Sedimentology and stratigraphy of a thick, areally extensive fluvial–marine transition, Missisauga Formation, offshore Nova Scotia, and its correlation with shelf margin and slope strata

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ABSTRACT

A 100 m thick, more than 20 km wide upward-fining succession at the top of the Lower Cretaceous Upper Member of the Missisauga Formation was investigated in the Panuke Field, offshore Nova Scotia, using core, well logs and 3-D seismic data. The succession consists of 50 m of dune cross-stratified sandstone overlain by 50 m of tide-influenced heterolithic strata, which in turn is overlain by 150 m of mudstone of the Naskapi Member of the Logan Canyon Formation. The succession is interpreted to be a fluvial–marine transition formed during a long-term (3rd order) relative sea-level rise. The two main Panuke reservoirs are thin (<5 m) sheet-like sandstones at the Missisauga–Naskapi contact interpreted to be remnants of a wave-formed barrier system. In seismic data, the Upper Member of the Missisauga Formation correlates bas-inward with progradational shelf-margin reflections, suggesting that the sheet-like fluvial sandstone at the base of the upward-fining succession transferred sediment, and possibly sand, to the continental slope.

RÉSUMÉ

Une succession d’affinages ascendants de 100 m d’épaisseur sur plus de 20 km de large au sommet du Crétacé inférieur du Membre supérieur de la Formation de Missisauga, a été examinée dans le champ de Panuke, au large de côtes de la Nouvelle Écosse, en utilisant des données de carottes, de diagraphies et de sismiques en 3-D. La succession se compose de 50 m de dunes de grès à stratification entrecroisée recouvertes par 50 m de strates hétérolithiques à influence de marée, qui à leur tour sont recouvertes par 150 m de mudstone du Membre de Naskapi de la Formation Logan Canyon. La succession est interprétée comme étant une transition fluviale–marine qui s’est formée durant une élévation relative du niveau de la mer à long terme (3e ordre). Les deux réservoirs principaux de Panuke sont composés de grès en nappes minces (<5 m) au contact de Missisauga–Naskapi. Ces grès sont interprétés comme étant des restes d’un système de barrières formées par des vagues. D’après les données sismiques, le Membre supérieur de la Formation de Missisauga est en corrélation vers le bassin avec les réflexions de bordures de bassins progradantes, ce qui suggère que les nappes fluviales de grès, à la base de la succession d’affinages ascendants, ont transféré les sédiments, et probablement le sable, sur la pente continentale.

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INTRODUCTION

Stratal successions that pass upward from fluvial to marine deposits, here called fluvial–marine transitions, form during transgression following an episode of forced or normal regression. During the past half-century, these successions have been the subject of much geological research (Fisk, 1944; Posamentier and Vail, 1988; Penland et al., 1988; Dalrymple et al., 1994; 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 (Milliman and Haq, 1996), reconstruct paleogeography, and unravel the history of eustatic, tectonic, and climate change. With the recent focus on offshore hydrocarbon exploration basinward of the shelf edge (Weimer et al., 2000) fluvial–marine transitions have come under increased scrutiny because, when incised, they commonly correlate with sand bodies on the shelf edge, slope and basin-floor (e.g., Roberts et al., 2003). 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 sandstone 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, and as a result, how (and if) they feed sediment down dip to the shelf edge, slope and basin-floor is not well understood (Posamentier, 2001; Wellner and Bartek, 2003). Using core, well log and 3-D seismic data from the Panuke Field, offshore Nova Scotia, this study describes a thick, areally extensive fluvial–marine transition at the top of the Missisauga Formation, including the main Panuke reservoirs that occur within it. Using regional 2-D seismic lines, the fluvial–marine transition is then correlated down dip to the undrilled shelf-edge and slope. Implications for reservoir distribution within the western Sable Subbasin are discussed, and the potential of the fluvial system as a deep-water feeder system is evaluated.

GEOLOGIC SETTING

The Sable Subbasin is one of several interconnected Mesozoic–Cenozoic depocenters that make up the Scotian Basin, the passive-margin basin offshore Nova Scotia (Fig. 1). The center of the subbasin, which was a high-accommodation setting during the Mesozoic, is underlain by unstable syn-rift salt, and contains numerous growth faults and salt tectonic features. By contrast, the low-accommodation western rim of the subbasin, where the Panuke Field is situated (Fig. 2), is underlain by stable Jurassic carbonate rocks, and lacks such features. Terrigenous clastic sediment was delivered southwestward into the subbasin primarily by the paleo-St. Lawrence River, which,

Fig. 1. Depth to basement (in part estimated), Scotian Basin. Contours in kilometres. Modified from MacLean and Wade (1992).
during the Mesozoic, was a sediment-charged, continental-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 proto-Atlantic Ocean) was approximately 1000 km wide (Ziegler, 1989), and climate was warm and temperate, having become progressively colder, wetter and less seasonal following Pangean rifting in the Early Mesozoic (Rees et al., 2000).

