Variability in wave-dominated estuary sandstones: implications on subsurface reservoir development

S.M. Hubbard
Shell Canada Limited
400 - 4 Avenue SW
Calgary, AB T2P 2H5

M.K. Gingras
Department of Geology
University of New Brunswick
Fredericton, NB E3B 5A3

S.G. Pemberton
Ichnology Research Group
Department of Earth and Atmospheric Sciences
University of Alberta
Edmonton, AB T6G 2E3

M.B. Thomas
Shell Canada Limited
400 - 4 Avenue SW
Calgary, AB T2P 2H5

ABSTRACT

Although ancient estuarine deposits are generally characterized by complex facies distributions, their associated sandstones commonly constitute prolific hydrocarbon reservoirs. Ebb-tidal delta, barrier-bar, tidal-inlet, flood-tidal delta, tidal-channel, tidal-flat and bayhead delta sub-environments can all be associated with sandstones that may potentially have excellent reservoir properties. Distinguishing between depositionally distinctive sandstones is crucial to the accurate reserve and deliverability assessment of reservoirs within estuarine systems. This knowledge can help plan an optimum development strategy for a hydrocarbon play.

In this study, the quality and distribution of sandstones from wave-dominated estuaries is compared using subsurface data from the Lower Cretaceous Bluesky Formation of the Peace River area in Alberta. Modern sediments from Willapa Bay, Washington, are used to support observations made in the Bluesky Formation, and fill in information gaps inherent with subsurface datasets. The modern and fossil estuarine systems studied show that tidal-inlet and barrier-bar sandstones are characterized by the best reservoir qualities, followed by tidal delta, bayhead delta, tidal-channel, and lastly tidal-flat sandstones. Variability in preservation potential amongst ancient estuarine complexes can be significant however, and is an important factor with respect to recognizing, evaluating, and ranking the economic importance of individual units from any given estuarine deposit.

RÉSUMÉ

Malgré que les dépôts estuariens anciens soient généralement caractérisés par des distributions de faciès complexes, les grès associés sont communément constitués de réservoirs prolifiques d’hydrocarbures. Les sous-environnements de reflux de marée, de barrière littorale, de passe de marée, de delta d’inondation de marée, de chenal de marée, d’estran et de delta de fond de baie peuvent tous être associés avec des grès qui pourraient potentiellement avoir d’excellentes propriétés de réservoir. Faire la distinction entre ces grès de dépôts distincts est crucial pour l’évaluation de réserves précises et de la productivité des réservoirs à l’intérieur des systèmes estuariens. Cette connaissance peut aider à planifier une stratégie optimum de développement pour une cible d’exploration des hydrocarbures.

Dans cette étude, la qualité et la distribution des divers grès situés dans des estuaires à dominance de vagues sont comparés avec les données de subsurface provenant de la Formation de Bluesky du Crétacé inférieur de la région de Peace River en Alberta. Les sédiments modernes de la baie de Willapa, Washington, sont utilisés pour supporter les
INTRODUCTION

This paper focuses on a common seaward termination of a fluvial system — the estuary. Although estuarine deposits are characteristically variable, a common trait is that they contain hydrocarbons in the subsurface (e.g. Reinson et al., 1988; Barwis, 1990; Howard and Whitaker, 1990; Dyson, 1998). In this study, ancient and modern databases are used to assess the reservoir quality/potential of various sand bodies from wave-dominated estuaries. Common sub-environments that are characterized by sandy, potentially reservoir quality deposits include tidal inlet, ebb- and flood-tidal deltas, barrier bar, tidal channel, tidal flat and bayhead delta. The thickness, distribution, geometry, and reservoir properties of individual deposits are discussed.

The understanding of ancient estuarine deposits and their hydrocarbon potential has been significantly advanced through the development of incised valley/estuarine facies models (Roy et al., 1980; Clifton, 1982; Roy, 1984; Frey and Howard, 1986; Boyd et al., 1992; Dalrymple et al., 1992; Reinson, 1992). The premise of this study is to provide a relatively simple description of a series of common estuarine sedimentary deposits for potential application in industry. It is not meant to challenge the existing estuarine sedimentological paradigms, but rather to demonstrate the application of those models while focusing on the subsurface mapping of hydrocarbon reservoirs. The study demonstrates that, through estuarine facies identification and mapping, a better understanding of reservoir distribution is attainable and an effective hydrocarbon development strategy can be applied.

BACKGROUND AND METHODOLOGY

The preservation potential of estuarine deposits is extremely variable and normally examples in the rock record are dominated by a limited number of facies. Examples include the Pleistocene succession at Willapa Bay, Washington (predominantly point-bar, tidal-flat and shallow bay facies – Clifton, 1983; Gingras et al., 1999), the Cretaceous McMurray Formation of Alberta (predominantly point-bar and tidal-channel deposits – Wightman and Pemberton, 1997; Ranger and Gingras, 2001), and the Cretaceous Glauconitic Sandstone of Alberta (predominantly point-bar, bay and bayhead delta deposits – Broger et al., 1997). To make a legitimate comparison of various estuarine sandstones, an exceptionally well preserved ancient deposit is desirable, preferably one that comprises many genetically different sandstones.

ANCIENT DEPOSITS: STUDY AREA AND DATABASE

The database considered in this study is taken from the Lower Cretaceous Bluesky Formation in the north-central Alberta subsurface (Fig. 1; Table 1). The Bluesky Formation in this area was deposited in a large, wave-dominated estuary and is known to contain a significant proportion of the billions of barrels of bitumen that comprise the Peace River Oil Sands deposit (Hubbard et al., 1999). This extensive heavy oil field is currently being developed in Township 85 Range 18 W5, where fluvial-deltaic strata of the underlying Ostracode Zone also contain vast reserves of bitumen (Hubbard et al., 1999; 2001). The subsurface dataset includes wireline logs from approximately 250 wells, 81 of which have core that penetrate the study interval. Reservoir facies are interpreted to include bayhead delta, tidal-flat, tidal-channel, flood- and ebb-tidal delta, tidal-inlet, and barrier/shoreface deposits. The fossil estuary in the Bluesky Formation is somewhat exceptional in that it aggraded over time; a complicated history of fluvial and estuarine incision appears to be absent. As a result, units deposited in individual estuarine sub-environments across the study area are both recognizable and mappable (Fig. 2).

