>
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<tr>
<td>Facies P7:</td>
<td>Transgressive lag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facies P8:</td>
<td>Transgressive-shallow marine sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facies P9:</td>
<td>Offshore deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir</td>
<td>Non-reservoir</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Litho-strat</td>
<td>Naskapi Mbl, Logan Canyon Fm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Panuke J99 PP2**
core 1, boxes 9/25 to 1/25

**Upper Member, Mississauga Fm**

**HUMHOCK CROSS-STRATIFIED VERY FINE SANDSTONE**

- **Panuke P2 sandstone** (main Panuke reservoir)
- **Panuke P1 sandstone**
- **Panuke P4 sandstone**
- **Panuke P5 sandstone**
- **Panuke P6 sandstone**

**Trace Fossils**
- *Ophiomorpha* (High)
- *Ophiomorpha* (low)
- *Ophiomorpha* (no)
- *Ophiomorpha* (undetermined)
- *Ophiomorpha* (no)
Facies V2: Storm-dominated prodelta/lower delta-front deposits

Facies V3: Storm-dominated lower delta-front deposits

Venture sandstone 6m

Lower Member, Mississauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
</table>

**Venture B-13**
core 4
boxes 5/13 to 1/13
note enlarged scale

---

Coarsens upward from pink-orange mudstone to hummocky cross-stratified sandstone with mud interbeds to medium sandstone; medium sandstone looks identical to medium sandstone in underlying unit, although physical sedimentary structures are not identifiable.

---

Medium sandstone appears structureless, but upon closer inspection is high to low angle cross-stratified; significant play in the cross-strata dip directions.

---

Facies V-3 Storm-dominated upper delta front deposits?

---

Venture sandstone 6u7

---

Lower Member Mississauga Fm
Venture B-43
core 6
boxes 14/14 to 11/14

4966.7 m (WGS 84)

1 m

chilly interbedded medium to coarse sandstone and mudstone; sandstone looks like it has little flecks of black and orange in it ('salt, pepper and orange' looks); mudstone is not beautifully 'pleistripe' laminated, but typically has thin (0.5 - 2 cm) interbeds of salt pepper and orange sandstone...these are often loaded and often pinch and swell across core; bioturbation in the mudstone nullifies a few potential Thalassinoides burrows subbed from sandstone beds (hard to figure out sometimes); whether these are load structures or passively filled Thalassinoides burrows; sandstone beds typically appear structureless...some small-scale high angle dune cross-stratification observed

?DIPLOCRATERION BURROW
associated with 'transition-zone' where most pronounced upward-finining occurs
<table>
<thead>
<tr>
<th>Core</th>
<th>Voil</th>
<th>STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Member, Missisauga Fm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Facies**

- **Facies V7**: Tide-influenced fluvial deposits
- **Facies V9**: Transgressive lag
- ? Facies V4: Storm-dominated upper delta-front (shoreface)?

**Core 6**

- Core 6 boxes 01-43 to 71-43
<table>
<thead>
<tr>
<th>TRACE</th>
<th>FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>medium to very fine sandstone; macroscopically, this unit looks like clean fine sandstone; when you get your nose into it, there are higher angle cross-sets (max. -10-15 cm), often 3D, mixed with lower angle (&lt;15 degrees) cross-stratification, but not unequivocal hummocky cross-stratification; also, there is a section that is hummocky cross-stratified, with one Ophiomorpha burrow and nice low angle truncations; a section near the top has bipolax high angle 3D cross-sets (cross-sets are ~5 cm thick) intercalated with low angle cross-stratified beds. In one place, tosets of a 3D dune are muddy; no bioturbation except for several Ophiomorpha burrows; rare organic flake-rich layers.</td>
<td></td>
<td>Sandstone 6U</td>
<td>Lower Member Mississippian Fm</td>
</tr>
<tr>
<td>TRACE FOSSILS</td>
<td>DESCRIPTION</td>
<td>FACIES</td>
<td>RESERVOIR</td>
<td>LITHOSTRAT</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>very fine sandstone to muddy very fine sandstone; low angle cross-stratification with low angle truncations (hummocky cross-stratification) and bioturbated zones (Ophiomorpha, Policystites, <em>Zoophycos</em>); rusty patches occasional; as are organic chunks and flakes; no obvious internal surfaces</td>
<td>Facies V2 Storm-dominated offshore/delta-front deposits</td>
<td>Venture sandstone 5</td>
<td>Lower Member, Mistissini Fm</td>
<td></td>
</tr>
</tbody>
</table>

**Venture B-43**
core 5
boxes 4/4 to 1/4
note scale
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRATIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha</td>
<td>finned bioturbated laminitestum and matrix (?) salt pepper and orange speckled upper fine sandstone sandstone beds commonly massive (not laterally extensive up to 30 degrees cross stratified with thickness ~15 cm), no bioturbation except for one; Ophiomorphs below new base of extremely thick laminite; laminites are sharp based and topped; mudstone is locally very rich in organic materials and has occasional organic partings that lie at a very close to horizontal in two or three places; a thin layer of sandstone (~1 cm) is sometimes located between mudstone laminites; these are interpreted to be double muds deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facies M.1: shelf carbonate deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Venture limestone 9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mic. Muc. Fm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Venture B-52**
core 5
boxes 12/12 to 9/12

**1 m**

**5131.6 m**
**Facies V5:** Tide-influenced fluvial deposits

**Venture sandstone 7**

**Lower Member, Mississauga Fm**
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>5113.6 m</td>
<td>pinstripe laminated mudstone with a few thin medium to coarse sandstone interbeds</td>
<td>Facies V5: Tidal flat deposits</td>
<td>Ventura sandstone 7</td>
<td>Lower Member, Mississippian Fm</td>
</tr>
<tr>
<td>brownish (lightly oiled) lower medium to upper fine sandstone; no mudstone interbeds, and little disseminated mud or organic matter in the sandstone itself; although cross-stratification typically hard to pick out, some high angle cross-stratification present...the unit seems mostly dune cross-stratified, with cross-sets generally thicker than in underlying unit; unit fines up nicely (not muddy up); one layer of mud rip-ups and one group of organic laminae present; no bioturbation; becomes more salt-pepper and orange speckled and less brown moving up core; lower contact has no lag...hard to actually pinpoint; top contact is sharp and no lag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Venture B-52
core 4
boxes 11/11 to 8/11
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostratigraphy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oplocones</strong> (common)</td>
<td>Bioturbated medium sandstone: thinning upwards to mudstone; long, large vertical burrows are striking. <strong>Oplocones</strong>: max. 25 cm long; organic matter in unit is often held by rostyness; where sandstone fines up in muds (boxes 5-4), there is a nice paint-speckle (non-HCl reacting); other trace fossils include <strong>Ophiomorpha</strong> (at base only); PFactilis, otherwise, trace fossils are hard to identify.</td>
<td>Ventura sandstone 6M</td>
<td>Lower Member, Mississippian Fm</td>
<td>Facies V5: Tidal-influenced fluvial deposits</td>
</tr>
</tbody>
</table>

**Venture B-52**
core 4
boxes 7/11 to 4/11
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clean salt pepper and orange speckle medium sandstone; no mudstone interbeds; occasional Ophiomorpha burrows; high angle cross stratified in places; otherwise looks massive; some organic chunks; lower contact is arbitrary</td>
<td>Facies V5: Tide-influenced fluvial deposits</td>
<td>Venture sandstone 6M</td>
<td>Lower Member, Mississauga Fm</td>
</tr>
<tr>
<td></td>
<td>interbedded upper fine to medium sandstone and pin stripe laminated mudstone; sandstone has a 'salt pepper and orange speckle' to it; some organic partings; no bioturbation; hard to see sedimentary structures in sandstone; lower contact is sharp; top contact is somewhat arbitrary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>bioturbated medium sandstone fining upwards to mudstone; long large vertical burrows are striking (Ophiomorpha - max. 25 cm long); organic matter in unit is often halved by rustiness; where sandstone fines up in muds (boxes 5-4), there is a nice paint-speckle (non-HCl reacting); other trace fossils include Ophiomorpha (at base only?); fish fossils... otherwise, trace fossils are hard to identify</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRACE FOSSILS</td>
<td>DESCRIPTION</td>
<td>FACIES</td>
<td>RESERVOIR</td>
<td>LITHOSTRAT</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
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<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>5018.6 m</td>
<td>blisturated lower very fine sandstone with horizontal flat lamination to very low angle cross lamination; Ophiomorpha commons, rust spots and a small layer of small mud rip-ups present</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>lower very fine sandstone with not a lot in them (structure, blistur- ation etc...); the grey colour and feel of the sandstone at the base of this unit are strik- ing, very well sorted, no mudstone one small articulated bivalve shell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 m</td>
<td>top half consists of blisturated muddy very fine sandstone with rust spots; bottom half consists of sandstone that looks like underlying unit but is lower fine as opposed to lower medium sandstone, and has more mud and organic in it. Lower contact of unit could be placed at the top of this bed; the (blisturated) sandstone contain one nice Ophiomorpha, and although not striking, its presence might suggest a similar type of environment (as so far, Ophiomorpha have not been observed in up to marine shoreline or shell deposits, only coastal plane)</td>
<td></td>
<td></td>
<td>Ventures sandstone 6U</td>
</tr>
<tr>
<td>5036.0 m</td>
<td>clean salt pepper and orange speckle medium sandstone; no mudstone; interbeds occasional Ophiomorpha burrows, high angle cross stratified in places; otherwise looks massive; some organic chunks; lower contact is arbitrary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Venture B-52
core 3
boxes S/5 to 1/5

Lower Member, Mississauga Fm
Venture B-52
core 2
boxes 13/13 to 10/13

Description of Facies V5: Tide-influenced fluvial deposits

- Sandstone with flute casts (bottom). Fine to very fine sandstone with a sharp or gradational boundary.
- The sandstone is fine to lower very fine sandstone which are typically low angle flat to gently curved cross-lamination.
- Smaller rock types are typically hard and hummocky cross-stratified.
- Ophiomorpha flutes are present in the sandstone, indicating storm dominance.
- The sandstone in this zone is typically lower to middle slope in fluvial depositional environments.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.
- The sandstone is medium to coarse sandstone with a sharp or gradational boundary.
- The sandstone is fine to medium sandstone with flute casts and some tidal flat elements.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.