**Lithostratigraphy**

In the Sable Subbasin, the Missisauga Formation forms a sandstone-rich lens of fluvial to continental slope clastics with minor carbonates that thickens basinward to an estimated maximum thickness of 3500 m below the modern shelf margin (Wade, 1991), and then thins basinward below the modern slope. It also thins laterally westward onto the low-accommodation western subbasin rim, and is approximately 950 m thick 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. It is overlain by marine shale of the Naskapi Member of the Logan Canyon Formation (Fig. 3).

The Missisauga Formation is typically divided into Upper and Lower members, or Upper, Middle and Lower members (Fig. 3). 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 northwest of the Onondaga Field. In the distal subbasin southeast of Onondaga, the O Marker becomes difficult to identify in both seismic and well-log data because of growth faults, poor quality seismic data, and facies change and/or erosion.

**Panuke Field History and Reservoir Stratigraphy**

The Panuke Field discovery well, Panuke B-90, was drilled in 1986 to test a drape structure formed by differential compaction of Lower Cretaceous clastics over Abenaki carbonates (LASMO, 1990; Canada-Nova Scotia Offshore Petroleum Board, 2000). The B-90 well penetrated five oil-bearing sandstones in an interval approximately 40 m thick at the transition between the Upper Missisauga and the overlying Naskapi mudstone (Fig. 4). The field was delineated in 1987 with a second
vertical well, Panuke F-99. 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 x 10^6 m³, or 42 MMbbls (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 naturally pressured flow. Pressure data collected during this phase suggested that 75% of the hydrocarbons came from the P2 sandstone, the remaining 25% from the P3 sandstone (Rick Werzbicki, personal communication, 2002). Primary production was suspended in 1995. In 1998, a water-flood program was initiated. During this phase, the P2 and P3 sandstones, along with the P4 sandstone and the C9 sandstone (C9 is a sharp-based sandstone at the base of the Cree Member, Logan Canyon Formation; LASMO, 1990), were perforated and produced as a co-mingled zone under pump flow. Production ceased in 1999 because of high water production and low volumes of hydrocarbon recovery. In total, 38.5% of the original oil-in-place, or 2.2568 x 10^6 m³ (16.155 MMbbls), was recovered from the Panuke Field.

**DATASET AND METHODOLOGY**

The results of this study are based on the analysis of geo-physical well-log data from 20 wells in the western Sable Subbasin, eight cores (~320 m), a 3-D seismic survey from the Panuke Field and regional 2-D seismic lines (Fig. 2). 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 the 3-D seismic data using synthetic seismograms generated from sonic logs or sonic and density logs (Fig. 5). 3-D seismic geomorphology, which involves the description and interpretation of depositional and erosional features in seismic plan view, was performed using seismic time slices flattened on the O Marker. A flooding surface within the Naskapi Member 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, is picked at an easily correlatable surface at the top of the main reservoir, the P2 sandstone, several metres above the MacLean and Wade (1993) pick (Fig. 4).

**SEDIMENTOLOGY AND 3-D SEISMIC GEOMORPHOLOGY**

Ten facies were identified in core data from the Missisauga–Naskapi transition in the Panuke Field region (Table 1). These are grouped into three facies associations (Table 2). Stratigraphically upward, facies associations are interpreted to have been deposited in: 1) braided fluvial, 2) coastal plain and 3) offshore marine environments (Fig. 4).
Facies Association 1: Braided Fluvial Deposits

Facies Association 1 is interpreted to be a sheet-like, multi-storied braided fluvial sandstone deposit. It occurs in the middle of the Upper Member of the Missisauga Formation. The unit has a blocky gamma ray signature (Fig. 4), and consists predominantly of decimetre-thick, high-angle (dune) cross-stratified medium sandstone beds organized into metre-scale upward-fining units (maximum ~8 m) interpreted to be channel fills (Fig. 6a). Evidence of tidal- and/or marine-influence is typically absent, except for an interval approximately 4 m thick in the middle of the unit and an interval approximately 15 m thick immediately below the top of the unit, which contain double mudstone drapes, *Skolithos* burrows and/or mudstone with oyster shells (Fig. 6b). Facies Association 1 erosively overlies undifferentiated shallow marine deposits (Fig. 6c).