The economic potential of many units in the Bluesky Formation is significantly influenced by the presence of water zones, especially toward the southern and westernmost edges of the study area. Because this study is not intended to be a case example of the Bluesky Formation reservoir, fluid saturation values for each of the different sandstones in the field are not compared. Instead, we focus on a selection of rock/reservoir properties and consider all the potential reservoir facies, to offer broader application. Porosity values are primarily from core measurements, supplemented by values derived from wireline logs. Gamma-ray logs, supplemented by qualitative estimates during core examination, provide estimates of the sand/shale ratio in each deposit. The relative abundance of shale interbeds was also derived qualitatively from core observations. Isopach maps, using the constraints of a wave-dominated-estuary model, delineate the areal distribution and geometries of reservoir sandstones.

MODERN DEPOSITS: STUDY AREA AND DATABASE

The modern database employed in this study is Willapa Bay, Washington (Fig. 3). The dataset used is derived from field observations faites dans la Formation de Bluesky, et permettent de combler les lacunes d’information inhérentes aux jeux de données de subsurface. Les systèmes estuariens modernes et fossiles étudiés montrent que les grès de passe de marée et de barrière littorale sont caractérisés par les meilleures qualités de réservoir, suivis par ceux de delta de marée, de delta de fond de baie, de chenal de marée et en dernier par les grès d’estran. Toutefois, la variabilité du potentiel de préservation parmi les complexes estuariens anciens peut être significative, et est donc un facteur important pour d’abord reconnaître, puis évaluer et mettre en ordre l’importance économique des unités individuelles de tout type donné de dépôt estuarien.
observations and recent reports pertaining to this estuary (Clifton et al., 1989; Gingras, 1999; Smith et al., 1999). Data includes textural trends, unit thicknesses, internal heterogeneities, and the areal extent of sand bodies. Inferences drawn from Willapa Bay are predominantly used to bolster interpretations of the Bluesky Formation, and refine them where information from the subsurface is limited by poor core or well control. Sands from Willapa Bay comprise tidal-flat, tidal-channel, tidal-inlet and barrier-spit deposits.

Estuarine sedimentation is characteristically variable (Howard and Frey, 1973; Clifton, 1982; Boyd and Penland, 1984), and hence, no two estuaries are exactly alike. Willapa Bay, although useful as an analog to the Bluesky Formation, has many inherent differences from the subsurface deposit (Hubbard, 1999; Hubbard et al., 2000). A summary of the main controls on deposition for the Bluesky Formation and Willapa Bay is presented in Table 2 in order to outline some of the more obvious differences between the two estuarine systems.
Some of the major differences are related to depositional realm and coastal configuration, tectonic regime, and sediment sources. Despite these differences, common sedimentological and stratigraphic elements link the two deposits, as demonstrated herein.

**ESTUARINE SANDSTONES**

**BLUESKY FORMATION**

Hubbard et al. (1999) interpreted the Bluesky Formation at Peace River as a wave-dominated estuary; a modified version of this model is presented in this paper (Fig. 2A). Gross sand distribution within the Bluesky Formation was particularly influential in arriving at this interpretation (Fig. 2B). Gross sand, for the purpose of this study, includes bitumen-saturated sandstone, water-saturated sandstone, interbedded sandstone and mudstone where sandstone is the predominant component, and muddy or silty sandstone.

Table 3 describes the individual reservoir facies in the Bluesky Formation. Figure 2C summarizes the areal distribu-

---

**Table 1.** Subsurface Lower Cretaceous stratigraphy of the northwest plains, Alberta.

<table>
<thead>
<tr>
<th>Period</th>
<th>Stage</th>
<th>Northwest Alberta Plains</th>
</tr>
</thead>
<tbody>
<tr>
<td>97.5 Ma</td>
<td>Albian</td>
<td>Shaftsbury Formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peace River Formation</td>
</tr>
<tr>
<td></td>
<td>Fort St. John Group</td>
<td>Notikewen Member</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fahler Member</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wilrich Member</td>
</tr>
<tr>
<td>107 Ma</td>
<td>Aptian and older</td>
<td>Bluesky Formation</td>
</tr>
<tr>
<td></td>
<td>Bullhead Group</td>
<td>Ostracode Zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gething Formation</td>
</tr>
<tr>
<td>114 Ma</td>
<td></td>
<td>Cadomin Fm.</td>
</tr>
<tr>
<td>Paleozoic (carbonates and clastics)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 2.** A) Schematic diagram of the wave-dominated estuary facies model interpreted for the Bluesky Formation in the study area. Lines A–A’, B–B’ and C–C’ reflect locations of cross-sections presented in Figures 5 and 9. B) Gross sand map of the Bluesky Formation. C) Areal extent of the estuarine sandstone reservoirs in the Bluesky Formation.
tion of each of the main facies in the subsurface. These were
determined using the 10 m gross sand contour (Fig. 2B) to
delineate the outer boundary of each deposit. The areas of tidal-
channel and tidal-flat deposits were not calculated, because
associated sandstone units are typically <10 m thick. Individual
reservoir deposits are defined on the basis of sedimentary tex-
ture, sedimentary structure, geographical position, and overall
geometry.

WILLAPA BAY, WASHINGTON

As an analogous system to the Bluesky Formation, Willapa
Bay (Figure 3) is significantly influenced by both waves and
tides. Most of the sand in the bay is derived from the Columbia
River, which discharges into the Pacific Ocean approximately
60 km south of Willapa Bay. The sand is transported northward
by longshore currents. Tides then bring the sediment through
the inlet at the north end of the estuary (Figure 3; Luepke and
Clifton, 1983). Fluvial input into the bay is limited to the dis-
charge of 5 small rivers that originate on the northern and eastern
sides of the Willapa Hills watershed. Fluvially derived
sands are present in the uppermost, landward reaches of the
estuary in river-dominated channels (Luepke and Clifton,
1983). Table 4 summarizes some of the sedimentary character-
istics of various sandy deposits at Willapa Bay.

FACIES DESCRIPTIONS

Prior to discussing the sandstone deposits from the various
estuarine sub-environments of the Bluesky Formation and
Table 2. Depositional controls that influence(d) sediment accumulation and preservation in the Bluesky Formation and at Willapa Bay. The controls result in differences in the nature, type, and quantity of facies and facies associations preserved.