Facies V5: Storm-dominated delta front deposits

- Ophiomorpha flutes are present in the sandstone, indicating storm dominance.
- The sandstone in this zone is typically lower to middle slope in fluvial depositional environments.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.
- Fine to medium sandstone (top) is fine to medium sandstone with flute casts and some tidal flat elements.
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostrat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha</td>
<td>Interbedded fine to medium sandstone (salt pepper and orange speckle) with pin stripe laminated mudstone; sandstone often high angle cross-stratified, but typically looks massive; cross beds are typically 10 cm thick, maximum 25 cm thick; sandstone beds range from 2 to 35 cm thick; sandstone beds occasionally have a low density fluid-like assemblage; sandstone beds in bottom few meters of unit have no bioturbation; sandstone beds typically have no fining or coarsening upward trends; trace fossils are predominantly Ophiomorpha; but there is another trace fossil in a few beds that I can’t ID but looks like Tastenidium or Maiaspondios (similar to traces in same facies in West Venture C22); pin stripe laminated mudstone very occasionally exhibits paint-speckle look which seems to be infill in larger burrows (Kathastitoldius) otherwise mudstone is bioturbation free; there are two weird distinctly light grey mudstone beds (one which seems to be HCB that are not pin stripe laminated; lower contact of unit has no lag et al. but is sharp i.e. not intercalated; some define small-scale wave formed structures in boxes 1-2...could this be true coupled with increase in bioturbation up unit suggest increased marine influence up core?</td>
<td>Facies V5: Tide-influenced fluvial deposits</td>
<td></td>
<td>Lower Member, Mississippian Fm</td>
</tr>
<tr>
<td>Ophiomorpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Facies VS: Tide-influenced fluvial deposits

Venture sandstone 5

Lower Member, Missisauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 8

Lower Member, Mississauga Fm
interbedded mudstone and clean low angle cross-stratified very fine sandstone with low angle internal truncations. Pyroclastics and bioturbation in the mudstone decreases nicely up core from fully bioturbated at base to unbioturbated near top of unit. Trace fossils include Ophiomorpha, Planolites, Palaeophycus, Chondrites.
Facies V2: Storm-dominated offshore/distal delta-front deposits
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 8

Lower Member, Mississauga Fm
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 8

Lower Member, Missisauga Fm
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 8

Lower Member, Mississauga Fm
VENTURE H-22
core 6
boxes 22/24 to 19/24

TRACE FOSSILS

DESCRIPTION

FACIES

RESERVOIR

LITHOSTRAT

Tens of cms to m-thick beds of clean very fine sandstone with thinner (1 to 25 cm thick) mudstone interbeds; sandstone beds often go from a parallel laminated or low angle cross stratified lower portion (lummokey cross stratification or oscillatory plane bed) to small-scale scoop-based ripple cross sets (small wave ripple cross sets) in the top 5-10 cm; mudstone typically not bioturbated and have a similar look as mudstone in underlying unit (i.e. lots of wavy siltstone interbeds)

Facies V2: Storm-dominated offshore/delta front deposits

Venture sandstone 7

Lower Member Mississauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Facies V3: Storm-dominated delta-front deposits

Venture sandstone 7

Lower Member, Mississauga Fm
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE</th>
<th>FOSSILS</th>
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<tbody>
<tr>
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</table>

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESEAL</th>
<th>VOIR</th>
<th>LITHO</th>
<th>STRAT</th>
</tr>
</thead>
<tbody>
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</table>

**Facies V3: Storm-dominated delta-front deposits**

**Venture sandstone 7**

**Lower Member, Missisauga Fm**
<table>
<thead>
<tr>
<th>TRACE</th>
<th>FOSSILS</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Venture sandstone 7</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>FACIES</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3: Storm-dominated delta-front deposits</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>RESUB</th>
<th>VOIR</th>
<th>LITHO</th>
<th>STRAT</th>
</tr>
</thead>
</table>

Lower Member, Mississauga Fm
Venture H-22
core 5
boxes 22/24 to 19/24
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>interbedded mudstone and lower very fine sandstone; sandstone beds are typically low angle cross-stratified (wavelocky cross-stratified); bioturbation in mudstone ranges from very low to intense where bioturbation is very low; mudstone contains lots of thin siltstone interbeds that are wavy parallel laminated with some small-scale wave ripple cross sets; trace fossils include Chondrites, Paleophycus, Teretellina, Astromioidea (in mudstone) and Ophiomorpha (in sandstone)</td>
<td>Facies V2: Storm-dominated offshore/distal delta-front deposits</td>
<td>Ventura sandstone 6L</td>
<td>Lower Member, Mississippian Fm</td>
</tr>
</tbody>
</table>
Interbedded mudstone and lower very fine sandstone; sandstone beds are typically low angle cross-stratified (hummocky cross-stratified); bioturbation in mudstone ranges from very low to intense where bioturbation is very low, mudstone contains lots of thin siltstone interbeds that are wavy parallel laminated with some small-scale wave ripple cross-sets; trace fossils include Chondrites, Paleoshopfycus, Trebiellia, Astrorosomos (in mudstone) and Ophiomorpha (in sandstone).

Facies V2-Storm-dominated offshore/delta-front deposits

Venture sandstone 6L

Lower Member, Mississauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mudstone; non-fossil; coarsens upwards (more siltstone interbeds up core); internally laminated to thinly interbedded siltstone and mudstone; siltstone laminae thickness increases up core from an average of ~0.75 cm to ~1.5 cm thick close to top contact; bioturbation also increases up core from none close to lower contact to intense in top ~1.5 m of unit; siltstone interlaminae are typically sharp-based with sharp tops and are internally wavy parallel laminated to small-scale wave-ripple cross-stratified; some siltstone interlaminae are graded; siltstone beds commonly pinch and swell gently across core trace fossils include Astrorhizos, Rosella, Ophthalmopha, Planolites, Helminthopis; lower contact is not a distinct lag, but HCS bed at base of unit reacts with HCS; small CaCO3 nodules present, some of which are septarian</td>
<td>Facies V2: Storm-dominating offshore/delta front deposits</td>
<td>Venture sandstone 6M</td>
<td>Venture sandstone 6L</td>
</tr>
</tbody>
</table>
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Facies V3: Storm-dominated delta-front deposits

Venture sandstone 6M

Lower Member, Mississauga Fm
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm

TRACE
FOSSILS

DESCRIPTION

FACES

RESERVOIR

VOIR

LITHOLOG

VENTURE H 22

core 4, box 31/7 to

core 5, box 12/6

tone blown up scale

484
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Venture H-22
core 3
boxes 3/16 to 1/16
note blown up scale

DOUBLE MUD DRAPEs?

Facies V: Storm-dominated upper delta-front deposits.

Venture sandstone 6 M

Lower Member Mississauga Fm

fine to medium sandstone; no bioturbation save for two Skolithos burrows; sandstone is a mix of low angle (<10 degrees) and moderate angle (10 to 13 degrees) cross stratified beds; cross sets are several to ~25 cm thick; some potential double mud stone drapes; lower contact is sharp
Facies V7: Tide-influenced fluvial deposits

Venture sandstone 5

Lower Member, Missisauga Fm

Mudstone with 'sharp' sandstone pinstripes

mudstone with diffuse sandstone pinstripes (note rhythmic stratification)

massive sandstone (note loaded lower contact)
Facies V7: Tide-influenced fluvial deposits

Venture sandstone 5

Lower Member, Missisauga Fm
Facies V7: Tide-influenced fluvial deposits

Venture sandstone 5

Lower Member, Missisauga Fm
Facies V7: Tide-influenced fluvial deposits

Venture sandstone 5

Lower Member, Missisauga Fm
West Venture C-62
DEVIATED WELL
core 13
boxes 9/13 to 6/13

<table>
<thead>
<tr>
<th>TRACÉ FOSSILS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dark blue grey lime mudstone; faint 'amphibole-look' lamination; very rare bioclasts boxes 13 to 6; becomes progressively whiter upcore from box 6 upwards; more bioclasts after box 6 as well; more detrital non-HCl reacting mud layers moving upcore (from none in boxes 13 to 6 to rare above box 6); very low porosity --&gt; rocks clink like pieces of hard ceramic when you knock them together</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FACIES</th>
<th>RESERVOIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facies V: Shelf carbonate deposits</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venture limestone 9</td>
</tr>
</tbody>
</table>

Mic Mac Fm

"BLUEISH" LIME MUDSTONE
note progressive white colour up-core
West Venture C-62
DEVIATED WELL
core 13
boxes 5/13 to 2/13

"BLUEISH" LIME MUDSTONE
note progressive whiter colour up-core
**Facies V1: Shelf carbonate deposits**

Venture limestone No. 9

Mic Mac Fm

---

**LIME MUDDSTONE**

- Terrestrial shale layer

---

**West Venture C42**

DEVALED WELL

core 13

box 7/13
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>black mud; moderately fissile; still reactive moderately with HCl; has a distinct laminations (thin silt laminae); unit coarsens-upwards slightly to top of box 2; disturbance = none (!)</td>
<td>V1: Inner shelf, storm-dominated delta front deposits</td>
<td>Venture sandstone 8</td>
<td>Lower Member, Mississauga Fm</td>
</tr>
<tr>
<td></td>
<td>nature of contact core is chucks here, however, no distinct lag and lenticular slate layers in carbonate increase up towards contact. They a sloping veins-like with yellow calcite, which in turn can be associated with calcite exposure</td>
<td>V1: Shelf carbonate deposits</td>
<td>Venture limestone 9</td>
<td>MicMac Fm</td>
</tr>
</tbody>
</table>

