RECOGNIZING TIDE-DOMINATED VERSUS TIDE-INFLUENCED DELTAS: MIDDLE DEVONIAN STRATA OF THE BALTIC BASIN

KATI TANAVSUU-MILKEVICIENE AND PIRET PLINK-BJÖRLUND
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado 80401, U.S.A.
e-mail: ktanavas@mines.edu

ABSTRACT: This paper examines the differences between tide-dominated and tide-influenced deltas, as well as tide-dominated deltas and tide-dominated estuaries. The deltaic deposits of the Middle Devonian Kernave and Arukuša formations were documented in cores and outcrops in the Baltic Basin and interpreted as tide-dominated delta deposits. These tide-dominated deposits consist of three vertically stacked progradational to aggradational packages, 20–40 m thick. Each package consists of two stratigraphic intervals. The lower upward-coarsening interval contains seaward-accreting prodelta to distal tidal-bar and proximal tidal-bar deposits. The upper upward-fining interval consists of tidal-flat deposits and minor tidal gullies, distributary-channel, supratidal muds, and paleosol deposits. The overall character of these delta deposits indicates a subaqueous delta with no river-dominated delta-plain. Comparison of these successions with modern and ancient tide-dominated and tide-influenced deltas suggests that tide-dominated deltaic deposits tend to form in conditions of relative sea-level rise succeeding transgressions, when tidal currents are strong enough to redeposit most river-derived sediments. Tide-dominated deltas form subaqueous deltas, where the bulk of the deposits are tidally reworked. In contrast, tide-influenced deltas contain tidal indicators in delta-front and lower-delta-plain deposits, whereas the upper delta plain is river-dominated. Our data suggest that tide-dominated deltas may change into tide-influenced deltas during delta evolution when they prograde to the mouth of the restricted or funnel-shaped bay, given the rate of fluvial sediment supply exceeds the rate of accommodation increase.

INTRODUCTION

Most of the largest modern rivers feed tide-dominated or tide-influenced deltas (e.g., Saito et al. 2001; Hori et al. 2002a, 2002b; Lambiase et al. 2003; Roberts and Sydow 2003). Tide-dominated and tide-influenced deltas are also described in the ancient record (e.g., Mellere and Steel 1996; Willis et al. 1999; Kitazawa 2007); however, some ancient tide-dominated deltas have been interpreted as estuaries (see Walker 1992, Willis and Gabel 2003) or as shelf sand ridges (see Nio and Yang 1991a, Willis et al. 1999). In recent years, details of tide-dominated delta depositional systems and deltaic architecture have been documented (Hori et al. 2002b; Dalrymple et al. 2003; Dalrymple and Choi 2007), but most data on tide-dominated deltas have been derived from modern environments.

The term tide-dominated delta has been more widely used only during the last decade, especially in modern deltaic successions (e.g., Harris et al. 1993; Saito et al. 2001; Hori et al. 2002a, 2002b; Dalrymple et al. 2003; Choi et al. 2004; Heap et al. 2004), and less frequently applied to interpret ancient deltaic deposits (e.g., Mellere and Steel 1996; Willis and Gabel 2003; Kitazawa 2007). Differentiation between modern tide-dominated and tide-influenced deltas is based on deltaic morphology. Modern tide-dominated deltas possess a straight, funnel-shaped geometry such as the Fly River delta in Papua New Guinea (Dalrymple et al. 2003), or in the Changjiang (Yangtze River) delta in China (Hori et al. 2002b). Modern tide-influenced deltas form morphological features that are generally more similar to river- or wave-dominated deltas than tide-dominated deltas, as in the Song Hong delta in Vietnam (Hori et al. 2004) or the Mahakam delta in Indonesia (Storms et al. 2005).

In ancient deposits, differences between tide-dominated or tide-influenced deltas can be difficult to recognize. In this paper, deltas are called tide-dominated when tidal facies dominate, and tide-influenced when fluvial or wave-generated facies dominate and tide-generated facies are subordinate. However, this definition is not widely accepted.