<table>
<thead>
<tr>
<th>DEPOSIT</th>
<th>DEPOSITIONAL REALM / COASTAL CONFIGURATION</th>
<th>CYCLICITY REFLECTED BY DEPOSITS</th>
<th>CLIMATE</th>
<th>TECTONIC REGIME</th>
<th>ACCOMMODATION SPACE</th>
<th>SEDIMENT SOURCE</th>
<th>TIDAL RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluesky Formation</td>
<td>Low gradient intra-continental sea-depo-system/broad slope-shelf</td>
<td>3rd or 4th order sea-level fluctuation</td>
<td>temperate to tropical</td>
<td>foreland basin</td>
<td>up to 25 m</td>
<td>large river and tidal inlet (siliciclastics)</td>
<td>1.5–3 m (estimated)</td>
</tr>
<tr>
<td>Willapa Bay</td>
<td>high gradient coastal depo-system/narrow shelf</td>
<td>5th order sea-level fluctuation</td>
<td>interglacial/temperate</td>
<td>active (compressional) margin/tsunami deposits recognized</td>
<td>~30 m at estuary mouth; ~15 m generally</td>
<td>tidal inlet and small rivers (siliciclastics and volcanics)</td>
<td>mesotidal (2–4 m)</td>
</tr>
</tbody>
</table>

Table 3. Sedimentological characteristics of reservoir facies from the Bluesky Formation at Peace River. HWB = heterolithic wavy bedding; IHS = inclined heterolithic stratification.

<table>
<thead>
<tr>
<th>FACIES</th>
<th>SORTING/GRAIN SIZE OF SANDSTONES</th>
<th>PHYSICAL SEDIMENTARY STRUCTURES</th>
<th>BIOTURBATION</th>
<th>LITHOLOGICAL ACCESSORIES</th>
<th>AVERAGE THICKNESS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebb-Tidal Delta</td>
<td>well sorted/ fine-grained</td>
<td>HWB common, Planar-parallel to low-angle crossbedding moderately abundant.</td>
<td>moderate to rare</td>
<td>Shale interbeds in moderate to rare abundance. Wood fragments and coaly debris moderately abundant.</td>
<td>15.5 (up to 20)</td>
</tr>
<tr>
<td>Barrier Bar</td>
<td>well sorted/ very fine- to fine grained</td>
<td>Planar-parallel bedding and low-angle cross-stratification moderately abundant.</td>
<td>rare to moderate</td>
<td>Shale interbeds, coaly debris and pebbly horizons rarely to moderately abundant</td>
<td>17 (up to &gt; 20)</td>
</tr>
<tr>
<td>Tidal Inlet</td>
<td>well sorted/ upper fine-grained</td>
<td>Planar-parallel to low-angle bedding pervasive. Tidal bundles/reactivation surfaces present locally.</td>
<td>absent</td>
<td>Shale interbeds absent to rare.</td>
<td>15.8 (up to 23)</td>
</tr>
<tr>
<td>Flood-Tidal Delta</td>
<td>well sorted/ upper fine-grained</td>
<td>Low-angle to planar-parallel bedding common. IHS moderately abundant.</td>
<td>rare to moderate</td>
<td>Shale interbeds rarely to moderately abundant.</td>
<td>14.4 (up to 22)</td>
</tr>
<tr>
<td>Tidal Channel</td>
<td>well sorted/ fine-grained</td>
<td>IHS common, Low-to high-angle, and trough crossbeds rarely to moderately abundant.</td>
<td>rare to moderate</td>
<td>Shale interbeds moderate to common. Chert pebble lags and bioclastic debris moderately abundant</td>
<td>7.2 (stacked channels up to 15)</td>
</tr>
<tr>
<td>Tidal Flat</td>
<td>muddy/ moderately well sorted/fine-grained</td>
<td>Absent</td>
<td>extensive</td>
<td>Shale interbeds, bioclastic debris and organic detritus rare</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Bayhead Delta</td>
<td>poorly to well sorted/ very fine- to fine-grained</td>
<td>Crossbedding and current ripples common</td>
<td>rare to absent</td>
<td>Shale interbeds rare to moderate</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Willapa Bay, clarification of the term tidal channel as it is used in the context of this paper is necessary. Tidal channels are present throughout wave-dominated and mixed (wave- and tide-influenced) estuaries; however, their importance as reservoirs is more or less limited to bay mouth facies associations (tidal inlets and tidal deltas) in wave-dominated estuaries (Roy et al., 1994). As tidal channels translate into the inner estuary they commonly become increasingly heterolithic or muddy (Smith, 1989; Gingras et al., 1999). In this study, economically significant tidal channels are grouped with genetically similar deposits; for example, tidal channels dominated by flood-tidal currents on the bayward side of the barrier/inlet complex are considered as flood-tidal delta deposits. Where tidal channels are specifically focused on in the paper, they are 1) composed of reservoir quality sediments, and 2) distinguishable from other sandy estuarine units within the data available.

### Ebb-Tidal Delta

Sandstones interpreted to have been deposited on an ebb-tidal delta in the Bluesky Formation are moderately well sorted, fine grained and have average porosities of 24.5%. Gamma-radioactivity measures 52.5 API units on average, and shale interbeds are moderately abundant to rare (Fig. 4). Wood fragments and coaly debris are moderately abundant, and sand-dominated heterolithic wavy bedding is characteristic (Fig. 4A, B). Bioturbation is typically rare to moderate (Table 3). The lithology of the ebb-tidal delta changes systematically, and mud laminae and biogenic reworking increase notably towards the distal, western edge of the deposit. The best reservoir sandstones are adjacent to the gradational boundary with tidal-inlet facies. To the west, progradational ebb-tidal delta deposits interfinger with marine mudstones (Fig. 5A).

Ebb-tidal delta deposits of the Bluesky Formation at Peace River encompass approximately 44 sections, or 1.1 x 10^6 m² (Fig. 2). Where their average gross thickness is 15.5 m (Table 3), sandstones up to 20 m thick accumulated in inferred ebb-tidal channels proximal to the fossil tidal inlet (Fig. 2B). Comparison with deposits at Willapa Bay is speculative, because the ebb-tidal delta deposits are largely inaccessible. However, the ebb-tidal delta platform extends up to 4 km into the Pacific Ocean (Fig. 4D; Clifton et al., 1989).