In the low-accommodation Panuke Field region, Facies Association 1 forms a sheet approximately 50 m thick that consists almost entirely of sandstone (Fig. 7A). The unit doubles in thickness to approximately 100 m and becomes more mudstone rich when correlated southeast into the higher-accommodation central Sable Subbasin (Fig. 7B). Facies Association 1 cannot be confidently correlated into the distal Sable Subbasin southeast of the Thebaud Field because of intervening syndepositional growth faults, facies change and/or erosion.

In cross-sections from the Panuke 3-D seismic survey, Facies Association 1 is typically characterized by discontinuous reflections (Fig. 8A, B). Enigmatic reflections are observed in one location in the 3-D seismic data that resemble large lateral accretion surfaces. The reflections dip to the north (i.e., perpendicular to the axis of the channel at the underlying unconformity) and are traceable for 1 to 1.5 km (Fig. 8C). They are approximately 50 m high, which, assuming they formed by lateral accretion, suggests they formed in a 50 m deep channel. This estimate seems incompatible with channel-depth estimates obtained independently from dune cross-bed and channel-fill-succession thicknesses (for method see Bridge and Tye, 2000), which suggest fluvial channels were at most approximately 10 m deep, and aggraded to form a multi-storied sandstone sheet approximately 50 m thick (Cummings, 2004). Furthermore, modern fluvial channels rarely attain depths of 50 m (e.g., Best and Ashworth, 1997). Therefore, although the dipping reflections may record lateral accretion in a locally overdeepened part of the channel (e.g., at a channel confluence scour), their large scale is not likely representative of the fluvial system that deposited Facies Association 1.

In 3-D seismic plan view, a prominent, uncored channel approximately 12 m thick is present at the top of the O Marker

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**Fig. 4.** Panuke reservoirs (P1 to P5 sandstones), Upper Missisauga–Naskapi transition, Panuke B-90 well. Lithostratigraphic picks from MacLean and Wade (1993) and LASMO (1990). Reservoir picks from LASMO (1990) and in-house data (Encana Corporation, unpublished). Note that for convenience, the Upper Missisauga is picked so it coincides with top of main reservoir (P2 sandstone) and top of coastal plain deposits (Facies Association 2). The base of the Upper Missisauga is the base of the O Marker (not shown; see MacLean and Wade, 1993).
reflection (Fig. 9a). This channel lies below the base of Facies Association 1, and is interpreted to have formed during an earlier episode of lowstand fluvial erosion. The erosive basal contact of Facies Association 1 is relatively flat and horizontal in Panuke 3-D seismic data (Fig. 9b) and in well-log cross-sections (Fig. 7A, B). The similarity of a rhombohedral feature approximately 6 m thick present just below the top of Facies Association 1 (Fig. 9c) with modern fluvial braid bars (e.g., Best et al., 2003), along with the medium to coarse caliber of the sandstone and the lack of cohesive overbank mudstone, suggests that the fluvial system that deposited Facies Association 1 had a braided channel pattern. Note that the thinness of the braid-bar-like feature supports the idea that the sandstone sheet is a multi- as opposed to a single-storied unit.

**FACIES ASSOCIATION 2: COASTAL PLAIN DEPOSITS**

Facies Association 2 is interpreted to be a coastal plain deposit. It occurs at the top of the Upper Member of the Missisauga Formation. The unit is heterolithic, has a serrated gamma log signature, and forms a sheet approximately 50 m thick that conformably overlies braided fluvial sandstone in the Panuke Field region (Fig. 7A, B). Lenticular- and pinstripe-bedded tidal flat mudstone and oyster shell-rich lagoonal mudstone predominate, with subordinate sandy tidal channel and bayhead delta deposits (Facies 3–6; Figure 6d–g). Evidence of sediment deposition influenced by large waves (i.e., hummocky cross-stratification) is absent. Roots were observed once, but well developed paleosols were not. Burrowed mud firmground surfaces are common throughout Facies Association 2 (Fig. 6e). Facies Association 2 is characterized by discontinuous seismic reflections in cross-section (Fig. 8A, B, C). In seismic plan view, two undrilled features, elongate and narrow in plan view (200 m and 500 m wide) and 60 m and 40 m deep, are interpreted to be fluvial channels (Fig. 9d, e). The width-to-depth ratio of these channels, compared to modern coastal plain channels (e.g., Jones et al., 2003), is anomalously high. Their possible sequence stratigraphic significance is discussed further below.