5258.41m

UNBIOTURBATED MUDSTONE

West Venture C-62
DEVIATED WELL
core 12
boxes 5/5 to 3/5
Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone 8

Lower Member, Missisauga Fm

UNBIOTURBED MUDSTONE
Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone No. 8

Lower Member, Mississauga Fm
Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone 8

Lower Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodosarthrops</td>
<td>mudstone with interstratified lower very fine sandstone; bioturbation increases up core from very low to moderate levels; unit seams to coarsen-upward from underlying unit (at the top of core 12); sandstone laminae are often lenticular, and internally are small scale wave rippled or low-angle cross stratified with concave low angle truncations (convincing hummocky cross-stratification); trace fossil assemblage includes Nodosarthrops, Chondrites, Planolites, Palaeophycus, Acracoma, Zoophycos; subvertical burrows become more common upward (the first one is in the lower 15 cm of box 17/21)</td>
</tr>
<tr>
<td>Chondrites</td>
<td></td>
</tr>
<tr>
<td>Planolites</td>
<td></td>
</tr>
<tr>
<td>Palaeophycus</td>
<td></td>
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<tr>
<td>Acracoma</td>
<td></td>
</tr>
<tr>
<td>Zoophycos</td>
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</tr>
</tbody>
</table>

Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone 8

Lower Member, Mississauga Fm

West Venture C-62
DEViated WELL
core 11
boxes 13/21 to 10/21
**West Venture C-62**

**DEVIATED WELL**

core 11

boxes 9/21 to 6/21

---

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
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<th>LITHO STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>very clean upper very fine sandstone; unit has a coarsening upward grain size trend, but also starts to have more larger mudstone interbeds up core...I guess you could call it a coarsening up then fining-up trend; lower contact has been sawed, but no obvious lag apparent; not one trace fossil found in the sandstone...mudstone interbeds are bioturbated at very low levels; mudstone is black and non-fissile; structure in clean sandstone is generally hard to define because well is turned and there are few mud interlaminar to interbeds to define horizontal, as for bedding and grading within each sand bed — very hard to see</td>
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</tr>
<tr>
<td></td>
<td>Venture sandstone 8</td>
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</tr>
</tbody>
</table>

**WELL SORTED VERY FINE SANDSTONE**

---

**Lower Member, Mississauga Fm**

---

1 m
Facies VS: Tide-influenced fluvial deposits

Venture sandstone B

Lower Member, Missisauaga Fm
Facies V5: Tide-influenced fluvial deposits

Facies V7: Fluvial deposits

Venture sandstone 8

Lower Member, Mississauga Fm

West Venture C-42

DEVIATED WELL

core 10

boxes 2275 to 1975
West Venture C-62
DEVIATED WELL
core 10, boxes 18/25 to 15/25

Facies V9, Transgressive lag
- Mixed (sorted) poorly sorted gravel conglomerates to very coarse sandstone; very little primary matrix
- Transgressive surface of shoreline

Facies V7, Fluvial deposits
- Similar to underlying unit, but without mudstone interbeds; physical structures are hard to ID
- Lewly shows dune-like stratification (c.20cm thick)

Lower Member, Missoula Fm

<table>
<thead>
<tr>
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<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Venture sandstone 7</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Venture sandstone 8</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Facies V9, Transgressive lag</td>
<td></td>
</tr>
</tbody>
</table>

1 m
West Venture C-62
DEVIAED WELL
core 10
boxes 14/25 to 11/25

MUDSTONE
with thin, bioturbated,
low-angle cross-stratified
sandstone interbeds
Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
<table>
<thead>
<tr>
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<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chondrites</td>
<td>interbedded lower very fine sandstone and mudstone; low to moderate bioturbation; intensely thinly interbedded; siltstone/very fine sandstone beds are wavy low angle wave ripple cross-stratified, often with nice low angle truncations; laminae commonly fan internally within a sandstone bed and are gently curved to flat; sandstone beds often fine-upward; also, between box 2/25 and 23/06, bedding gradually becomes thinner and thinner until you get that big thwack of sandstone in the middle of box 23/06 core 9. Above this bioturbation switches immediately into moderately to moderate high; trace fossils include Astero-aeon, Planolithes, Melanithopsis, Teichichnus.</td>
<td></td>
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</tr>
<tr>
<td>Ophistomopha</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemicirrhopus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Facies V2: Storm-dominated inner shelf/delta front deposits

**West Venture C-62**

**DEVIAET WELL**

core 10
boxes 6/25 to 3/25

**Lower Member, Mississauga Fm**

**HUMMOCKY CROSS-STRATIFICATION**
Facies V2: Storm-dominated inner shelf/distal delta front deposits

Venture sandstone 7

Lower Member, Mississauga Fm
Interbedded lower very fine sandstone and mudstone; low to moderate bioturbation; laterally thinly interbedded; siltstone/very fine sandstone beds are wavy low angle wave ripple cross-stratified, often with nice low angle truncations; laminae commonly fan internally within a sandstone bed and are gently curved to flat; sandstone beds often fine-upward; also, between box 22/25 and 23/26, bedding gradually becomes thinner and thinner until you get that big thck of sandstone in the middle of box 23/26 core 9. Above this bioturbation switches immediately to moderate to moderate high; trace fossils include *Asteroceras*, *Planollines*, *Helminthopsilis*, *Teichichnus*.

**Facies V-2**: Storm-dominated inner shelf/delta front deposits
West Venture C-62
DEViated WELL
core 9
boxes 20/26 to 17/26

NORMALLY-GRADED
HUMMOCKY CROSS-STRATIFIED BED
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-angle (&lt;15 degrees) cross-stratified very fine to fine sandstone (hummocky cross-stratified); some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and thinning of laminae, and are commonly capped by one or several small-scale wave ripple crosssets; these often have real nice low angle, scoop-shaped truncations; rip-ups rare overall, but abundant in one bed; biogenic structures typically absent; some rare Ophiomorpha burrows near the top and lower contacts; diagenetic features - rare yellow rust bands; disseminated organic mud flakes (millimetric) can reach very high levels in the sandstone, and occur at various concentrations pretty much throughout unit (although locally none); lower contact is arbitrary; no high angle (&gt;15 degrees) cross stratification.</td>
<td>Facies V2: Storm-dominated inner shelf/delta front deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
West Venture C-62
DEVIATED WELL
core 9
boxes 12/26 to 9/26

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-angle (&lt;15 degrees) cross-stratified, very fine to fine sandstone (hummocky cross-stratified), some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and fanning of laminae, and are commonly capped by one or several small-scale wave ripple cross-sets.</td>
<td>Facies V2: Storm-dominated inner shelf/delta front deposits</td>
<td>Venture sandstone 7</td>
<td>Lower Member, Mississauga Fm</td>
</tr>
</tbody>
</table>

AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE BEDS
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Palynology Sample - Geological Survey Sample P38358-01</strong>&lt;br&gt;&quot;Poorly preserved material - one possible marine element found.&quot;&lt;br&gt;(Rob Fensome, personal communication, 2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interbedded pelite/packstone (beach deposits) and salt, pepper and orange upper the sandstone; sandstones often look massive - although I don’t think they are, they are structurally - just hard to see! Blackish-grey or only well-observed mud is very common in sandstone; lower contacts of sandstone beds usually show irregularities due to loading into mudstone. Loading causes thinner sandstone beds to pinch and swell across the cross-laminations at the bottom of the mudstone. Isolated cross-laminations and gradational contacts between sandstone beds and sandstone. Lower contact of unit is sharp, irregular, and has some mud flutes; matrix is not well-sorted. Bioclastic features vary, but include some fossiliferous matrix. Bottom contact (lithified)

<table>
<thead>
<tr>
<th>Facies</th>
<th>V2: Storm-dominated inner shelf/delta front deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-angle (&lt;15 degrees) cross-stratified very fine to fine sandstone (harmody or cross-stratified); some rare mud interbeds near lower and top contacts of unit; HCS beds often have nice low angle truncations and branching of laminae, and are commonly capped by one or several small-scale wave ripple cross sets. These often have real nice low angle scoop-shaped truncations; ripple sets are rare overall, but abundant in one bed; biogenic structures typically absent; some rare Ophiomorpha burrows near the top and lower contacts; diagenetic features - rare yellow rust bands; disseminated organic mud flake layers (mm-scale) can reach very high levels in the sandstone, and occur at various concentrations; pretty much throughout unit (although locally none); lower contact is slightly rounded; no high-angle (&lt;15 degrees) cross-stratification</td>
</tr>
</tbody>
</table>

| CANDIDATE SEQUENCE BOUNDARY/TRANSgressive SURFACE |
Facies V5: Tide-influenced fluvial deposits

Venture sandstone 7

Lower Member, Missisauga Fm
Facies V5: Tide-influenced fluvial deposits

Venture sandstone 7

Lower Member, Missisauga Fm
Facies V5: Tide-influenced fluvial deposits

Facies V7: Fluvial deposits

Venture sandstone 7

Lower Member, Missisauga Fm
West Venture C-62
DEViated WELL
core 8
boxes 10/18 to 7/18

PLATE 57
S1553.18 m

**FOSSILS**
- roots

**DESCRIPTION**
- strongly oil-stained

**FACIES**
- siltstone
- mudstone

**RESERVOIR**
- Venture sandstone 7
- Lower Member Mississauga Fm

**LITHOSTRAT**

---

**OIL STAINED COARSE SANDSTONE**

- High-angle (dune) cross-stratification
- High-angle (dune) cross-stratification

---

**1 m**
**West Venture C-62**
**DEViated WELL**
core 8, boxes 6/18 to 3/18

**Palynology Sample** - Geological Survey of Canada Sample P38355
"Poorly preserved Jurassic-Early Cretaceous miospores - no marine elements identified." (Rob Fensome, personal communication, 2002)