The Kernave and Arukuša formations of the Middle Devonian Baltic Basin documented here are dominated by gradaationally based tidal-bar and tidal-flat successions that fine seawards into prodelta muds. Only in rare places do channel deposits and paleosols occur. This is in contrast to the earlier documented, younger tide-influenced Gauja Formation deltas from the Baltic Basin, where fluvial facies dominate and consist of different types of distributary-channel fills that grade seaward into tide-influenced mouth bars and prodelta muds (see Pontén and Plink-Björklund 2007). Although tidal influence has been documented throughout the Gauja deltaic succession, only in a few places do tie-dominated facies associations occur. The documented Kernave and Arukuša formations are also distinctly different from the older Pärnu Formation tide-dominated estuarine deposits of the Baltic Basin, where the sediments fine into the estuarine system from both ends, the tidal bars are sharply based, and the prodelta muds are lacking (see Tovmasyan 2004).

In this paper, we contrast tide-dominated and tide-influenced deltaic successions and document the specific criteria for recognizing tide-dominated deltas from other tide-dominated deposits, such as estuaries. We discuss whether the tide-dominated and tide-influenced deltas may represent different stages of deltaic development and what conditions are likely to cause the transition from tide-dominated to tide-influenced deltas. This study is limited to tide-dominated, tide-influenced, and river-influenced deltas only.
The Baltic Basin is situated in the western part of the Baltica Plate and was at an equatorial position in Devonian time (Cocks and Torsvik 2006). The Baltic Basin developed during the Devonian time as a back-bulge and later a foreland basin in front of the Scandinavian Caledonides (Plink-Björklund and Björklund 1999). The Devonian Baltic Basin formed as a restricted shallow epeiric sea that was at times closed to the south, east, and west, with the main denudation area in the north and the basin area in the south (Kursys 1992; Alekseev et al. 1996; Paskevičius 1997; Narbutas 2005; Marshall et al. 2007; Tännavsuu-Milkevičiene et al. 2009). During the second part of Eifelian, in the Narva time (Fig. 1), transgressive mixed carbonate–siliciclastic shallow marine deposits partially filled the Baltic Basin (Plink-Björklund and Björklund 1999; Tännavsuu-Milkevičiene et al. 2009). This transgressive episode was followed by a southward progradation of deltaic deposits in the end of Narva time (Plink-Björklund and Björklund 1999; Tännavsuu-Milkevičiene et al. 2009), and continued through the Middle Devonian, up to the end of the Givetian (Kursys 1992; Plink-Björklund and Björklund 1999; Plink-Björklund et al. 2004; Pontén and Plink-Björklund 2007). The deltaic succession shows an overall coarsening-upward character (see Fig. 1; Kursys 1992; Paskevičius 1997; Plink-Björklund and Björklund 1999).

In the lower part of the studied succession, the Kernave Formation is interpreted to have been deposited in a shallow marine setting (Kleesment 1997; Paskevičius 1997). The main part of the deltaic succession, the Arukuļa Formation of Estonia and Latvia, which is correlative with the Kukliai Formation in Lithuania (Fig. 1), is interpreted to have been deposited in a shallow marine (Kleesment 1997; Paskevičius 1997) and deltaic (Plink-Björklund and Björklund 1999) setting. In Estonia, the Arukuļa Formation is divided into three depositional units based on lithological and mineralogical data. Each unit starts with sandstones and grades upwards into mudstones and siltstones. These depositional units are interpreted to indicate sea-level fluctuations (Kleesment 1997; Kleesment and Mark-Kurik 1997).