### Barrier

The barrier in the Bluesky Formation is composed of well sorted, very fine- to fine-grained sandstones deposited in a shoreface to shelfal/offshore environment (Table 3). The average porosity of the sandstones is 26.6%, and the average gamma-radioactivity 43.5 API units (Fig. 6C). The succession systematically coarsens upward, and the reservoir quality increases upwards as a result (Fig. 6C). Mud-lined burrows are moderately abundant; however, bioturbation is rare overall (Fig. 6B). Mud laminae, coaly debris and pebbly horizons occur in rare to moderate abundance (Fig. 6A). Low- to high-angle cross-stratification is common (Fig. 6A). Sandstone quality varies along the length of the barrier, with the thickest, most continuous sand present in the northern part of Township 83 Range 19W5. Variability within the deposit is difficult to characterize due to poor core control. Deposits are gradational with tidal-inlet sandstones northward, and central estuary mudstones and sandstones to the east (Fig. 5B). They are disconformably overlain by distal, shelfal-offshore sandstones and siltstones to the west (Hubbard et al., 1999).

### Table 4. Sedimentological characteristics of sandy facies from Willapa Bay, Washington. (Note*: Tidal inlet/delta deposits are analyzed from Pleistocene outcrop at the northern edge of the current bay-mouth at Willapa Bay; these sediments are interpreted to have been deposited in an analogous setting to those of the modern bay: see Clifton et al., 1989 for further discussion).

<table>
<thead>
<tr>
<th>FACIES</th>
<th>SORTING/GRAIN SIZE OF SANDS</th>
<th>PHYSICAL SEDIMENTARY STRUCTURES</th>
<th>BIOTURBATION</th>
<th>LITHOLOGICAL ACCESSORIES</th>
<th>EQUIVALENT BLUESKY UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Inter tidal Flat</td>
<td>well sorted/ fine-grained</td>
<td>ripple lamination, low-angle lamination, thin bedded, run-off channels (scours and fill)</td>
<td>low or complete</td>
<td>rare organic detritus, shell detritus, in situ bivalves</td>
<td>Tidal Flat</td>
</tr>
<tr>
<td>Large Point Bar (Middle Estuary)</td>
<td>moderately well sorted/medium-grained</td>
<td>ripple lamination, wavy to flaser bedded, inclined heterolithic strata (IHS), trough crossbedding, climbing ripples</td>
<td>low to moderate</td>
<td>terrestrial organic detritus, rare bivalves</td>
<td>Tidal Channel</td>
</tr>
<tr>
<td>Sandy Mid-Channel Bar (Lower Estuary)</td>
<td>well sorted/medium-grained</td>
<td>ripple lamination, low-angle lamination, inclined bedding (10 degrees), trough crossbedding</td>
<td>absent to moderate</td>
<td>rare organic detritus, rare heavy minerals, granules and pebble stringers</td>
<td>Flood-Tidal Delta</td>
</tr>
<tr>
<td>Sandy Tidal Inlet/Delta*</td>
<td>well sorted/medium-grained sand to pebbles</td>
<td>inclined strata, trough cross-bedding, planar-tabular bedding, ripple lamination, sigmoidal bedding</td>
<td>rare</td>
<td>shale interbeds rarely to moderately abundant.</td>
<td>Tidal Inlet/Delta Tidal Deltas</td>
</tr>
</tbody>
</table>

*Note*: Tidal inlet/delta deposits are analyzed from Pleistocene outcrop at the northern edge of the current bay-mouth at Willapa Bay; these sediments are interpreted to have been deposited in an analogous setting to those of the modern bay.
The sand body in the Bluesky Formation is up to 8 km wide, and greater than 23 km long (Fig. 2A). Due to a paucity of wells south of the study area, the actual length of the barrier is unknown. The area of the sand body includes more than 113 sections (Fig. 2C). Deposits typically average 17 m in thickness, but are > 20 m in some localities (Fig. 2B; Table 3). These dimensions are comparable with North Beach Peninsula at Willapa Bay, which is 38 km in length, and has a subaerially exposed width of 3.5 km (Fig. 3). The total width of the sand body at Willapa Bay including the seaward, subtidal shoreface sands is considerable, extending many kilometres offshore (Ed Clifton, pers. comm., 2001). The maximum thickness of the modern barrier is greater than 25 m, comprised of lower shoreface (10–16 m), upper shoreface (about 9 m), and eolian sands (<2 m) (Smith et al., 1999).

**Tidal Inlet**

Tidal-inlet deposits in the Bluesky Formation consist of well sorted, upper fine-grained sandstones (Table 3). The average porosity of associated units is approximately 28%, ranging up to 32% locally (Fig. 7C). The radioactivity of inlet deposits averages 42.0 API units. A characteristic feature of tidal-inlet deposits in the Bluesky Formation is planar-parallel to low-angle crossbedding (Fig. 7A, B), and little internal variability. Tidal bundles and reactivation surfaces are present locally (Fig. 7A; Hubbard, 1999). Evidence of biogenic reworking is absent. Shale laminae are generally absent within the central part of the inlet. Tidal-inlet deposits grade laterally into barrier-bar sandstones to the south, and tidal delta sandstones to the east and west (Fig. 5).
Tidal-inlet deposits of the Bluesky Formation occur in an area approximately 7.2 km by 6.7 km (19 sections; Fig. 2C). The sedimentary package averages 15.8 m in thickness, with a maximum measured thickness of 23 m (Fig. 2B; Table 3). Due to a lack of internal heterogeneity within associated facies, the net-to-gross ratio of tidal-inlet sands is typically one. At Willapa Bay, the inlet is approximately 7 km by 9 km in area and associated channels can exceed 30 m in depth (Figs. 3 and 7D; Smith et al., 1999).

**Flood-Tidal Delta**

Moderately well sorted, upper fine-grained sandstones are characteristic of flood-tidal delta deposits in the Bluesky Formation. The porosity of the deposit averages 27%, with gamma-ray values of 49.8 API units (Fig. 8C). Low-angle to planar-parallel bedding is pervasive, with inclined heterolithic stratification present in some cores (Fig. 8A, B). Wood fragments and coaly debris are present in rare to moderate abundance. Bioturbation is rare overall; however, it increases towards the edges of the delta. Mud laminations also increase in abundance towards the edges of the deposit; however, overall, the laminae are rarely to moderately abundant within associated facies. The area characterized by the best reservoir quality sandstones occurs in the northwestern part of Township 84 Range 17W5, proximal to the tidal inlet (Fig. 2). Flood-tidal delta deposits overlap central estuarine mudstones and sandstones to the east, and are interpreted to grade into tidal-inlet deposits to the west (Fig. 9).