**Palynology Sample** - Geological Survey of Canada Sample P38354
"Poorly preserved Jurassic-Early Cretaceous miospores - no marine elements identified." (Rob Fensome, personal communication, 2002)

"mudstone with pyrite "blebs""
thinly interbedded mudstone and lower very fine sandstone (more sandy than muddy unit) coarsens upwards; sandstone interbeds are low-angle, long wavelength cross-stratified (thummeloid cross-stratified); mudstone is very low to moderately bioturbated; unit gets sandier upwards; diagenetic features — rusty yellow bands are very common in mudier stratified portion; one region directly overlying mudstone and underlying a low angle long wavelength cross-stratified sandstone bed is beautifully unidirectional ripple drifted coal debris (organic partings and disseminated flaked are common; bioturbation in thicker sands is typically absent, save for the occasional Ophiomorpha burrow, some Chondrites, and one ?Ophiomorpha burrow; in mudstones, bioturbation is very high; trace fossils in mudstone include Planolites, Helminthopsis...
West Venture C-62
DEViated WELL
core 7
boxes 20/26 to 17/26

Facies V3: Storm-dominated delta front deposits

Oplosomorpha (very low)

mostly clean, low-angle cross-stratified lower very fine sand (hummocky cross-stratification) with no to low bioturbation (mostly Oplosomorpha); low mud in mudstone; top of unit is hard to pick...are there several sub-environments between near top of unit below overlying mudstone, or does transgression occur over several steps?

Oplosomorpha
Pelosomorpha
YR nodules (moderate)

Pelosomorpha (moderate)

Lower Member, Mississauga Fm

AMALGAMATED HUMMOCKY CROSS-STRATIFIED SANDSTONE
Facies V3: Storm-dominated delta front deposits

Venture sandstone 6L

Lower Member, Missisauga Fm

INTERBEDDED HUMMOCKY SANDSTONE AND MUDSTONE

West Venture C-82
Core 7, 16/26 to 13/26
Core deviated well
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Litho-Strat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monotonous interlaminated to thinly interbedded mudstone and lower very fine sandstone (ave = 1.5 cm for lower very fine sandstone interbeds; very low to high bioturbation, which increases upcore; sandstone interbeds are often graded, and typically are low-angle cross-stratified (hummocky cross-stratified) to wavy parallel laminated; thicker interbeds are hummocky cross-stratified looking; diagenetic features include smaller, smaller (micritic) grey, non-rusty, HCl-reacting CaCO3 nodules (sometime cracked); organic content does not seem especially high (one or two organic partings; no yellow rust) near base to high just below top contact; trace fossils include Orbitolina (near top), Aassocia (in lower 3/4 of unit); and Rapholithina (near top); silty interlaminations are often sharp-based (some small scale nodules) and fine upward in lower 1/2, number of wavy parallel laminated to small wave ripples sit laminases increase slightly towards top</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

West Venture C-62
DEVIATED WELL
core 7, boxes 12/26 to 9/26

OFFSHORE MUDSTONE
with thin, very fine sandstone interbeds

Lower Member, Mississippian Fm
Venture sandstone 6M

1 m
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although at this point, the general appearance of the unit is similar to the description below, there seems now to be some gradation in the top contacts of the silt and lower very fine sandstone interbeds. The top contacts are now either gradational or sharp. Mudstone overlying the siltstone or very fine sandstone interbeds is either wave parallel laminated or nicely small-scale wave ripple cross-stratified. The siltstone interbeds are also more distinctly low-angle and wavy than they are below.

*OFFSHORE MUDSTONE*

with thin, very fine sandstone interbeds
West Venture C-62
DEVIATED WELL
core 7
boxes 4/26 to 1/26

Amalgamated Hummocky Cross-Stratified Sandstone
Overlying Offshore Mudstone
Facies V3: Storm-dominated delta front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Facies V3: Storm-dominated delta front deposits

Venture sandstone 6M

Lower Member, Mississauga Fm
**Facies V3: Storm-dominated delta front deposits**

**Facies V4: Upper delta front deposits**

**Lower Member, Mississauga Fm**
Facies V6: Tidal flat deposits

Venture sandstone 6M

Lower Member, Missisauga Fm

LITHO
STRAT

DEVATED WELL
core 6, boxes 6/18 to 3/18
### West Venture C-62
**DEVIA TED WELL**
core 6, box 2/18 to core 5, box 25/26

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(?)Deltoides (zone)</td>
<td>boreread mud/limed ground surface</td>
<td>Channel bed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>()Rhizosaurus erectus (moderata)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core 5</td>
<td>interbedded pinstripe mudstone (quite sandstone rich...FS/SO mudsand ratio) and medium sandstone; sand pinstripes pinch and swell across core, commonly are ripple cross-laminated, and occasionally are biplanar unidirectional. Ripple cross-stratified; small Planolites present; rarely in pinstripe mudstones, but generally biplanar; rare gynaecoliths also occur in several places (both on tops of medium sandstone interbeds and within the pinstripe mudstones); structure in medium sandstone interbeds is hard to see (most look massive)... Occasionally tops of medium sandstone beds are small-scale unidirectional cross-stratified (either unidirectional ripple cross-laminated or small-scale 3-D dune cross-stratified). Ophiomorpha present in one medium sandstone interbed.</td>
<td>Facies V7: Tidal flat deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>core 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha (zone)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5100.5 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**East Venture**
**Member, Mississauga Fm**

-ินเตอร์เบดเด็ดเป็นกระดาษที่ไม่เรียบ (quite sandstone rich...FS/SO mudsand ratio) และ medium sandstone; sand pinstripes จมและนิ่งขึ้นและล้มลงตาม core, ซึ่งร่วมกันเป็น ripple cross-laminated และบางครั้งเป็น biplanar unidirectional. Ripple cross-stratified; ขนาด Planolites อยู่ที่น้อยใน pinstripe mudstones, แต่ส่วนใหญ่ biplanar; rare gynaecoliths อาจเกิดขึ้นในหลายที่ (ทั้งบนผิวของ medium sandstone interbeds และภายใน pinstripe mudstones); ลักษณะใน medium sandstone interbeds ค่อนข้างยากที่จะเห็น (ส่วนใหญ่ดูเป็น mass). บางครั้งเป็น biplanar unidirectional. Ripple cross-stratified (หรือ small-scale 3-D dune cross-stratified) และ Ophiomorpha อยู่ใน one medium sandstone interbed.
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Maestracta</em> (high)</td>
<td>thickly interbedded pisolithic mudstone (low sand/mud ratio), lime bedded and medium to thin beds of sandstone and siltstone; often hard to PQ, but locally sandstone beds are high angle (&gt;15 degrees) and organic laminae are common</td>
<td>?TAENIDIUM BURROWS</td>
<td>Lower Member, Mississauga Fm</td>
<td>Venture sandstone 6M</td>
</tr>
<tr>
<td><em>Maestracta</em> (high)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><em>Maestracta</em> (high)</td>
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<td></td>
</tr>
<tr>
<td><em>Maestracta</em> (high)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><em>Maestrichtia</em> (high)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Maestrichtia</em> (high)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Maestrichtia</em> (high)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

West Venture C-62
DEVIATED WELL
core 5
boxes 24/26 to 21/26

Facies V7: Tide-influenced fluvial deposits

- mud burrow infills
- sand burrow infills
- white-coloured sandstone burrow linings
- curved sprays
- mud burrow linings
**West Venture C-62**
DEVIATED WELL
core S
boxes 20/26 to 17/26

TRACE FOSSILS | DESCRIPTION | FACIES | RESERVOIR | LITHOSTRAT
--- | --- | --- | --- | ---
Muensteria | Similar to underlying unit, except no pin stripe mudstone interbeds, more unidirectional ripples, smaller dunes. Although mudstone interbeds are scarce with respect to underlying unit, sandstone beds are finer grained and contain more mud internally. | Facies V7: Tide-influenced fluvial deposits | Venture sandstone 6M | Lower Member, Missisauga Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO-STRAT</th>
</tr>
</thead>
</table>
| Diplacranion (moderate) | bioturbated muddy lower very fine sandstone; some rice hammer-bone ripple cross-stratification; unit fines upward; some fossiliferous, taphonomic, trace fossils include striking, elongate Diplacranion, plus Telichthys, Asterozona, and 10 phonotomorphs | Facies V7: Tide-influenced fluvial deposits | Lower Member, Missisauga Fm | West Venture C-62
| | | | Core 5, boxes 16/26 to 13/26 | |
| Planolites (moderate) | channel base, chert cut-off | | | |
**Facies V3: Storm-dominated shoreface deposits (transgressive)**

Venture sandstone 6U

Lower Member, Missisauga Fm
West Venture C-62
DEViated WElL
core 5
boxes 4/26 to 1/26

Facies V3: Storm-dominated shoreface deposits (transgressive)

Distrubuted very fine sandstone; no mudstone interbeds; trace fossils include Ophiomorpha & Paleoeophractus; physical sedimentary structures not identifiable; unit fines upward from clean sandstone into slightly muddy clean sand with organic flecks and associated yellow rust locally.