This study is based on centimeter-scale descriptions of outcrops and cores. Altogether, 13 cores and 16 outcrops, with a total of 45 measured sections, were documented across the Baltic Basin and combined with additional 30 published core descriptions (see Fig. 2). Core recovery was ca. 70%, and each core penetrates the whole thickness of the Kernave and Arukuļa formations. The sedimentary facies were defined by sedimentary structures, textures, and composition (carbonate–siliciclastic ratio; Table 1) and were grouped into facies associations based on the lateral and vertical association of sedimentary facies. Division of deposits into formations and members is based on lithological–mineralogical and paleontological data (Kleesment et al. 1987; Valiukevičius et al. 1986; Valiukevičius and Kruchek 2000; Kleesment and Shogenova 2005). However, most of these boundaries, as well as the boundary between the Kernave and Arukuļa formations, are lithostratigraphical and were not followed specifically in this work. The lower boundary of the deltaic succession is a downlap surface onto the maximum flooding surface that occurs at the top of the transgressive portion of the Narva succession (see Tännavsuu-Milkevičiene et al. 2009). The upper boundary of the deltaic succession of the Kernave and Arukuļa formations is not distinct and is covered by the deltaic succession of the Burtnieki Formation.

The deltaic deposits of the Kernave and Arukuļa formations are exposed in an east–west-oriented outcrop belt, several hundred kilometers wide, with discontinuous outcrops (Fig. 2). The largest of the outcrops are several kilometers wide and up to a several meters high. The total thickness of the Kernave and Arukuļa deltaic succession is variable, ranging from 20 m in northeastern Estonia to 130 m in southwestern Latvia (Paškevičius 1997).

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### Table 1.— Depositional facies of the Kernave and Aruku deltaic succession of the Middle Devonian Baltic Basin.