Flood-tidal delta sands in the Bluesky Formation extend over nearly 70 sections (Fig. 2A, C). The gross sand thickness averages 14.4 m, with a maximum of 22 m (Fig. 2B; Table 3). Analogous deposits at Willapa Bay are largely absent owing to the geometry of the bay whereby a large channel system normal to the inlet prevents development of a flood-tidal delta (Fig 2A; Clifton et al., 1989). As the bay fills, however, the composite sand body generated by these flood-tidal-dominated channels is comparable in size and geometry to the interpreted flood-tidal delta deposits in the Bluesky Formation (Figs. 3, 8D). Measuring from the southern limit of the tidal inlet at Willapa Bay to the distal end of the sand deposits, the area of the sedimentary package being produced is 209 km²; the flood tidal complex present in the Bluesky Formation covers an area of approximately 176 km². The depth of the flood-tidal channels at Willapa Bay average 10 to 20 m (Clifton and Phillips, 1980), sufficient to generate a flood-tidal delta sand package as thick as that in the Bluesky Formation.

**Tidal Channel**

Tidal-channel deposits in the Bluesky Formation units are rare overall. They consist predominantly of point-bar deposits composed of well sorted, fine-grained sandstones commonly interbedded with thin mud laminae (Fig. 10A; Table 3). The dominant characteristic is inclined heterolithic stratification (IHS) where mud laminae are common, and low- to high-angle crossbedding where mudstones are absent. Trough crossbedding is also present locally (Fig. 10B). The average porosity of associated units is 24.4% and shaliness, as measured from gamma-ray logs, averages almost 54 API units (Fig. 10C). Bioturbation is rare to moderately abundant, mostly associated

---

**Fig. 5.** Stratigraphic cross-sections through lower estuary deposits in the Bluesky Formation. The top of the Bluesky Formation is used as the datum. A–A’ shows progradation of ebb-tidal delta deposits to the west whereas B–B’ shows the gradational relationship between tidal inlet and barrier-bar sandstones (refer to Fig. 2A for location). Note the relatively “clean” log character through thick tidal-inlet sequences in wells 8-17-85-18W5 (A–A’) and 7-9-85-18W5 (B–B’). Gamma-ray logs are shown. Core intervals are indicated by the black rectangles. For a more comprehensive analysis of the Lower Cretaceous stratigraphy in the Peace River area, see Hubbard et al. (1999).
with the mudstone laminae. Chert pebble lags and bioclastic debris are rare to moderate. Tidal-channel reservoirs in the Bluesky Formation are highly variable and unpredictable, related to numerous facies of the middle to upper estuary including those deposited on tidal flats, in quiescent embayments and on the distal flood-tidal delta.

Tidal-channel trends in the Bluesky Formation are difficult to map. Individual channel deposits are typically up to 7 m thick, although stacked tidal-channel sands attain thicknesses of 15 m (Table 3). At Willapa Bay, tidal channels are the dominant morphological features present in the estuary. Meandering channels in the middle to upper estuary, typically 300 to 600 m wide and 6 to 15 m deep at low low tide (Clifton and Phillips, 1980), are most comparable with tidal channels interpreted in the Bluesky Formation (Fig. 10D).

**Tidal Flat**

Sandy tidal-flat deposits in the Bluesky Formation are fine grained and moderately well sorted, with an average porosity of 24%. Sandstones are typically muddy, as reflected by the relatively higher average gamma-radioactivity of 56.3 API units (Fig. 11C). Mud laminae, shelly debris, coal fragments, and organic detritus are rarely present (Table 3). Primary physical structures are absent, due to the reworking of sediment by benthic organisms; a diagnostic feature of the sandstones is a burrow-mottled texture (Fig. 11A, B). Lateral variability within individual tidal flat units is difficult to assess, because facies cannot be correlated between wells. Tidal flat sandstones are associated typically with tidal-channel deposits of the middle to upper estuary in the Bluesky Formation.

Individual tidal flat deposits in the Bluesky Formation are less than 2 m thick (Table 3). Modern tidal flat deposits at Willapa Bay extend up to 1500 m laterally (Fig. 11D), and are postulated to be up to 3 m in thickness based on the tidal range of 2 to 3 m.

**Bayhead Delta**

Very fine- to fine-grained sandstones are characteristic of bayhead delta deposits in the Bluesky Formation (Table 3). Deposits range from poorly to well sorted, with 26.5% porosity on average. Density-porosity logs demonstrate an overall upward increase in reservoir quality, typical of deltaic deposits (Fig. 12C). Shale interbeds are rarely to moderately present, with the gamma-ray averaging 51 API units (Fig. 12C). Sedimentary structures, including current ripples and crossbedding are common, and bioturbation is rare to absent (Fig. 12A, B). Coaly debris and laminae are present in moderate abundance. Lateral variability across associated deposits is moderate to high. Bayhead delta deposits, restricted to the southeastern corner of the study area (Fig. 2A), prograde onto central estuary mudstones, and are commonly interbedded with units associated with tidal flat deposition (Fig. 9).

In the Bluesky Formation, bayhead delta sandstones averaging 12.1 m in thickness cover an area extending greater than 38 sections (Fig. 2; Table 3). Bayhead delta deposits at Willapa Bay are restricted to the narrow river channels landward of the bay. Coarse-grained sediment is located only in the upper extremes of the rivers, and, therefore, is incomparable to the relatively vast bayhead delta deposits in the Bluesky Formation. Fluvial currents and resultant sediment input into Willapa Bay is much less dominant than that originating from tides (Clifton et al., 1989). In contrast, the Cretaceous estuary that deposited the Bluesky Formation in the study area had tidal and fluvial sources of comparable current energy, resulting in the obvious tripartite sediment texture variation (sand–mud–sand) across the estuary (see Fig. 4 from Dalrymple et al., 1992).
DISCUSSION

A summary of results from core and well-log analysis of the various estuarine reservoir facies of the Bluesky Formation is presented in Figure 13A. In general, the reservoir potential of a sedimentary unit depends fundamentally on the following: 1) a minor porosity, shaliness, and reservoir homogeneity (Fig. 13B); and, 2) size, thickness, and predictability (Fig. 13C) of the reservoir units. From a reservoir development strategy point of view, understanding the quality and distribution of deposits present in the various depositional environments can help optimize hydrocarbon extraction over the duration of the capital-intensive project.