**FACIES ASSOCIATION 3: STORM-DOMINATED SHALLOW MARINE DEPOSITS**

Facies Association 3 is interpreted to be a storm-dominated shallow marine deposit. The unit, which corresponds to the entire Naskapi Member of the Logan Canyon Formation, forms an areally extensive sheet approximately 150 m thick overlying coastal plain deposits in the Panuke Field region (Fig. 7A, B). It is composed of several stacked, wave-ravine-mantle-lag-capped upward-coarsening units (“parasequences”; maximum ~20 m thick) composed primarily of mudstone with rare, thin hummocky cross-stratified fine sandstone beds (Facies 7, 9, 10; Fig. 6h).

**REGIONAL SEISMIC STRATIGRAPHY**

Flat, parallel reflections of the Upper Missisauga in the Panuke Field correlate basinward with progradational, distorted,
<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 (cross-sets are maximum 1 m thick, average 10–30 cm thick); 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</td>
<td>same as Facies 1, but with wispy mud laminae on dune foresets; rare double mud drapes</td>
<td>Rare <em>Skolithos</em> and escape traces; coal chunks common</td>
<td>same as Facies 1</td>
<td>blocky to slightly upward-fining; always grades out of 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>siltstone 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 <em>Planolites</em>, <em>Teichichnus</em>, <em>Asterochir</em>, <em>Zoophycos</em>, <em>?Cylindrichnus</em> and <em>Rosselia</em>.</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 lenticular, wavy or pinstripe 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 syneretic cracks</td>
<td>bioturbation is typically absent or low, but locally intense. Trace fossils include small <em>Planolites</em>, <em>Arenicolites</em>, <em>Teichichnus</em>, <em>Chondrites</em>, <em>Diplocraterion</em>, <em>?Skolithos</em>, <em>?Thaumasitoides</em>, and <em>?Rosselia</em>.; rare oyster shells</td>
<td>serrated</td>
<td></td>
<td>tidal flat deposits</td>
</tr>
<tr>
<td>5</td>
<td>very fine to fine sandstone</td>
<td>current ripple cross-stratified; dune cross-stratified (max=10 cm); planar lamination; rare bipolar cross-stratified; mud wisps to thin layers common</td>
<td>rare roots; rare <em>Opisthomerpha</em> and <em>Skolithos</em> burrows, small <em>Planolites</em> burrows (in mudstone laminae), and escape traces</td>
<td></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-stratified; mud rip ups present</td>
<td>disseminated mm-scale organic flecks abundant; rare <em>Opisthomerpha</em> in sandstone and small <em>Planolites</em> in mudstone laminae; rare oyster shells</td>
<td>rare dm-scale patches of carbonate cement</td>
<td>gradiationally based, coarsening upwards</td>
<td>bayhead delta deposits</td>
</tr>
</tbody>
</table>
Table 1. Continued