Lower Member, Mississippian Fm
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>this seems to be a composite unit</td>
</tr>
<tr>
<td></td>
<td>a) the base of the unit (boxes 17 to 14) is composed of interbedded mudstone and very fine sandstone; mudstone is typically featureless with no bioturbation; sandstone shows nice evidence of wave influence (e.g. HCS-like beds, wavy parallel laminated beds), small-scale, scoop-based wave ripple cross-setts; sandstone contains rare <em>Ophiomorpha</em> burrows and escape traces; no major visible diageneric features; organisms --&gt; mudstone is very organfic; <em>Flecks</em> rich, sandstone laminae often highlighted by organic flecks; no large coral chunks, but lots of organic flecks throughout</td>
</tr>
<tr>
<td></td>
<td>b) the top of the unit (boxes 13); save for the occasional yellow, rusty mudstone drape drops out and sandstone grain size increases to medium (the contact between (a) and (b) is not obviously erosive --&gt; seems more gradual...coarse-up); sandstone becomes &quot;salt, pepper, and orange&quot; speckled (is the &quot;pepper&quot; macerated organic debris (coffee ground), the &quot;salt&quot; quartz, and the &quot;orange&quot; small pockets of yellow rust?); wave-formed sedimentary structures are not observed; a few <em>Ophiomorpha</em> present; no obvious play in paleo-currents</td>
</tr>
</tbody>
</table>

---

**West Venture C-62**

**DEVOTED WELL**

core 4

boxes 17/17 to 14/17
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
<th>VENTURE SANDSTONE 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opalsmorpha</td>
<td>each subunit in core 4, box 3/17 to 5/17 coastsen-</td>
<td></td>
<td></td>
<td></td>
<td>Lower Member, Mississauga Fm</td>
</tr>
<tr>
<td></td>
<td>up整理ed from a thin layer of interbedded mudstone &amp; sandstone with no or very little bioturbation into HCS-like fine sandstone with some (Opalsmorpha turnerii) into III; fine s-talozed medium to coarse sandstone with Opalsmorpha each subunit coarsens-upwards and is abruptly overlain by mudstone.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>are these stacked wave-dominated delta mouth bars? (upper delta-front deposits)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opalsmorpha</td>
<td>each subunit in core 4, box 3/17 to 5/17 coastsen-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>up整理ed from a thin layer of interbedded mudstone &amp; sandstone with no or very little bioturbation into HCS-like fine sandstone with some (Opalsmorpha turnerii) into III; fine s-talozed medium to coarse sandstone with Opalsmorpha each subunit coarsens-upwards and is abruptly overlain by mudstone.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>are these stacked wave-dominated delta mouth bars? (upper delta-front deposits)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

West Venture C-62
DEVIATED WELL
core 4
boxes 13/17 to 10/17
Facies V4: Storm-dominated upper delta-front deposits

Facies V5: Tide-influenced fluvial deposits

Facies V6: Tidal flat deposits

Venture sandstone 5

Lower Member, Missisauga Fm
<table>
<thead>
<tr>
<th>Facies V2: Storm-dominated offshore/ delta-front deposits</th>
<th>Facies V3: Storm-dominated delta-front deposits</th>
</tr>
</thead>
</table>

Venture sandstone 8

Lower Member, Missisauga Fm
### West Venture N-91

**core 8**

**boxes 24/24 to 21/24**

<table>
<thead>
<tr>
<th>TRACÉ FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHO STRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>very clean very fine sandstone; no mudstone interbeds except for those close to base; no bioturbation except close to top (Ophiomorpha); slight coarsening upward trend from very fine sandstone to fine sandstone; planar laminated to low angle (&lt;10 degrees) cross stratified (oscillatory plane bed and hummocky cross stratification) throughout; beds hard to distinguish (they are amalgamated); lower contact is either sharp, little mud to highlight laminations; disseminated organics present, but not outstanding; several rust-haloed organic partings close to top contact</td>
<td>Facies V3 Storm-dominated delta-front deposits</td>
<td>Venture sandstone 8</td>
<td>Lower Member, Missima Fm</td>
</tr>
</tbody>
</table>

1 m

5132.43 m BMD
**Facies V3: Storm-dominated delta-front deposits**

Venture sandstone 8

Lower Member, Missisaugua Fm

**West Venture N191 core 8 boxes 2024 to 1724**
West Venture N-91
core 8
boxes 16/24 to 13/24

Facies V2: Storm-dominated offshore/delta-front deposits

very close to very fine sandstone no mudstone interfaces except for those close to bases 
no bioturbation except close to top (Ophiomorphs), slight coarsening-upward trend from 
very fine sandstone to fine sandstone plane laminated to low angle (<10 degrees) 
cross stratified (discontinuous plane bed and hummocky cross stratification) throughout 
beds hard to distinguish (they are amalgamated), lower contact is sharper 
shallow lagoonal to highstand lagoonal 

disseminated organics present, but not outstanding; several rust-colored organic partings 
close to top contact

organics content increases up core (now highlighted biotite)

low angle cross stratified 

fine sandstone
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES V2: Storm-dominated offshore/delta front deposits</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ophiomorpha</td>
<td>Blотurbated sandy mudstone to muddy sandstone; unit initially fines-up from</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysiphonites</td>
<td>bloturbated muddy/lower very fine sandstone to a laminated bloturbated (mod)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attenborough</td>
<td>mudstone... then bloturbation drops out a little (to low) and lamination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysiphonites</td>
<td>becomes slightly more pronounced.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha</td>
<td>Above this unit coarsens up slightly, and interbeds become slightly thicker</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and ripple cross-stratified. Bloturbation also increases slightly close to top contact; beds typically ungraded.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ophiomorpha</td>
<td>Salt-pepper and orange speckled bloturbated medium to coarse sandstone</td>
<td>FACIES V8: Marsh deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysiphonites</td>
<td>with lots of usual fragments; &quot;paint-speckles&quot; common (isolated white quartz sand</td>
<td>Venture sandstone 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(right)</td>
<td>grains); unit coarsens up from medium to coarse sandstone; Ophiomorpha and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polysiphonites become blackened (above the black speckles).</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

West Venture N-91 core 8
boxes 8/24 to 5/24

Lower Member, Mississauga Fm

**TRANSGRESSIVE LAG**
West Venture N-91
core 8
boxes 4/8 to 1/8

Facies V2: Storm-dominated offshore delta-front deposits

V venture sandstone 7

Lower Member, Mississauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
West Venture N-91
core 7
boxes 21/25 to 18/25

Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 7

Lower Member Mississauga Fm
West Venture N-91
Core 7
Boxes 17/25 to 14/25
<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clean very fine to fine sandstone (top ~ 50 cm is medium sandstone); no bioturbation; low angle cross-stratification with low angle truncations; hummocky cross stratification; hard to see laminations or bedding surfaces.</td>
<td>Facies V2: Storm-dominated offshore/delta-front deposits</td>
<td>Venture sandstone 7</td>
<td>Lower Member, Mississauga Fm</td>
</tr>
<tr>
<td></td>
<td>Facies V3: Storm-dominated delta-front deposits</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
Facies V3: Storm-dominated delta-front deposits

Venture sandstone 7

Lower Member, Missisauga Fm
interbedded clean, thicker beds of low angle cross stratified very fine sandstone (HCS) with muddy, typically bioturbated fine sandstone; muddy bioturbated interbeds (commonly have reme-thick rusty layers, and are commonly rich with silty laminae (which) are usually planar to wavy planar laminated (tornill scale wave rippled); bioturbation in muddy very fine sandstone interbeds is moderate to moderate High, and includes Ophiomorpha, Chronomorpha, Asterosoma, Planolites, Palaeophycus, Textularia; lower contact is not a beautiful lag, but some poorly sorted sandstone beds present

moderate to poorly sorted sandstone; physical sedimentary structures not identifiable

clean very fine to fine sandstone (top ~50cm) medium sandstone; no bioturbation; low angle cross stratified with low angle truncations (hummocky cross strat单位); hard to see laminition or bedding surfaces

coal

mudstone with pyrite 'blebs'

ROOTED COAL

TRIANGULAR}}
West Venture N-91
core 6
boxes 7/10 to 4/10

TRACE FOSSILS

DESCRIPTION

FACIES

RESERVOIR

LITHOSTRAT

interbedded clean, thicker beds of low angle cross stratified very fine sandstone (HCS) with muddy, typically bioturbated fine sandstone; muddy bioturbated interbeds commonly have mm thick rusty layers and are commonly rich with silty laminae (which are usually planar to wavy planar laminated to small scale wave ripples); bioturbation in muddy very fine sandstone interbeds is moderate to moderate-high, and includes Ophiomorpha, Chondrites, Asterosomus, Planolites, Polynoides, Teichichnus; lower contact is not a beautiful lag but some poorly sorted sandstone beds present

Facies V2: Storm-dominated offshore/delta front deposits

Venture sandstone 6L

Lower Member, Missisauga Fm
West Venture N-91
core 6, box 3/10 to core 5, box 24/24

Facies V2: Storm-dominated offshore/delta-front deposits

Litho-Strat: Lower Member, Mississauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 6L

Lower Member, Mississauga Fm
Interbedded clean, thicker beds of low angle cross stratified very fine sandstone (PCS) with muddy, typically bioturbated fine sandstone; muddy, bioturbated interbeds commonly have mm-thick rusty layers, and are commonly rich with silty laminae (which are usually planar to wavy planar laminated to small scale wave ripples); bioturbation in muddy very fine sandstone interbeds is moderate to moderate high, and includes Ophiomorpha, Chondrites, Arenosoma, Planolites, Palaeophycus, Reticulina; lower contact is not a beautiful log, but some poorly sorted sandstone beds present.
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Lithostrat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper fine sandstone; no mudstone interbeds; typically high-angle cross-stratified (tangential cross-set); cross-set thickness ranges from 7.5 to 30 cm; foresets are sometimes muddy; no bioturbations; lightly oil-stained throughout; lower contact has some rounded pebble-sized clasts (mudfl); some minor vertical fractures present.</td>
<td>Facies V3: Storm-dominated delta-front deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interbedded clean, thicker beds of low angle cross-stratified very fine sandstone (HCS) with muddy, typically bioturbated fine sandstone; muddy bioturbated interbeds commonly have mm-thick rusty layers, and are commonly rich with silty laminae (which are usually planar to wavy planar laminated to small scale wave rippled); bioturbation in muddy very fine sandstone interbeds is moderate to moderate high, and includes Ophiomorpha, Chondrites, Asterosoma, Planolites, Helicocyclus, Skolithos; lower contact is not a beautiful lag, but some poorly sorted sandstone beds present.</td>
<td>Facies V2: Storm-dominated offshore/delta-front deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Venture sandstone 6L</td>
<td>Lower Member, Mississauga Fm</td>
<td></td>
</tr>
<tr>
<td>Fossils</td>
<td>Description</td>
<td>Facies</td>
<td>Reservoir</td>
<td>Lithostrat</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>--------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>Trace fossils up to around box 5/24; biostatification is non-existent to very low, and allstone interbeds are common (allstone laminae are a few mm to a few cm thick) - these are typically graded with little or no internal structure; in box 6/24 and increasingly so above, allstone interbeds have various types of low angle cross stratification (long, medium and short wavelength cross-stratified) - BCS to small wave ripple and are sharp-topped (do not fine up); biostatification becomes moderate to high around bottom of box 4/24; trace fossils include Planolites, Astromeres, and Chondrites, with Ophiomorpha in sandstone beds; few relicts of skeletal material - see core 4.4 box 1/F1 to 2/F1 but no more significant deposits of large-scale transgressive systems. Depositional environment may have not changed significantly.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**West Venture N-91**