Estuarine sandstones in the Bluesky Formation are largely unconsolidated as a result of early oil migration into the reservoir which reduced the effects of later diagenetic processes (Hubbard, 1999). The data collected suggests that variability between measured values, such as porosity and shaliness is not extreme amongst the different reservoir sandstones (Fig. 13). When these values are compared, however, a distinctive trend is evident, whereby reservoir quality is highest in sandstones associated with the tidal inlet, and degrade in both seaward and landward directions (with the exception of bayhead delta deposits) (Fig. 13B). These observations are consistent with those of Zaitlin and Shultz (1990) and Peijs-van Hilten et al. (1998) from other subsurface estuarine deposits of western...
Fig. 8. Flood-tidal delta deposits. Inclined heterolithic stratification (A) and crossbedding (B) in Bluesky Formation sandstones (A: 3-20-84-17W5, 611.4 m; B: 4-5-85-17W5, 602.4 m). C) Typical geophysical well-log profile through flood-tidal delta deposits in the Bluesky Formation (11-28-84-17W5). D) Magnified Landsat image of sandy, flood tidally dominated channels in Willapa Bay (refer to Fig. 3 for location).

Fig. 9. Stratigraphic cross-section through middle to upper estuary deposits in the Bluesky Formation, demonstrating the interpreted progradational nature of both flood-tidal delta and bayhead delta sandstones. The top of the Bluesky Formation is used as the datum. Core intervals are indicated by the black rectangles (refer to Fig. 2A for location).
Canada. The fossil estuary preserved in the Bluesky Formation is sand dominated, and, in muddier estuarine systems, this trend may be more sharply delineated. Limitations in wireline-log measurements must also be considered; for example, gamma-ray log values give average shaliness across an interval, and cannot distinguish whether a unit is a bioturbated muddy sandstone or a sandstone with common, thin mud interbeds. Therefore, qualitative core observations are an important component in assessing the hydrocarbon potential.

The resource potential is estimated for each estuarine subenvironment in the Bluesky Formation (Fig. 13A, last column). The hydrocarbon present in the subsurface at Peace River is heavy oil (API <10). The bitumen in-place (BIP) is estimated by multiplying the area, average thickness, and porosity of each estuarine sandstone by a bitumen saturation of 80%.

TIDAL-INLET RESERVOIRS

The highest quality reservoir was clearly formed in a tidal inlet (Fig. 13B). These relatively homogeneous sands have a high porosity (28% average) and contain little fine-grained material. The importance of these sediments is somewhat mitigated because of their limited areal extent; however, with an average pay thickness of 15.8 m, they provide one of the most attractive development targets (Fig. 13C). The estimated BIP in the tidal-inlet deposits of the Bluesky Formation is just over one billion barrels (Fig. 13A).

The preservation potential of tidal-inlet deposits is considered to be high (Hoyt and Henry, 1967; Tye and Moslow, 1992). The recognition of numerous documented examples support this statement (subsurface examples: Lower Mannville – Zaitlin and Shultz, 1990; Triassic Halfway Formation – Willis and Moslow, 1994a) (outcrop examples: Horseshoe Canyon Formation at Drumheller, Alberta – Saunders, 1989; Milk River Formation in southern Alberta – Cheel and Leckie, 1990). This excellent preservation potential adds to the attractiveness of tidal-inlet deposits as reservoir targets, as does their propensity to be overlain regionally by marine shale and mud seals (Allen and Posamentier, 1994).
BARRIER-BAR RESERVOIRS

The Bluesky Formation and Willapa Bay case studies indicate that barrier-bar deposits are characterized by good reservoir quality and tremendous lateral extent. The average porosity of the deposits is excellent (26.6%), although sediments are somewhat heterogeneous, with mud laminae common locally (Fig. 13A, B). However, these deposits are extensive (about 113 sections) and potentially thick (up to 25 m) (Fig. 13C). Furthermore, during stillstand and highstand, barrier bars are typically restricted geographically due to a close association with the bay mouth environment, and, therefore, are quite predictable (Roy et al., 1994). The BIP is a staggering 6.5 billion barrels if an 80% bitumen saturation is assumed (Fig. 13A).

Numerous changes in relative sea level may eradicate estuarine barrier-bar deposits. For example, the modern barrier at Willapa Bay is among the bay’s most prominent geomorphological features (Fig. 3). However, although Pleistocene bay sediments are common in the area, very few represent earlier, Pleistocene barriers. However, in the final phase of bay infilling, a fossil barrier is more commonly preserved (the terminal barrier). This is supported by several subsurface studies (e.g. Chiang, 1984; Willis and Moslow, 1994b), and is reflected in the widely accepted tripartite wave-dominated estuary facies model (Dalrymple et al., 1992). Notably, this facies association is not recognized in Neogene shelf-margin estuaries of the Celtic Sea (Reynaud et al., 1999). In these (wave-dominated) estuaries, tidal-inlet deposits are most commonly preserved near the bay mouth.

TIDAL DELTA RESERVOIRS

Flood-tidal delta sands are characterized by high porosity (27%) and relatively thick pay (14.4 m) (Fig. 13B, C). The
sands are clean in the central part of the deposit, but are progressively muddier towards the bayward margins. The flood-tidal delta encompasses a large lateral area, and is relatively predictable. Elsewhere, this depositional environment invariably represents a large component of the reservoir quality sands of a wave-dominated estuary deposit (Roy et al., 1980; Boyd and Honig, 1992). Flood-tidal delta sandstones in the Bluesky Formation contain approximately 3.5 billion barrels of bitumen, based on an 80% bitumen saturation value (Fig. 13A).

The location of the flood-tidal delta inside the estuary increases its preservation potential and, thus, associated units are known to be prolific reservoirs (e.g. Yang and Nio, 1989; Willis and Moslow, 1994a), indicating that their potential should not be discounted. This is especially evident at Peace River, where 2.2 billion barrels (BIP) is estimated for these deposits in the Bluesky Formation (Fig. 13A).