<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>7</td>
<td>poorly sorted sandstone with many isolated, white quartz sand grains and granules (“paint-speckles”)</td>
<td>obliterated by bioturbation</td>
<td>intensely bioturbated; unlined <em>Thalassinoïdes</em> burrows (and rarely large <em>Teichichnus</em> burrows) sublith from lower contact; trace fossils include <em>Ophiomorpha, Paleophycus, ?Cylindrichnus, Teichichnus, and 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 ‘diagenetic’ rings and are rarely coated with carbonate; occasionally glauconite rich</td>
<td>sharp based, thin blocky units; &lt;2 m thick; commonly overlies a firmground -burrowed surface</td>
<td>transgressive ravinement lag</td>
</tr>
<tr>
<td>8</td>
<td>very fine to medium sandstone</td>
<td>typically hard to see, but include small-scale wave ripple cross-stratification, high-angle dm-scale cross-stratification, hummocky cross-stratification</td>
<td>moderately to intensely bioturbated; trace fossils include <em>Ophiomorpha, Cylindrichnus, ?Rosselia, Chondrites</em> (in the <em>Rosselia</em>), <em>?Teichichnus</em>; Facies 8 sandstones overlie burrowed mud firmground surfaces mantled with transgressive lag (Facies 7)</td>
<td>cm-scale 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 barrier sandstone</td>
</tr>
<tr>
<td>9</td>
<td>mudstone with thin siltstone and very fine sandstone beds and laminae</td>
<td>hummocky cross-stratification, small- to medium-scale wave ripple cross-stratification</td>
<td>low to moderately bioturbated; trace fossils include <em>Planolites, Teichichnus, Paleophycus, Terebelina, Chondrites, Cylindrichnus, ?Astrosoma, Ophiomorpha, ?Rosselia</em></td>
<td>rare small siderite nodules</td>
<td>coarsening-upwards</td>
<td>shallow marine mudstone deposited above storm 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>Ophiomorpha</em> burrows</td>
<td></td>
<td>coarsening-upwards</td>
<td>shallow marine storm beds</td>
</tr>
</tbody>
</table>
undrilled clinoform-shaped reflections approximately 25 km to the southwest (Fig. 10). Clinoform reflections associated with the Missisauga Formation are approximately 13 km long, and, based on well-log data, have approximately 0.8 km vertical relief and a basinward slope of 3.5°. The 0.8 km vertical relief suggests that the clinoforms are not deltaic, but rather formed by progradation of the entire continental shelf margin and slope (see Porebski and Steel, 2003; Donovan, 2003; Cummings and Arnott, 2005). At the Missisauga–Naskapi contact, the dip of the clinoforms decreases slightly, and the top-Missisauga reflection is onlapped by a landward thinning package of reflections that has the stratigraphic character of a healing phase wedge (e.g., Posamentier and Allen, 1999, p. 165). Reflections associated with offshore mudstone of the overlying Naskapi Member are parallel, have slightly lower amplitude, and exhibit no obvious internal downlap. The base of the blocky Cree Member, which truncates Naskapi mudstone in the Panuke Field, is associated with rejuvenated shelf margin progradation (Fig. 10).

By contrast, in the central Sable Subbasin, Missisauga slope clinoforms are typically difficult to resolve because of growth faults and noisy seismic data (Cummings et al., 2006). The Upper Missisauga (Barremian) shelf margin trend can, however, be correlated into the central Sable Subbasin using a combination of seismic, well-log and core data. It is interpreted to be located roughly several kilometres basinward of the Alma and Glenelg fields (Fig. 11; Cummings, 2004; Piper et al., 2004).

### Sequence Stratigraphy

Two major (3rd order) sequences are interpreted to occur between the base of the Upper Missisauga and the base of the Cree Member (Fig. 7A, B). The uppermost, Sequence 2, spans the Missisauga–Naskapi contact, and consists (stratigraphically upward) of Facies Associations 1 to 3. The lower sequence, Sequence 1, is interpreted to exist between the top of the O Marker and the base of Sequence 2. Biostratigraphic data suggest that these sequences likely formed during two separate third order (1 to 10 million years long) relative sea-level fluctuations between the Albian and Hauterivian (MacLean and Wade, 1993).

<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. 11)</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>Erousive, overlies undifferentiated shallow marine deposits</td>
<td>A N-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 3, 4, 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 deposits</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, except for thin, deep channel that subdues from a surface near the lower contact</td>
<td>Muddy, stacked coarsening-upward units</td>
<td>~150 m thick sheet</td>
</tr>
</tbody>
</table>

Fig. 6. (opposite) Core photos from Facies Associations 1 (a–c), Facies Association 2 (d–g) and Facies Association 3 (h): (a) High-angle (dune) cross-stratified medium sandstone, Facies 1 (braided fluvial channel fill deposits), Panuke B-90 well, 2390.2 m MD; (b) High-angle (dune) cross-stratified medium sandstone with double mud-drape (lower arrow) and Skolithos burrow (upper arrow), Facies 2 (tide-influenced braided fluvial channel fill deposits), Panuke B-90 well, 2354.91 m MD; (c) Sharp lower contact of Facies Association 1, Panuke B-90 well, 2400.52 m MD. Note abrupt basinward lithofacies shift across contact; (d) Lenticular and pinstripe laminated fine sandstone in mudstone, Facies 4 (tidal flat deposits), Panuke B-90 well, 2333.15 m MD; (e) Burrowed firmground surface, with unlined Thalassinoides burrows subduing from sharp-based sandstone, Lawrence D-14 well, 2280 m MD; (f) Synaeresis cracks, Facies 4 (tidal flat deposits), Panuke B-90 well, 2363.61 m MD; (g) Oyster shells, Facies 3 (lagoonal deposits), Panuke J-99 PP2 well, 2305.8 m MD; (h) Low-angle (hummocky) cross-stratified fine sandstone from Facies Association 3 (storm-dominated shallow-marine deposits), Lawrence D-14 well, 2272.8 m MD. Note low-angle internal truncation surface (arrow) with onlapping laminae whose dip is shallow upward, a common feature of hummocky cross-stratified sandstone beds.
SEQUENCE 1