<table>
<thead>
<tr>
<th>Facies</th>
<th>Textures</th>
<th>Structures</th>
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<th>Interpretation</th>
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<tr>
<td>1 Homogeneous mudstone</td>
<td>Mudstones and siltstones</td>
<td>Homogeneous, in places cemented with carbonate cement</td>
<td>Root traces</td>
<td>Deposited in a low-energy environment (FA 1, 2), and in slack-water conditions (FA 4, 6)</td>
</tr>
<tr>
<td>2 Laminated mudstone</td>
<td>Mudstones and siltstones</td>
<td>Planar lamination, current-ripple lamination, mm-scale thin lamination. Occur desiccation cracks</td>
<td>Ferric mineral accumulations, shell fragments, and fish scales</td>
<td>Deposited in a low-energy environments on tidal flats (FA 2), supratidal muds (FA 4), distal tidal bars (FA 5.1), and on prodelta (FA 6)</td>
</tr>
<tr>
<td>3 Heterogeneous mudstones and siltstones</td>
<td>Mudstones, siltstones with very fine- to fine-grained sandstone layers and lenses</td>
<td>Lenticular and wavy bedding. In places, desiccation cracks and soft-sediment deformation</td>
<td>Shell fragments, ferric mineral accumulations</td>
<td>Deposited from bidirectional currents on tidal flats (FA 2) and tidal bars (FA 5). In many places, occur together with bioturbated mudstones (FA 4)</td>
</tr>
<tr>
<td>4 Bioturbated mudstones</td>
<td>Mudstones and siltstones</td>
<td>Structureless, bioturbated</td>
<td>Totally or partially bioturbated with root traces and simple, vertical and subvertical trace fossils. Ferric-mineral accumulations, and shell fragments</td>
<td>Occur together with heterogeneous mudstones and siltstones (F 3) on tidal flats (FA 2) and on distal tidal bars (FA 5.1)</td>
</tr>
<tr>
<td>5 Brecciated mudstones</td>
<td>Mudstones and siltstones with subangular to rounded mud clasts (up to 3 cm in diameter)</td>
<td>Breciated, structureless, in places, desiccation cracks</td>
<td>Rich in ferric mineral accumulations and root traces</td>
<td>Formed due the subaerial exposure in a pakosols (FA 1), and in supratidal muds (FA 4)</td>
</tr>
<tr>
<td>6 Structureless sandstone</td>
<td>Very fine- to coarse-grained sandstones</td>
<td>Structureless, normally graded, in places with carbonate cement and desiccation cracks</td>
<td>Brachiopod shell fragments</td>
<td>Deposited on sandy tidal flats (FA 2.2), channel deposits (FA 3), and on tidal bars (FA 5). In places occur as sand sheets in pakosols (FA 1)</td>
</tr>
<tr>
<td>7 Ripple-laminated sandstone</td>
<td>Very fine- to fine-grained sandstones</td>
<td>Current-ripple lamination, in very few places wave-ripple lamination</td>
<td>None</td>
<td>Formed on tidal flats (FA 2), channel deposits (FA 3), tidal bars (FA 5), and on supratidal flats (FA 4) during floods</td>
</tr>
<tr>
<td>8 Sandstones with mudstones</td>
<td>Very fine- to fine-grained sandstones with mudstone layers and lenses</td>
<td>Wavybedding, flaserbedding. In places, soft-sediment deformation and carbonate-cemented concretions</td>
<td>In places partially bioturbated with simple, vertical and subvertical trace fossil</td>
<td>Deposited on sandy tidal flats (FA 2.2) and on the tops of the tidal bars (FA 5)</td>
</tr>
<tr>
<td>9 Plane-parallel-laminated sandstones</td>
<td>Very fine- to fine-grained sandstones</td>
<td>Subhorizontal lamination</td>
<td>None</td>
<td>Deposited in channels (FA 3) and in tidal bars (FA 5)</td>
</tr>
<tr>
<td>10 Small-scale cross-stratified sandstones</td>
<td>Very fine- to fine-grained sandstones; rounded mud clasts up to 5 cm in diameter</td>
<td>Planar and trough cross stratification (5–60 cm thick sets), with ubiquitous single and double mica, mud drapes. In places, mud clasts on bedding planes</td>
<td>Shell fragments and fish scales</td>
<td>Formed in high-energy conditions in tidal flat (FA 2), channel (FA 3), and tidal-bar (FA 5) complexes</td>
</tr>
<tr>
<td>11 Large-scale cross-stratified sandstones</td>
<td>Fine- to medium-grained sandstones; rounded mud clasts up to 5 cm in diameter</td>
<td>Planar and trough cross stratification (60–150 cm thick sets), with ubiquitous single and double mica, mud drapes. In places, mud clasts on bedding planes</td>
<td>None</td>
<td>Deposited in high energy conditions in proximal tidal bars (FA 5.2)</td>
</tr>
<tr>
<td>12 Sigmoidal bedding</td>
<td>Very fine- to medium-grained sandstones</td>
<td>Sigmoidal bedding. Rich in single and double mica, mud drapes.</td>
<td>None</td>
<td>Deposited from tidal currents in tidal bars (FA 5)</td>
</tr>
<tr>
<td>13 Soft-sediment-deformed sandstones</td>
<td>Very fine- to fine-grained sandstones</td>
<td>Soft-sediment-deformed cross-stratified deposits</td>
<td>None</td>
<td>Formed due the fast deposition in tidal bars (FA 5)</td>
</tr>
<tr>
<td>14 Bioturbated sandstones</td>
<td>Very fine- to medium-grained sandstones</td>
<td>Bioturbated, in places brecciated</td>
<td>Root traces</td>
<td>Formed in subaerial conditions in pakosols (FA 1), and tidal flats (FA 2)</td>
</tr>
<tr>
<td>15 Mud-clast conglomerate</td>
<td>Mudstones and siltstones with subrounded to rounded mud clasts (up to 3 cm in diameter)</td>
<td>Normally graded</td>
<td>In places, shell fragments and fish scales</td>
<td>Formed as channel lags in tidal gullies and distributary channels (FA 3)</td>
</tr>
<tr>
<td>16 Structureless carbonate</td>
<td>Carbonate mudstone</td>
<td>Structureless</td>
<td>Shell fragments</td>
<td>Form in places in tidal flats (FA 2), tidal bars (FA 5), and prodelta (FA 6)</td>
</tr>
<tr>
<td>17 Nodular carbonate</td>
<td>Carbonate mudstone with fine- to coarse-grained sandstones, mud clasts (up to 2 cm in diameter)</td>
<td>Carbonate nodules, concretions and networks of calcite veins filled with sandstones and mud clasts</td>
<td>Ferric mineral accumulations</td>
<td>Deposited in subaerial conditions due carbonate dissolution in pakosols (FA 1)</td>
</tr>
</tbody>
</table>
Facies Association 1 occurs mainly in the southern part of the basin and is up to 4 m thick. Thin units of Facies Association 1, up to 1.5 m thick, occur also in the northern and middle parts of the basin. Facies Association 1 is divided into two types: (1) red, purple, and ochre colored homogeneous, bioturbated, and brecciated mudstones to very fine- and fine-grained sandstones (Facies 1, 4, 5, 6, and 14; Table 1, Fig. 3A), and (2) cemented, structureless, normally graded medium- to coarse-grained sandstones (Facies 6; Table 1, Fig. 3B). Ferric minerals occur as accumulations on bed tops and as thin layers within the deposits. Root traces and desiccation cracks filled with coarser-grained sediments occur in the first type. Carbonate concretions, nodules, and mud clasts, in places interbedded by networks of calcite veins (Facies 17; Table 1, Fig. 3C) occur in the second type. This facies association is found only in cores, associated with Facies Association 2.