**Core 5**

**Boxes 11/24 to 8/24**

---

**Facies V3:** Storm-dominated delta-front deposits

- Upper fine sandstone; no mudstone interbeds; typically high-angle cross-stratified (tangential cross-set); cross-set thickness ranges from 7.5 to 30 cm; toesets are sometimes muddy; no bioturbation; lightly oil stained throughout; lower contact has some small rounded pebble sized clasts (median); some minor vertical fractures present.

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**Lower Member, Mississippian Fm.**

**Venture sandstone 6M**

**VENTURE SANDSTONE**

**Paint-speckle mudstone**

**Sandstone pebbles**

**Transgressive Lag**
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 6M

Lower Member, Mississauga Fm
<table>
<thead>
<tr>
<th>Trace Fossils</th>
<th>Description</th>
<th>Facies</th>
<th>Reservoir</th>
<th>Litho-strat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mudstone, up to sandstone</td>
<td>Facies V2: Storm-dominated offshore/distal delta-front deposits</td>
<td>Venture-sandstone 6M</td>
<td>Lower Member, Mississauga Fm</td>
</tr>
</tbody>
</table>

West Venture N-91
core 4
boxes 19/24 to 16/24
**West Venture N-91**
core 4
boxes 15/24 to 12/24

<table>
<thead>
<tr>
<th>TRACE FOSSILS</th>
<th>DESCRIPTION</th>
<th>FACIES</th>
<th>RESERVOIR</th>
<th>LITHOSTRAT</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Chondrites</em></td>
<td>multitone up to around box 6/4. Bioturbation is non-existent to very low, and subtidal intertubules are common (silstone laminae or a few mm to a few cm thick) — these are typically graded, with little or no internal structure in box 6/4. and increasing to progressively, silstone intertubules have various types of low angle cross stratification (long, medium and short wave length cross-stratified). JCS to small wave rippled and are sharp-topped. do not fine slickular stratification becomes moderate-high around bottom of box 6/4. Trace fossils include Planolites, Atrichops, and Chondrites, with Opalina-ophite in sandstone beds, few pelagic back into finer grained stuff as we move upcore 6 to 4 core 4 box 14/24 but no nice surface associated. Possible smaller scale transgressive events — depositional environment however does not change significantly.</td>
<td>Facies V2: Storm-dominated offshore/delta shale-front deposits</td>
<td>Lower Member, Mississippian Fm.</td>
<td></td>
</tr>
</tbody>
</table>

1 m
Facies V2: Storm-dominated offshore/distal delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Facies V2: Storm-dominated offshore/distal delta-front deposits

Facies V4: Storm-dominated upper delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
Facies V4: Storm-dominated upper delta-front deposits

Venture sandstone 6M

Lower Member, Missisauga Fm
APPENDIX 2: DETAILED FACIES ANALYSIS,
GLENELG & ALMA FIELDS
Alma Field (Upper Missisauga) – Facies analysis

At Alma, the Missisauga sandstone package is relatively thin (~268 m; MacLean and Wade, 1993) and young (Barremian to Aptian; Lentin, 1987; late Hauterivian to Barremian, Jason Crux, personal communication, 2004), suggesting that sand did not reach Alma until the final stages of Missisauga shelf margin outbuilding (see Figure 5.14). Because of its age, the sandstone package at Alma is assumed correlative with the Upper Member of the Missisauga Formation, and is therefore referred to here as the “Upper Missisauga” (as opposed to “Missisauga”; see MacLean and Wade, 1993).

Core coverage of the Alma reservoirs is reasonably good (see Figure 5.14). Upper Missisauga sandstone at Alma is commonly intensely bioturbated. Upper Missisauga mudstone at Alma is typically rich in nannofossils (Gunnilla Gard, personal communication, 2001; Jason Crux, personal communication, 2004) and contains abundant disseminated organic matter and small shell fragments locally ( gastropod, mollusc, scaphopod, echinoid, and ammonite). Soft-sediment deformation features are relatively common at Alma compared to more proximally located fields (e.g., Panuke). Five facies have been identified from core, as described below (see also Appendix 1, table 1).

Alma facies A1. Mudstone

Facies A1 mudstone is commonly fissile and/or friable and is moderately rich in siderite nodules. Bioturbation is absent or very minimal, and includes Teichichnus, Planolites, Asterosoma, Helminthopsis, Chondrites, Zoophycos, ?Arenicollites, Palaeophycus, Terebellina. Where, present, burrows are commonly large. Cm-scale
shells and shell fragments (echinoid, gastropod, ammonite, bivalve) and disseminated organic matter are common on bedding surfaces. Microfaults are present locally. Thin (<1 mm), short (1 to 6 cm), light-coloured, vertical to subvertical “streaks” barren of organic particles are rarely present in particularly organic-rich intervals (they look like vertical “knife scratches” on the core; see p. 369). Although pipe-like in cross-section, the “streaks” are commonly sheet-like when viewed from above.

**Interpretation. Offshore mudstone**

Facies A1 is interpreted to be mudstone deposited in an open marine environment below storm-weather wave base. Specialized feeding traces such as *Zoophycos* and *Asterosoma* and presence of ammonite shells and echinoid plates suggest that fully marine conditions existed during deposition. Thin, vertical, organic-free sheet-like “streaks” are interpreted to be pillar structures formed by fluidization (e.g., Druitt, 1995; Middleton et al., 2003). (Pillar structures, despite their name, are commonly sheet-like; cf. Middleton et al., 2003). The presence of pillar structures is suggests that of episodic rapid deposition of mud from suspension occurred.

**Alma facies A2. Interbedded mudstone and very fine sandstone**

Strata of Facies A2 gradationally overlie Facies A1, and consist of mudstone with rare to very common very fine sandstone beds that are on average <10 cm and at maximum 50 cm thick. Bioturbation in mudstone is generally low, and includes *Asterosoma, Planolites, Teichichnus, Zoophycos,* and ?*Cylindrichnus.* Sandstone beds are typically planar laminated, low-angle (<10°) cross-stratified, or rarely small-scale (<5 cm thick).
cm) high-angle (>15°) cross-stratified. High-angle cross-sets are typically flat-based, overlie planar laminated sandstone, and climb at low angles (<5 degrees). Sandstone beds contain rare escape traces and *Ophiomorpha* burrows. Weakly to highly deformed heterolithic units several centimeters to several meters thick occur locally within Facies A2.

*Interpretation: Storm-influenced lower shoreface (delta front?) deposits*

Facies A2 is interpreted to have been deposited in an open marine, storm-influenced delta front (or possibly lower shoreface) between storm and fairweather wave base. Facies A2 is similar to storm-dominated lower shoreface deposits in adjacent fields such as Panuke in that it contains low-angle cross-stratified beds interpreted to be hummocky cross-stratified sandstone, whose presence suggests deposition under the influence of large, long-period storm waves (Southard *et al.*, 1990; Arnott and Southard, 1990). However, Facies A2 also contains planar laminated sandstone beds (<20 cm thick) that grade upwards into small-scale (<5 cm), climbing, high-angle cross-strata interpreted to be climbing current ripples. Planar laminated beds with overlying current ripples are interpreted to be turbidity current deposits (Bouma Tbc units) that evolved either from hyperpynical river outflows (*e.g.*, Johnson *et al.*, 2001; Wright *et al.*, 2001), updip slope failures (*e.g.*, Piper *et al.*, 1988), or storm-generated sediment-laiden downwelling flows (*e.g.*, Morton, 1981). Deformed units are interpreted to be mass movement deposits. The presence of turbidite and mass movement deposits may be an indication of deposition onto a high-gradient seafloor near or basinward of the shelf edge,
because the low-gradient seafloor typical of continental shelves (<0.1°) theoretically hinders turbidity current ignition (Pantin, 1979, 1983; Parker, 1982).

**Alma facies A3. Upward-coarsening sandstone**

Facies A3 is only cored in one location (the A "sand" in Alma F-67). It consists of very fine to medium sandstone that coarsens upward. Bioturbation ranges from low to intense, and includes *Ophiomorpha Palaeophycus, Helminthopsis, Planolites, Skolithos, Teichichnus, Zoophycos, Asterosoma, ?Thalassinoides, ?Conichnus* and ?*Diplocraterion*. Burrows are typically large and thick-walled. Wispy mud laminae (<3 mm) are common at spacings of ~5 to 50 cm. Bedding planes delineated by wispy mud laminae gradually increase upward in dip from 0° to ~25° (Fig. 12). Pore-filling patches of carbonate-cement between 10 and 300 cm are present locally. Where not obscured by bioturbation, sandstone beds are either planar laminated, low-angle (<10°) cross-stratified, or medium-scale (10-20 cm) high-angle cross-stratified. Facies A3 sandstone either gradationally or sharply overlies Facies A1 mudstone.