Sequence 1 is not cored in the Panuke Field region; rather, its presence is inferred based on 3-D seismic data. A prominent channel incised into the top of the O Marker is interpreted to be the base of Sequence 1 (Fig. 9a). From the Panuke Field, this channelized reflection correlates approximately 25 km southwest (basinward) to progradational clinoform reflections at the shelf margin (Fig. 10). The channel at the top of the O Marker is therefore interpreted to be a fluvially incised sequence boundary formed during relative sea-level fall below the shelf edge (cf. Cummings et al., 2006). Well-log data shows the channel to be filled with a heterolithic assemblage of sandstone, mudstone, and carbonate. This suggests that as a result of low sediment supply the incised valley did not fill completely with fluvial and estuarine sediment during transgression. Rather, shelf sediment, including carbonates, was deposited as a late stage valley fill following transgressive passage of the shoreline (e.g., Posamentier, 2001).

SEQUENCE 2

Sequence 2, which erosively overlies Sequence 1 in the Panuke Field region, fines upward from approximately 50 m of braided fluvial sandstone (Facies Association 1) to approximately 50 m of coastal plain heterolithics (Facies Association 2) to approximately 150 m of shallow-marine mudstone (Facies Association 3; Fig. 9). The base of Sequence 2 is the fluvial...
Fig. 7B.
erosion surface at the base of Facies Association 1, which has less than 10 m relief and extends over more than 20 km laterally normal to paleoflow (paleoflow is interpreted to be southwestward based on braid-bar orientation; see Fig. 9c). The upper contact of Sequence 2 is the base of the blocky Cree Member, which truncates shallow-marine mudstone of the Naskapi Member, and is associated with rejuvenated shelf-margin progradation.

Although minor amounts of fluvial sediment may have been deposited at the base of Sequence 2 during falling relative sea-level (cf. Blum and Törnqvist, 2000), significant fluvial aggradation probably did not start until relative sea-level began to rise. The rate of accommodation space increase was likely low relative to channel avulsion rate, allowing a sheet-like sandstone to form over the sequence boundary (e.g., Blakey and Gubitosa, 1984; Holbrooke, 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 during net base-level rise (cf. Curay, 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 (Facies Association 2) deposits is gradational to sharp, lacks a coarse lag deposit, and is preceded by 15 m of marine- and tidally-influenced braided fluvial deposits (Facies 2). This suggests that the contact is conformable, and formed by backstepping of the tidally and marine-influenced coastal plain over fluvial deposits (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 net base-level rise (cf. Curay, 1964).

The contact between coastal plain heterolithics and overlying shallow marine mudstone is characterized by interstratification...
Fig. 8C.

Two-way sound travel time (seconds)

8.25 km

SEQUENCE STRATIGRAPHY

- - - - fluvially incised sequence boundary
- - - - - - - - maximum flooding surface

Panuke Field

Cohasset
C

Panuke 3-D seismic survey

Naskapi
Facies Association 3
Storm-dominated shallow marine

Mississauga
Facies Associations 1&2
Fluvial & coastal plain deposits
undifferentiated shallow marine