**Interpretation.**—The bioturbated and brecciated intervals together with root traces, ferric mineral accumulations, and carbonate concretions indicate paleosol units formed during periods of subaerial exposure, landscape stability, and nondeposition (Ruskin and Jordan 2007). The red, ochre, and purple pigments indicate variable content of goethite and hematite (Tardy and Roquin 1992). The brecciated, bioturbated mudstone and siltstone units with root traces and ferric mineral accumulations suggest paleosol formation in arid climatic conditions.
conditions as ferruginous soils (Collinson 1996). Cemented sandstones with carbonate concretions, nodules, and networks of calcite veins are interpreted to be formed in semiarid or arid conditions with low precipitation level (Mack 1992), as calcretes (Collinson 1996). Formation of the deposits in arid climates is also supported by the position of the Baltic Basin during the Devonian time (see Cocks and Torsvik 2006).

**Facies Association 2: Tidal Flats**

Facies Association 2 is in association with Facies Associations 3 and 4, gradationally overlies Facies Associations 5, and is capped by Facies Association 1. Facies Association 2 consists of heterolithic, rhythmic deposits of mudstones and sandstones (Fig. 4), in depositional units up to 10 m thick. Small-scale soft-sediment deformation and vertical to
subvertical simple trace fossils occur throughout the units (Fig. 5A). Root traces (Fig. 5B), shell fragments, and fish-scale fragments are also common. In many places, deposits are red and rich in ferro mineral accumulations that occur as thin layers or aggregates (Table 1). Facies Association 2 can be divided into two types: (1) deposits where mudstones and siltstones dominate, and (2) deposits where sandstones dominate. The first type, Facies Association 2.1 consists of homogeneous (Facies 1), thinly laminated (Facies 2), and lenticular- and wavy-bedded mudstones and siltstones (Facies 3), 0.1–1.5 m thick, with planar-laminated and current-ripple-laminated sandstones (Facies 7) interlayers or interbeds up to 0.25 m thick. Locally, gray lenticular and wavy-bedded siltstones (Facies 3) occur together with structureless and bioturbated red siltstones (Facies 4). Carbonate-cemented siltstones (Facies 1) and dolomitic marlstones (Facies 16), up to 1.3 m thick occur (Fig. 4A).

The second type, Facies Association 2.2, consists of flaser-bedded (Facies 8), planar-laminated, current-ripple-laminated (Facies 7), and planar cross-stratified sandstones (Facies 10; Table 1) 0.05–1.3 m thick, rich in mud and mica drapes (Fig. 5C). In places, structureless sandstones occur (Facies 6; Table 1). Sandstones are interbedded with planar-laminated and current-ripple-laminated (Facies 2) or homogeneous (Facies 1) mudstones and siltstones up to 0.45 m thick. Carbonate clasts and carbonate-cemented bed tops occur in structureless sandstones.