**Bayhead Delta Reservoirs**

Compared to lower estuary sandstones (tidal inlet, tidal deltas and barrier bar), bayhead delta deposits are considered to have less economic importance, based on observations from the Bluesky Formation and Willapa Bay. The quality of resource in such accumulations can be reduced by the presence of mud, lower overall sorting, and less average pay thickness (Fig. 13). Nichol et al. (1994) noted that, where estuaries undergo filling during continual relative transgression with a dominant marine sediment source, bayhead delta deposits are often underdeveloped. In many cases, sediments are often laterally heterogeneous, with zones of reservoir quality sands confined to narrow channels. Workers studying Holocene and modern bayhead

---

**Fig. 12.** Bayhead delta deposits. Cross bedding (A) and ripples (B) in sandstones of the Bluesky Formation (A: 6-25-83-15W5, 615.8 m; B: 6-25-83-15W5, 620.9 m). C) Typical geophysical well-log profile through bayhead delta deposits in the Bluesky Formation (6-25-83-15W5). Note that porosity increases upwards, through the reservoir interval. The core interval is indicated by the black rectangle. D) Facies distribution in a modern bayhead delta, Upper Hawkesbury River, Australia (modified from Nichol et al., 1997). Land is to the west.
**VARIABILITY IN WAVE-DOMINATED ESTUARY RESERVOIRS**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Average Porosity (%)</th>
<th>Shaliness GR (API)</th>
<th>Number of Interbeds</th>
<th>Lateral Variability</th>
<th>Average Thickness (m)</th>
<th>Area of Deposit (sect.)</th>
<th>BIP (bbls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebb-Tidal Delta</td>
<td>24.5</td>
<td>52.5</td>
<td>moderate-rare</td>
<td>moderate</td>
<td>15.5</td>
<td>44.25</td>
<td>2.21E+09</td>
</tr>
<tr>
<td>Barrier Bar</td>
<td>26.6</td>
<td>43.5</td>
<td>rare-moderate</td>
<td>moderate</td>
<td>17.2</td>
<td>113.5+</td>
<td>6.70E+09</td>
</tr>
<tr>
<td>Tidal Inlet</td>
<td>27.9</td>
<td>42.0</td>
<td>rare</td>
<td>low</td>
<td>15.8</td>
<td>19</td>
<td>1.06E+09</td>
</tr>
<tr>
<td>Flood-Tidal Delta</td>
<td>27.0</td>
<td>49.8</td>
<td>rare-moderate</td>
<td>moderate</td>
<td>14.4</td>
<td>68.75</td>
<td>3.45E+09</td>
</tr>
<tr>
<td>Tidal Channel</td>
<td>24.4</td>
<td>53.6</td>
<td>moderate</td>
<td>high</td>
<td>7.2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Tidal Flat</td>
<td>24.0</td>
<td>56.3</td>
<td>rare</td>
<td>high</td>
<td>&lt; 2</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Bayhead Delta</td>
<td>26.5</td>
<td>51.0</td>
<td>moderate-rare</td>
<td>moderate</td>
<td>12.1</td>
<td>38.5+</td>
<td>1.59E+09</td>
</tr>
</tbody>
</table>

**Fig. 13. A)** Summary of reservoir properties of the various estuarine sandstones in the Bluesky Formation (Note: 1 Section = 1.6 km by 1.6 km). A consistent 80% bitumen saturation was utilized for all BIP calculations. Characteristics related to resource quality (porosity and shaliness) are compared in **(B)** while characteristics associated with resource size (area and thickness) are compared in **(C)**.

Delta deposits have recognized the localized nature in associated upper estuarine sediments (Nichol et al., 1997; Fig. 12D).

The potential size of bayhead delta deposits (1.5 billion barrels in the Bluesky Formation; Fig. 13A) and their high preservation potential, however, imply that this is an exceptionally important unit for prospective development. In fact, bayhead delta deposits have proven to be economical at many localities, such as in the Bluesky Formation of central Alberta (Terzuoli and Walker, 1997), and in the development of the Glauconitic Sandstone in southern Alberta (Broger et al., 1997; Peijs-van Hilten et al., 1998).

**TIDAL-CHANNEL AND TIDAL-FLAT RESERVOIRS**

Although they locally exhibit excellent reservoir quality, tidal-channel accumulations are characterized by high facies variability. Locally, they are dominated by inclined heterolithic stratification and low vertical permeability relative to horizontal permeability (Strobl et al., 1997; Peijs-van Hilten et al., 1998). Furthermore, they are generally thin and difficult to map. This is well illustrated in the McMurray Formation of northern Alberta where reservoir rocks are almost exclusively composed of channel sands (Mossop and Flach, 1983; Wightman and Pemberton,
channel trends cannot be projected in the subsurface, despite exceptionally close well spacing (100 m). Even in outcrop, tidal-channel complexes can seldom be mapped. Channel sand reservoirs offer excellent reservoir quality, but are generally present over a small area (Dekker et al., 1987).

Sediments deposited in tidal-flat environments are considered to have the least resource potential because they are thin, often muddy, heterogeneous and have a complex areal distribution (Weimer et al., 1982; Gingras et al., 1999). In general, these are poor resource targets.

**LIMITATIONS**

The application of this study has some obvious limitations, an understanding of which can allow the reservoir geologist to apply the most useful aspects to any given estuarine reservoir.

1) Dalrymple et al. (1992) defined wave-dominated and tide-dominated estuaries as the estuarine facies model end-members. The databases utilized in this study consist of wave-dominated (ancient) to mixed wave- and tide-influenced (modern) estuarine deposits. Where tidal energy is the predominant control on estuarine sediment distribution and sand body geometry, tidal channels, sandy tidal flats, and elongate sand bars comprise the most prospective reservoir units (Dalrymple and Zaitlin, 1989; Dalrymple et al., 1990). As presented in this paper, where wave energy is dominant, tidal-inlet, barrier-bar, tidal-delta, and bayhead delta sandstones typically have the best reservoir potential.

2) There is no definitive, or diagnostic size of an estuary, and therefore the size of estuarine reservoir sand bodies is highly variable. Table 5 demonstrates the variability in areal extent of composite estuary mouth sand bodies (tidal inlet/tidal delta/barrier) from various modern wave-dominated estuaries as compared with sandstones of the Bluesky Formation at Peace River. The length of sand bodies along depositional dip is measured from the seaward end of the ebb-tidal delta to the up-estuary edge of the flood tidal delta.