O Marker
Fig. 9. 3-D seismic geomorphology across the Upper Missisauga–Naskapi transition, Panuke Field. All images are slices through a data volume that has been flattened on the O Marker reflection. Two major (3rd order) sequences are interpreted to occur in between O Marker and Cree Member in 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/transgressive ravinement surfaces at the base of the P2 and P3 sandstones). (a) Fluvially incised channel on top of O Marker. (b) Flat, horizontal erosion surface at base of braided fluvial unit (Facies Association 1). (c) Rhombohedral feature interpreted to be braid bar at top of Facies Association 1. (d) and (e) Narrow, elongate and deep features interpreted to be (incised?) channels in coastal plain deposits (Facies Association 2). LST, HST and TST refer to lowstand, highstand and transgressive systems tracts, respectively.
Fig. 10. Uninterpreted and interpreted regional seismic section, western Sable Subbasin (GSI-GSI-PA99-110 seismic line). Well logs are tied to seismic data by stretching linearly between reflections associated with Wyandot and O Marker. Note that shelf margin continues to prograde throughout deposition of Upper Missisauga, Naskapi and Cree members, although shelf-margin trajectory has a greater basinward component during deposition of Upper Missisauga and Cree.
of thin (<5 m), sharp-based sandstone sheets (the P2 and P3 sandstone reservoirs) and coastal plain mudstone (Fig. 12, Table 3). Given their stratigraphic position, sharp lower contacts with basal lags, high density/diversity trace fossil assemblages, and very well-sorted nature, the P2 and P3 sandstones are interpreted to have been emplaced during backstepping of a sandy wave-formed barrier island overtop of coastal plain mudstone (Fig. 13). Both sandstone reservoirs are interpreted to overlie transgressive ravinement surfaces; however, the P3 sandstone is both under- and overlain by coastal plain mudstone, whereas the P2 sandstone occurs above coastal plain mudstone and below shallow marine mudstone. As such, the P3 sandstone is interpreted to be an abandoned flood-tidal delta that overlies a tidal ravinement surface formed by migrating channels in the flood tidal delta (e.g., Boyd and Honig, 1992), and the P2 sandstone is interpreted to be a shallow marine sandstone that overlies a wave-ravinement surface formed during erosive shoreface retreat (e.g., Snedden and Dalrymple, 1999).

Although the Missisauga–Naskapi contact represents a landward shift in lithofacies (shallow marine mudstone over coastal plain deposits), evidence for a major transgression and backstepping of the shelf margin (i.e., a resolvable downlap surface, such as that which exists at the top of the Upper Cretaceous Wyandot Formation offshore Nova Scotia) is absent in seismic data at the Missisauga–Naskapi contact. Rather, Naskapi reflections are parallel and concordant with those in the underlying Upper Missisauga and overlying Cree Member, and continue to prograde the shelf margin (Fig. 10). In core data from the Panuke Field, which is 25 km landward of the terminal-Missisauga shelf edge, the Naskapi mudstone consists of upward-coarsening units (“parasequences”) that are commonly lag-capped and contain rare hummocky cross stratified sandstone beds. As such, it is argued that progradation of the shelf edge during Naskapi deposition was facilitated by multiple, high-frequency relative sea-level falls that forced shorelines repeatedly back to, or at least close to, the shelf edge. Parallel seismic reflections in the Naskapi likely represent transgressive surfaces, not passive mudstone drapes (Cummings et al., 2005). The erosion surface at the top of the Naskapi Member (sharp Naskapi–Cree contact) is associated with rejuvenated shelf-margin progradation, and is interpreted to be the upper boundary of Sequence 2 (Fig. 9).

**DISCUSSION**

Studies of fluvial sheets in Late Pleistocene continental-shelf successions suggest that they form during lowstands that do not expose the shelf edge, are unincised, and do not correlate
Fig. 12. P2 and P3 sandstones, showing constituent facies, permeability variations, and sequence stratigraphic interpretations. Dashed lines along facies boundaries indicate gradational contacts; solid lines indicate sharp contacts. Both sandstones overlie transgressive ravinement surfaces, and are interpreted to have formed during landward passage of sandy wave-dominated barrier system over back-barrier mudstone deposits. Given stratigraphic positions, lower sandstone is interpreted to be an abandoned flood-tidal delta, whereas upper sandstone is interpreted to be shallow marine sand sheet. SB – sequence boundary, TR – transgressive ravinement surface. Permeability data was obtained from horizontal core plugs, and is available from Canada-Nova Scotia Offshore Petroleum Board.
Table 3. Sedimentology and reservoir quality of Panuke reservoir sandstones.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Lower Contact</th>
<th>Reservoir is underlain by...</th>
<th>Reservoir is overlain by...</th>
<th>Facies (in stratigraphic order)</th>
<th>Permeability (from core plugs)</th>
<th>Potential Flow Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2 sandstone</td>
<td>erosive, with unlined <em>Thalassinoides</em> burrows subterminating from contact</td>
<td>lagoonal mudstone (Facies 3)</td>
<td>shallow marine mudstone (Facies 9)</td>
<td>poorly sorted glauconite-rich sandstone (Facies 7)</td>
<td>0 to 667</td>
<td>0 to 0.2</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 <em>Thalassinoides</em> burrows subterminating 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>