Facies Association 2 is best exposed in cores. In outcrops, Facies Association 2 is not always a cliff former and tends to be partially covered (Figs. 4A, 6A, B). In outcrops, Facies Association 2 occurs as laterally discontinuous beds with maximum lateral extent of 70 m and a height of up to 2.5 m.

**Interpretation.**—Flaser-, wavy-, lenticular-bedded, and thinly laminated heterolithic and rhythmical deposits suggest deposition by low-energy tidal currents, most likely on tidal flats (e.g., Reineck and Wunderlich 1968; Yoshida et al. 2001). The mudstone- and siltstone-rich lenticular- and wavy-bedded deposits, together with bioturbated siltstones and current-ripple-laminated sandstone layers and interbeds in Facies Association 2.1, indicate deposition on a lower-energy muddy supratidal or mixed, upper-intertidal flat (Dalrymple et al. 1991). The overall sandy heterolithic deposits in Facies Association 2.2 indicate strong tidal currents and deposition on a higher-energy sandy, lower-intertidal flat near the channel or tidal creek thalweg (Dalrymple 1992; Davis and Flemming 1995).

**Facies Association 3: Tidal Gullies and Distributary Channels**

Facies Association 3 occurs as laterally discontinuous, erosionally based units, up to 3 m thick, within Facies Associations 2 and 4. Facies Association 3 consists of upward-fining depositional units. The lower part of unit consists of plane-parallel (Facies 9), planar- and trough-cross-stratified (Facies 10) and structureless (Facies 6) fine- and medium-grained sandstones that grade upwards into planar-laminated and current-ripple-laminated mudstones and mudstones (Facies 2) and very fine-grained sandstones (Facies 7). Locally, mud-clast conglomerate (Facies 15), as well as shell and fish fragments occur at the bases of depositional units or along the bases of the beds (Fig. 4B). Bidirectional dip directions in adjacent cross sets are common in cross-stratified deposits. Mica and mud drapes, and mud lenses with variable thickness, are also common. Facies Association 3 is documented only in cores located in the northern and central parts of the basin.

**Interpretation.**—The small-scale upward-fining depositional units of dominantly cross-stratified sandstones with conglomerate beds, and shell and fish fragments at the bases of the units, indicate deposition from high-energy currents in channels (Dalrymple et al. 1991; Willis et al. 1999). Bidirectional dip direction of cross-strata and mica and mud drapes suggest deposition by tidal currents (Nio and Yang 1991b). In addition to the latter, Facies Association 3 is laterally equivalent with Facies Associations 2 and 4, which suggests deposition in tidal gullies or tidally influenced distributary-channels.

**Facies Association 4: Supratidal Mud**

Facies Association 4 occurs in the western part of the basin, in association with Facies Associations 2 and 3, and passes laterally basinward into Facies Association 6. Facies Association 4 consists of 0.1–1.8 m thick beds of red and gray homogeneous (Facies 1), brecciated (Facies 5), planar-laminated (Facies 2) mudstones and siltstones that form units up to 10 m thick (Fig. 7, Table 1). Planar-laminated and ripple-laminated very fine- to fine-grained sandstones up to 0.2 m thick (Facies 7) occur in places. No wave ripples are found. Locally, deposits contain mud clasts, isolated root traces, and shell fragments. Bioturbation is very rare. Structureless carbonate (Facies 16) interbeds occur in few places. Facies Association 4 is represented only in cores.

**Interpretation.**—The homogeneous, planar-laminated mudstone units suggest deposition in low-energy conditions. The occasional sandstone beds and mud clasts indicate rare current events. The occurrence of brecciated deposits and isolated root traces suggests subaerial or supratidal conditions. The predominance of mudstone and rare coarser-grained interbeds suggests deposition in areas that received minimal amounts of sand.