**CONCLUSIONS**

The data presented herein stress the importance of identifying and mapping facies in hydrocarbon reservoirs located in estuarine deposits. The geological model provides the information that is necessary to 1) systematically and intelligently develop a reservoir; and 2) generate accurate reserve, resource, and deliverability assessments. Our case studies show that inlet, then barrier-bar deposits are the best resource, while intermediate-quality resources are present in strata associated with flood- and ebb-tidal deltas and the bayhead delta. Tidal-channel and sandflat deposits represent the lowest quality resource. Despite the obvious limitations of this study, it demonstrates the overall usefulness of accurately delineating depositions distinct sandstones in an oil or gas field.

**ACKNOWLEDGMENTS**

Funding for the subsurface component of this research was provided by Shell Canada Limited. The analysis of modern deposits at Willapa Bay was supported by Exxon Production Research, Union Pacific Resources and Texaco Inc. Additional funds were provided by Shell Canada Resources Ltd., and Alberta Resources and Development Institute.

**Table 5.** Areal extent of modern estuary mouth sand bodies (composite of tidal-inlet, tidal-delta and barrier sands) from various, modern wave-dominated estuaries as compared with sandstones of the Bluesky Formation at Peace River. The length of sand bodies along depositional dip is measured from the seaward end of the ebb-tidal delta to the up-estuary edge of the flood tidal delta.

<table>
<thead>
<tr>
<th>Estuary (reference)</th>
<th>Length Along Depositional Dip</th>
<th>Length Along Depositional Strike</th>
<th>Total Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gironde Estuary, France (Allen, 1991)</td>
<td>40 km</td>
<td>10 km</td>
<td>400 km²</td>
</tr>
<tr>
<td>Grays Harbor, Washington (Phipps et al., 1976)</td>
<td>13.5 km*</td>
<td>9.5 km</td>
<td>128.25 km²</td>
</tr>
<tr>
<td>Hawkesbury River Estuary, Australia (Roy, 1994)</td>
<td>6 km*</td>
<td>3 km</td>
<td>18 km²</td>
</tr>
<tr>
<td>Lawrencetown Lake, Nova Scotia (Boyd and Honig, 1992)</td>
<td>2 km*</td>
<td>1 km</td>
<td>2 km²</td>
</tr>
<tr>
<td>New South Wales, Australia, Barrier Estuary Model (Roy et al., 1980)</td>
<td>17 km</td>
<td>11 km</td>
<td>187 km²</td>
</tr>
<tr>
<td>Port Hacking Estuary, Australia (Roy, 1994)</td>
<td>7 km*</td>
<td>1 km</td>
<td>7 km²</td>
</tr>
<tr>
<td>SE Coast, U.S.A, Wave-dominated tidal-inlet model, (Maslow and Tye, 1985)</td>
<td>10.5 km</td>
<td>12.5 km</td>
<td>131.25 km²</td>
</tr>
<tr>
<td>Wapengo Lagoon, Australia (Nichol, 1991)</td>
<td>3 km*</td>
<td>1 km</td>
<td>3 km²</td>
</tr>
<tr>
<td>Willapa Bay, Washington</td>
<td>33 km</td>
<td>15 km</td>
<td>495 km²</td>
</tr>
<tr>
<td>Bluesky Formation, Alberta (this study)</td>
<td>30 km</td>
<td>13.5 km</td>
<td>405 km²</td>
</tr>
</tbody>
</table>

* length does not include ebb-tidal delta deposits
funding was provided by Natural Sciences and Engineering Research Council (NSERC) research grants to S.G.P. and M.K.G. Ian Armitage, Bo Henk and Errin Kimball assisted in gathering field data at Willapa Bay. Critical reviews by Drs. Ed Clifton and Brian Zaitlin, as well as suggestions from Bulletin editor Lisa Griffith, significantly improved the quality of the manuscript.

REFERENCES


Table 6. Dimensions of various estuarine reservoirs from the subsurface of western Canada compared with dimensions of reservoir sandstones in the Bluesky Formation at Peace River.

<table>
<thead>
<tr>
<th>Formation (reference)</th>
<th>Depositional Environment</th>
<th>Approximate Areal Extent Preserved (km²)</th>
<th>Maximum Sand Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaucolite Sst., S. Alberta Countess YY Pool (Peijs-van Hilten et al., 1998)</td>
<td>Bayhead Delta</td>
<td>9.1</td>
<td>&gt; 11</td>
</tr>
<tr>
<td>Glaucolite Sst., C. Alberta Hoadley Field (Chiang, 1984)</td>
<td>Barrier -composite deposits</td>
<td>3885</td>
<td>24.4</td>
</tr>
<tr>
<td>Halfway Fm., W. Alberta Wemblay Field (Willis and Moslow, 1994a, b)</td>
<td>Tidal Inlet -individual deposit -composite deposits</td>
<td>3.1</td>
<td>&gt; 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>114</td>
<td>&gt; 12</td>
</tr>
<tr>
<td></td>
<td>Ebb-Tidal Delta -Individual deposit -composite deposits</td>
<td>3.9</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>118</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Barrier Island</td>
<td>50</td>
<td>&gt; 6</td>
</tr>
<tr>
<td>Lloydminster Fm., W. Sask. Senlac Field (Zaitlin and Schultz, 1990)</td>
<td>Tidal Inlet</td>
<td>8.6</td>
<td>&gt; 7</td>
</tr>
<tr>
<td></td>
<td>Shoreface/ Barrier</td>
<td>3.7</td>
<td>&gt; 7</td>
</tr>
<tr>
<td></td>
<td>Flood-Tidal Delta</td>
<td>8.2</td>
<td>&gt; 7</td>
</tr>
<tr>
<td>Viking Fm., S. Alberta Crystal Field (Clark and Reinson, 1990)</td>
<td>Estuarine Channel Fill</td>
<td>64</td>
<td>30</td>
</tr>
<tr>
<td>Bluesky Fm., N. Alberta Peace River Oil Sands (this study)</td>
<td>Ebb-Tidal Delta</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Tidal Inlet</td>
<td>49</td>
<td>&gt; 20</td>
</tr>
<tr>
<td></td>
<td>Flood-Tidal Delta</td>
<td>180</td>
<td>&gt; 20</td>
</tr>
<tr>
<td></td>
<td>Barrier</td>
<td>290</td>
<td>&gt; 20</td>
</tr>
<tr>
<td></td>
<td>Bayhead Delta</td>
<td>100</td>
<td>15</td>
</tr>
</tbody>
</table>


Manuscript received: April 12, 2001
Revised manuscript accepted: August 28, 2001