Fig. 13. General depositional model for hydrocarbon-bearing sheet-like sandstones near top of Upper Missisauga (e.g., P2 and P3 sandstones), Panuke Field region, western Sable Subbasin.
basinward with volumetrically significant shelf-margin delta and/or slope turbidite deposits (e.g., Posamentier, 2001; Wellner and Bartek, 2003). A sheet-like fluvial deposit requires two criteria in order to form (Blakey and Gubitosa, 1984) — the ratio of channel avulsion to aggradation must be high, and avulsion must be unrestricted by physical barriers. These two conditions are commonly met in unincised fluvial systems, but not in narrow incised valleys, where, by definition, overbank flooding cannot occur. Arguably, however, sheet-like fluvial deposits may also form at the base of wide incised valleys. Modeling studies suggest that wide incised valleys can form during prolonged lowstands where valleys have the time to widen following rapid headward incision (e.g., Leeder and Stewart, 1996; Heller et al., 2001). In the Panuke Field, the sheet-like fluvial unit (Facies Association 1) lacks underlying delta-front facies (Fig. 6c) and correlates basinward with progradational shelf-margin clinoform reflections (Fig. 10). As such, despite its width (>20 km), the sheet-like fluvial unit is interpreted to lie within a wide, low-relief incised valley formed during a slow relative sea-level fall and lowstand.

Surprisingly, like underlying braided fluvial deposits, the 50 m thick coastal plain unit (Facies Association 2) also correlates basinward with progradational shelf-margin clinoform reflections (Fig. 10); shelf-margin progradation did not stop with the onset of transgression. Typically, continental shelf margins stop prograding and become sediment starved during transgression because most river-borne sediment is deposited close to the retreating coast (Dalrymple and Cummings, 2005). However, if transgression is punctuated by higher-frequency relative sea-level falls and the shoreline is relatively close to the shelf edge, sediment could theoretically bypass the shelf episodically and prograde the shelf margin. In the western Sable Subbasin the following data suggest that higher order (4th and 5th order) relative sea-level fluctuations did punctuate the slow (3rd order) relative sea-level rise during the terminal phases of Missisauga deposition: 1) the shelf margin progrades throughout; 2) several tide- and marine-influenced intervals occur in the approximately 50 m thick braided fluvial sheet; 3) narrow (<0.5 km), anomalously thick channels (40–60 m), interpreted to be incised valleys, are observed in 3-D seismic data within coastal plain deposits; and 4) several of the burrowed mud firmground surfaces that occur throughout the coastal plain unit are overlain by anomalously thick (<3 m), locally oxidized lag deposits (e.g., at the base of the P2 and P3 sandstones). Renewed shelf-margin progradation after the onset of transgression has been observed at a large outcrop of Eocene shelf-margin deposits in Spitsbergen, although it is unclear whether progradation resulted from a sediment supply pulse or a relative sea-level fall (Ron Steel, personal communication, 2004). There is no evidence that a significant sediment supply pulse occurred during coastal plain deposition at the top of the Missisauga; as such, it is suggested that continued shelf-margin progradation after the onset of transgression was facilitated by higher-order (4th and 5th order) relative sea-level falls to the shelf margin.

Conclusions

The main reservoirs in the Panuke Field (P2 and P3 sandstones) occur in a 100 m thick, more than 20 km wide fluvial–marine transition at the top of the Missisauga Formation. They are interpreted to have formed during transgressive passage of a wave-formed barrier system over back-barrier coastal plain deposits. Although they pinch out locally and do not exceed 5 m in thickness, the Panuke reservoir sandstones are sheet-like over tens of kilometres, consist of well-sorted sandstone with good reservoir quality (average permeability is 100–500 mD, with a maximum of ~2000 mD), and are overlain by thick mudstone of the Naskapi Member. Similar hydrocarbon-bearing sandstones occur at the top of the Missisauga Formation in the Alma Field (Cummings and Arnott, 2005), suggesting that transgressively emplaced shallow marine sandstones are a significant stratigraphic play type in the western Sable Subbasin.

In the Upper Missisauga at Panuke, fluviolastic incised sequence boundaries are interpreted to occur at the base of the 100 m thick fluvial–marine transition that contains the Panuke reservoirs, and at the top of the O Marker. Upper Missisauga seismic reflections at Panuke correlate with progradational slope clinoform reflections 25 km to the southwest, suggesting that sediment, and possibly sand, was transferred to the continental slope through these fluvial systems. Regional mapping of incised fluvial valleys in the Upper Missisauga should help determine the most probable along-strike distribution of coeval turbidite-fan systems on the continental slope offshore Nova Scotia.

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