**Interpretation: Unstressed shoreface deposits**

Intense bioturbation and large, thick-walled burrows common to Facies A3 suggest deposition in a fully marine, ecologically-unstressed environment. Upward gradation from offshore mudstone (Facies A1) and the upward-coarsening trend suggests that energy increased during deposition, likely as a result of progressive shoaling. These features are consistent with deposition in an ecologically unstressed shoreface setting. However, although ripple and dune clinoforms commonly dip at 25°, shoreface and delta-
front clinoforms rarely dip more than 5°, even at the shelf margin (Porebski and Steel, 2003; Donnovan, 2003). Significant relief may have existed on the seafloor across the master Alma growth fault, which caused steeply-dipping Gilbert-style foresets to form\(^1\). (Note: Relief can be significant across growth faults that intersect the seafloor. For example, at the modern shelf-margin offshore of the Orinoco River delta, growth-fault scarps have up to ~45 m relief (Sydow \textit{et al.}, 2003)). However, this interpretation must be considered preliminary until tested against additional data.

\textit{Alma facies A4. Poorly sorted sandstone}

Strata of Facies A4 are always poorly-sorted and commonly contain small, isolated quartz sand grains and granules. (These resemble white "paint-speckles" on the core.) Bioturbation is typically intense, and includes \textit{Ophiomorpha}, \textit{Planolites}, \textit{?Asterosoma}, \textit{?Thalassinoides}, and \textit{Helminthopsis}. Sedimentary structures are rarely preserved. The basal contact of Facies A4 is either sharp or bioturbated. Bivalve, scaphopod, and gastropod shell fragments are common. Facies A4 commonly reacts strongly to hydrochloric acid.

\textit{Interpretation: Wave-ravinement lag deposits}

Facies A4 is interpreted to have formed by wave ravinement during shoreface retreat (\textit{e.g.}, Fisher, 1961). Intense bioturbation and the high-diversity of traces suggest a fully marine environment. This facies, with its abundant "paint-speckles", strong reaction to hydrochloric acid, and common shell fragments, is arguably the most

\(^1\) The A "sand", unlike the underlying B and C "sands", thins southwestward from Alma F-67 to Alma K-85, suggesting movement on the master Alma growth fault occurred during or prior to deposition of the Facies A3.
omnipresent and distinctive siliciclastic facies within the Missisauca Formation in the Sable Subbasin.

Alma facies A5: Upward-finining sandstone

Facies A5, which consists of poorly-sorted, muddy coarse to very fine sandstone, was only observed at one interval in Alma F-67 (the top of the A “sand”). Bedding is generally unidentifiable because of intense bioturbation, with large Ophiomorpha and Palaeophycus traces predominating (many traces are unidentifiable because of the intensity of bioturbation). Facies A5 forms a ~20 m-thick, upward-finining unit that overlies several decimeters of coarse sandstone interpreted to be transgressive lag (Facies A4). Dm- to m-thick patches of pore-filling carbonate cement are present locally. Shell fragments and isolated coarse quartz sand grains and granules (“paint-speckles” - maximum 3 mm) are abundant near the base, and decrease in abundance upward; they are not longer present ~10 m above the base of the unit. The level of bioturbation decreases in the top several meters of Facies A5. Here, bedding is visible, and sandstone beds are parallel laminated to low-angle (<10°) cross-laminated and contain thin mudstone interlaminae. Facies A5 grades upward into interbedded mudstone and very fine sandstone of the Naskapi Member interpreted to be inner shelf to lower shoreface deposits (Facies A2).

Interpretation: Transgressive shelf sandstone

Facies A5 is interpreted to have been deposited in a shallow marine shoreface environment during transgression and shoreface retreat. The high-density/high-diversity
Skolithos-type trace fossil suggests deposition in an unstressed, fully marine setting (e.g., Pemberton et al., 2002). The stratigraphic position of Facies A5 above sharp-based lag deposits (Facies A4) and below lower shoreface mudstone and sandstone (Facies A2) suggests deposition during transgressive shoreface retreat (e.g., Fischer, 1961). Carbonate cementation and abundant shell fragments are features common in transgressive shelf sandstones (e.g., Penland et al., 1988; Snedden and Dalrymple, 1999; Molgat and Arnott, 2001; Posamentier, 2002).
Glenelg Field (Upper Missisauga) – Facies analysis

At Glenelg, the Missisauga Formation (*sensu* MacLean and Wade, 1993) forms a thick (up to 1.3 km), upward-coarsening succession that overlies monotonous Verrill Canyon shale, and is in turn overlain by ~80 to 300 m of Naskapi shale (see Figure 5.18). Cores partially sample the uppermost ~400 m of the Missisauga Formation. Biostratigraphic data indicate that this relatively sandstone-rich interval is Hauterivian to Barremian (Ascoli, 1990; MacLean and Wade, 1993), suggesting that sand arrived roughly coevally at Glenelg and Alma during the final stages of Missisauga shelf-margin outbuilding. The O Marker, which is present at the base of the Upper Missisauga throughout the proximal Sable Subbasin, has a patchy distribution in the Glenelg wells (MacLean and Wade, 1993) and was not identifiable in seismic data (Welsink *et al.*, 1989; Wade, 1991; MacLean and Wade, 1993). Six facies have been identified from core, as described below (see also Appendix 1, table 2).

*Glenelg facies G1: Mudstone with low-angle (<10°) cross-stratified sandstone interbeds and rare rhythmites*

Facies G1 consists of mudstone with rare to common well-sorted very fine sandstone interbeds. Beds are organized into upward-coarsening units that are tens-of-meters thick. Bioturbation in mudstone is typically very low, with *Planolites*, *Teichichnus*, *Terebellina*, and *Asterosoma*. Sandstone interbeds contain rare *Ophiomorpha* burrows, are 1 to ~50 cm thick, and are typically horizontally-laminated or low-angle (<10°) wavy to planar cross-stratified with low-angle internal truncation surfaces locally. Sandstone beds are rarely normally graded, and are rarely capped by

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2 Sand located below the Upper Missisauga at Glenelg may be slope turbidite deposits – see later
one or more thin (<3 cm), scoop-based, high-angle (>15°) cross-sets interpreted to be small wave ripples (see Boersma, 1970; de Raaf et al., 1977). Rarely, sandstone beds are composed of thin (<3 cm) flat-based high-angle (>15°) cross-sets interpreted to be current ripples. Sandstone beds are commonly deformed, and can be extensively sheared and "microfaulted". Disseminated organic particles are common. Internally, some of the sandstone and mudstone beds are rhythmically laminated.

Interpretation: Storm- and tide-influenced prodelta deposits

Facies G1 is interpreted to have been deposited in a gravitationally unstable prodelta environment that was influenced by both storm wave and tidal processes. Microfaults, thin sheared layers, and tilted beds suggest rotation and downslope translation of prodelta strata (e.g. Coleman and Prior, 1982). Current ripple cross-stratified sandstone and normally-graded horizontally-laminated sandstone beds are interpreted to be delta-front/prodelta turbidites. Storm wave influence is inferred based on the presence of sandstone beds which contain gently fanning laminae and low angle concave truncations, two features commonly associated with stratification formed by large, storm-generated hummocky bedforms (e.g. Campbell, 1967; Harms et al., 1975; Southard et al., 1990; Arnott and Southard, 1990; Dumas, 2004). Despite the apparent storm wave influence, rarely-observed mudstone-sandstone rhythmites imply that a cyclical forcing mechanism also episodically controlled sedimentation. Although repetitive mudstone-sandstone laminae are ubiquitous in the stratigraphic record and can form by many different mechanisms, the rhythmic nature and thickening-thinning trends exhibited by laminae in Facies G1 are most reasonably interpreted as being tidal in
origin. Although most commonly associated with tide-dominated fluvial and estuarine settings (e.g. Rahmani, 1988; Smith et al., 1990; Dalrymple et al., 1991; Li et al., 2000), tidal rhythmites have also been observed to form in modern delta-front and prodelta settings (e.g. Jaeger and Nittouer, 1995; Kuehl et al., 1996).

**Glenelg facies G2: Rhythmically interlaminated mudstone and sandstone**

Facies G2 consists of rhythmically laminated intervals (maximum 2 m thick) that grade in and out of mudstone. Internally, the rhythmically laminated intervals consist of thin (<1 mm to ~1 cm), rhythmically alternating layers of mudstone and siltstone to lower fine sandstone. Rhythmic laminae typically form successions that thicken and thin progressively. Contacts between rhythmic sandstone and mudstone laminae are typically gradational. Also, although flat, rhythmic laminae typically dip between 1 to 15°. Rarely, the bases of sandstone laminae are loaded. Bioturbation is absent in Facies G2, and disseminated coal flecks are abundant. Although the base of Facies G2 was not observed in core, log data suggests that Facies G2 gradationally overlies prodelta mudstone (Facies G1).

**Interpretation: Tidal rhythmites (delta front?)**

Facies G2 rhythmites are interpreted to be tidal in origin. The thickening and thinning of Facies G2 rhythmites, a commonly feature of tidal rhythmites, likely resulted from variation of the magnitude of daily tides (which are caused by the Earth rotating through high and low tides) over the course of a lunar month, in which the moon shifts from syzygy, where tide-raising forces are greatest (spring tides), to quadrature, where
tide raising forces are at a minimum (neap tides). Attempts to reconstruct the dominant
governing tidal periodicity (e.g. Kvale et al., 1998) have proven unsuccessful, likely due
to the short length and sporadic distribution of rhythmically laminated intervals
(maximum 42 mudstone-sandstone couplets in one rhythmically laminated interval).

Given the abundance of disseminated coal flecks, Facies G2 was likely deposited
close to a terrestrial organic source in a coastal plain setting. Furthermore, given that the
rhythmites commonly dip between 1 and 15°, it is likely that they were deposited by
lateral point bar accretion, a process that is very common in channelized tide-dominated
coastal environments (Dalrymple et al., 2003). Also, lack of evidence of significant
wave action suggests deposition in a relatively sheltered setting (Archer, 1998; Li et al,
2000). Taking all of these observations into consideration, Facies G2 might logically be
interpreted as being a tide-influenced subtidal to intertidal fluvial point-bar (e.g.,
Rahmani, 1988; Dalrymple et al., 1991) or intertidal mud flat deposit (e.g. Dalrymple et
al., 1991). However, this seems improbable given the stratigraphic position of Facies G2,
which, based on log data, appears to gradationally overlie tide-influenced prodelta
mudstone (Facies G1) and is in turn erosively overlain by tide-influence fluvial deposits
(Facies G3). Although more commonly observed in mudflat and tidally influenced
fluvial deposits in modern depositional environments (an observational bias?), tidal
rhythmites, as previously mentioned, have also been reported in prodeltaic and delta front
deposits (e.g. Smith et al., 1990; Williams, 1991; Jaeger and Nittouer, 1995; Kuehl et
al., 1996; Miller and Eriksson, 1997). Furthermore, unlike wave-dominated
environments, deep, submerged tidal channels and ridges commonly extend basinward of

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3 Although apparently absent, erosive basal channel contacts are perhaps simply cryptic mudstone on mudstone
contacts, which can form if fluid muds accumulate in channel thalwegs (e.g. Dalrymple et al., 2003).
the subaerial coastal plain onto tide-dominated delta fronts and shelves (e.g., Dalrymple et al., 2003; Allison et al., 2003; Willis and Gabel, 2003). As such, Facies G2 rhythmites are interpreted to have been deposited in a sheltered, channelized, tide-dominated delta front setting.

*Glenelg facies G3: High-angle (>15°) cross-stratified sandstone with thick mudstone interbeds and rare rhythmites*

Facies G3 consists of thickly interbedded mudstone (~25%) and very coarse to medium grained, honey brown-coloured sandstone (~75%). Sandstone beds range in thickness from 1 to 70 cm (average ~20 cm) and are commonly composed of one or more high-angle (>15°) cross-sets. Rarely, bipolar cross-stratification is observed. Pebble-sized coal fragments and mudstone intraclasts are common in sandstone beds. Double mud-drapes are present locally. Rare *Skolithos, Diplocraterion* and *Ophiomorpha* burrows were observed. Coal flecks commonly highlight lamination in sandstone beds.

Mudstone beds are several centimeters to several decimeters thick. Bioturbation in mudstone is typically absent, although rare, small *Planolites* were observed. Pebble-sized coal clasts and thin, organic-rich laminae are common. Laminae composed of medium grained sandstone are present locally in mudstone beds. Rarely, mudstone and fine sandstone laminae form rhythmically layered intervals in which laminae progressively thicken and then thin. Strata of Facies G3 are commonly organized into sharp-based, upward-fining units that are 6 to 10 m thick. The level of bioturbation commonly increases near the top of upward-fining units.
Interpretation: **Tidally influenced fluvial channel fills**

Facies G3 is interpreted to be a strongly influenced both by fluvial and tidal currents. The presence of abundant disseminated coal debris suggests deposition close to a terrestrial organic source. High-angle (>15°) sandstone cross sets are interpreted to have been deposited by dune bedforms migrating and aggrading under unidirectional flow (e.g., Leclair and Bridge, 2001). Rhythmic stratification, bipolar cross stratification, and abundance of mudstone suggest deposition in a tidally influenced environment (Nio and Yang, 1991). Furthermore, low diversity trace fossil assemblage and presence of diminutive traces suggest that the depositional environment was stressed, and perhaps brackish (Pemberton et al., 2002).

Sharp-based, upward-fining units indicate upward decreasing depositional energy, and are interpreted to be channel fill deposits. The upward increase in the level of bioturbation may suggest that marine incursion commonly accompanied the final stages of channel filling. Assuming that upward-fining units and dune cross-strata scale to flow depth (e.g., Leclair and Bridge, 2001; Bridge and Tye, 2000), channels were likely ~6 to 10 m deep. This suggests that deposition occurred in larger tide-influenced distributary channels (e.g., Gastaldo, 1995; Dalrymple et al., 2003) as opposed to small tidal channels that drain tidal flats (e.g., Barwis, 1978; Fenies, and Faugères, 1998). Also, given the abundance of thick mudstone beds, some of which are interbedded with the coarsest sandstone at the base of upward-fining units, it is possible (likely?) that fluid muds may have resided alongside coarse sand patches at the base of channels (e.g., Dalrymple et al., 2003; Dalrymple and Choi, 2003). (Arguably, this facies could be referred to as fluvially influenced tidal channel deposits).
Glenelg facies G4: Upward-finising mudstone with thin rooted coal beds

Facies G4 consists of organic-rich mudstone with thin (<25 cm) rooted coal layers. Bioturbation increases upwards. Trace fossils were difficult to identify, but *Teichichnus* burrows were observed locally. Mudstone containing oyster shells is present above a rooted in one upward-finising succession observed. Facies G4 gradationally overlies interbedded mudstone and sandstone interpreted to be tidally influenced fluvial deposits (Facies G3) or low-angle cross-stratified sandstone interpreted to be upper shoreface/beach deposits (Facies G6 – see below).

Interpretation: Transgressive abandonment deposits

Strata of Facies G4 are interpreted to have been deposited in a lagoonal to marsh environments during transgressive abandonment of either tidally influenced coastal plain channels (Facies G3) or wave-dominated strandplains (Facies G5). Together, the upward increase in mudstone, bioturbation, and shell content is suggestive of progressive inundation.

Glenelg facies G5: Sharp-based sandstone with *Ophiomorpha* burrows

Facies G5 is composed of moderately-sorted to moderately-well sorted brownish coarse sandstone. *Ophiomorpha* burrows, although rare, occur throughout. Stratification is typically not visible, although rare, high-angle (>15°) cross-sets (~15 cm thick) are visible locally. Several pebble-sized coal clasts are present. Facies G5 erosively overlies organic-rich mudstone (Facies G4).
**Interpretation: Tidal inlet fill?**

Based primarily on its stratigraphic position above coastal plain deposits (Facies G4) and below marine deposits (Facies G6), Facies G5 is interpreted to be a tidal inlet fill. The sharp-base, evidence of marine influence (*Ophiomorpha* burrows), and rare unidirectional current indicators (high-angle dune cross-strata) are consistent with this interpretation.

**Glenelg facies G6: Upward-coarsening mudstone with low-angle (<10°) cross-stratified sandstone interbeds**

Strata of Facies G6 form upward-coarsening units that pass upwards from mudstone with rare to common low-angle (<10°) cross stratified very fine sandstone interbeds into well-sorted low-angle cross-stratified fine sandstone with rare high-angle (>15°) cross-stratified beds. Bioturbation in mudstone is typically low, with *Planolites, Asterosoma, Zoophycos, Teichichnus, Terebellina*, and *Rosselia*. Rare *Ophiomorpha, Cylindrichnus Chondrites* and *Palaeophycus* burrows are present in sandstone. Facies G7 overlies poorly sorted sandstone interpreted to be transgressive lag (Facies G6).

**Interpretation: Storm-dominated shoreface and offshore deposits**

Facies G6 is interpreted to have been deposited in a storm-dominated shoreface environment. Mudstone-rich portions of Facies G6 are very similar to Facies G1 prodelta deposits, but lack rhythmically laminated zones. Low angle (<10°) cross stratification in sandstone interbeds is interpreted to be hummocky cross-stratification formed under the influence of large, long-period storm waves (*e.g.*, Southard *et al.*, 1990; Arnott and
Southard, 1990; Dumas, 2004). Because long-period waves require sufficient distance (fetch), depth, and travel time to form (Barnett and Wilkerson, 1967), the presence of hummocky cross-stratification suggests that Facies G6 was deposited in a large and unrestricted basin. Mudstone at the base of upward-coarsening units, which contains hummocky cross-stratified fine sandstone interbeds, is interpreted to have been deposited in a lower shoreface to offshore setting. High-angle cross-stratification present near the top of some of the upward-coarsening units is interpreted to have been deposited either by asymmetric wave ripples or unidirectional-dominated dunes in the upper shoreface.

_Glenelg facies G7: Poorly sorted, sharp-based sandstone_

Facies G7 forms thin units (<1 m) composed of poorly sorted, white-coloured sandstone. Bioturbation is locally intense, and _Ophiomorpha_ burrows are typically predominant. Sedimentary structures are typically not visible. Coal debris and oyster shell fragments are common, and the facies commonly reacts strongly with dilute hydrochloric acid. Isolated, white-coloured quartz coarse sand grains and granules ("paint-speckles") occur throughout. Typically, Facies G7 erosively overlies organic-rich mudstone interpreted to be coastal plain deposits (Facies G4). Unlined, sandstone-filled _Thalassinoides_ commonly penetrate down from Facies G4 into underlying organic-rich mudstone.

**Interpretation: Transgressive lag deposits**

Facies G7 is interpreted to have formed by wave reworking of the shallow seafloor during relative sea-level rise and shoreface retreat (e.g., Fischer, 1961; Demarest
and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Cattaneo and Steel, 2002). Burrowed mud firmground surfaces, which commonly occur at the base of Facies G7, are interpreted to be transgressive wave ravinement surfaces formed by the landward passage of the high-energy shoreface overtop of the coastal plain. Transgressive ravinement commonly erodes thick successions of previously deposited sediment (e.g., 10-20 m), exhumes mud firmgrounds, and then abruptly superimposes shallow marine sandstone on coastal plain deposits (Fischer, 1961; Suter and Berryhill, 1985; Demarest and Kraft, 1987; Bhattacharya, 1993; Abbott, 1998; Snedden and Dalrymple, 1999; Hwang and Heller, 2002; Pemberton et al., 2002; Cattaneo and Steel, 2002).