**Facies Associations 5: Tidal Bar**

Facies Association 5 occurs across the whole basin and is well exposed in both cores and outcrops (Figs. 6, 8, 9). Facies Association 5 passes laterally southward (basinward) to Facies Association 6 and is gradationally overlain by Facies Association 2. Facies Association 5 consists of gradationally based upward-coarsening successions, up to 30 m thick. Cross-laminated and cross-stratified siltstones and sandstones are common throughout the successions (Facies 2, 9, and 10; Table 1, Fig. 8). Complex cross sets with single and double mica and mud drapes (Fig. 5D), reactivation surfaces, and bidirectional cross sets occur in deposits. Overturned ripples and soft-sediment deformations (Facies 13; Fig. 5E) occur in sandstones. In a few places, homogeneous, structureless carbonate (Facies 16) beds up to 0.3 m thick and carbonate-cemented concretions up to 0.7 cm in diameter occur. Fish remains and shell fragments are abundant, but bioturbation is less common. Facies Association 5 consists of upward-coarsening depositional units, a couple of meters thick, separated by inclined master surfaces. In places inclined, low-angle master surfaces with dips of 7–15° can be traced across outcrops (Fig. 6). The amount and frequency of mudstone and siltstone layers, interbeds, and beds decrease upwards in the depositional units.

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**Fig. 5.—** A) Wavy-bedded deposits with small-scale deformation and vertical and subvertical trace fossils in muddy-, mixed-tidal-flat (FA 2.1) deposits. B) Root traces in muddy-, mixed-tidal-flat (FA 2.1) deposits. C) Current ripple-laminated sandstones with mud drapes in sandy-tidal-flat (FA 2.2) deposits. D) Single and double mica drapes in proximal-tidal-bar (FA 5.2) deposits. Note the rip-up clasts on bedding plane. E) Soft-sediment deformations and mica drapes in proximal tidal-bar (FA 5.2). F) Homogeneous mudstones in prodelta (FA 6) deposits.
Facies Association 5.1 consists generally of plane-parallel, current-ripple-laminated, flaser-, wavy-, and lenticular-bedded mudstones, siltstones, and very fine-grained sandstones (Facies 2, 3, 7, and 8; Table 1, Fig. 6C). In very few places, wave-ripple lamination occurs. Facies Association 5.1 is not always a cliff former and in outcrops tends to be partially covered. There is a limited number of exposures of inclined master surfaces, and it is thus difficult to evaluate the dip angles and dip orientations. Erosional surfaces with an erosion depth up to 0.7 m, filled with horizontal beds, occur locally. Paleo current directions derived from cross strata and ripples are bidirectional. The dominant group of paleocurrents varies between 260 and 300°, with most currents between 280 and 300°. The subordinate group varies between 60 and 180°, with most current directions between 60 and 90° and 160 and 180°.

Facies Association 5.2 consists generally of fine-grained, plane-parallel-stratified, planar- and trough-cross-stratified sandstones (Facies 9 and 10) with bed thickness of 0.05–0.6 m (Figs. 6A, B, 8, 9). Large-scale cross-stratified sandstones (Facies 11) with bed thickness of 0.6–1.5 m occur in places (Fig. 9). Mud clasts, with a diameter of 0.5–7 cm, occur along the bases of the cross sets (Fig. 8B). Sigmoidal bedding (Facies 12), with foreset thickness that thickens and thins from 0.2 to 1.5 cm within individual sets, occurs locally.

Facies Association 5.2 is laterally extensive in outcrops. The main succession is formed by sandstones, and no extensive mudstone or siltstone beds occur. The inclined low-angle master surfaces with dips of 7–15° can be traced across outcrops up to 250 m wide. Cross-set thickness between master surfaces varies from 25 cm to 150 cm. Macroforms up to 4 m high and 40 m long occur (Fig. 6A). Locally, concave-up erosion surfaces up to ca. 30 m wide and 2.5 m deep occur (Figs. 8A, 9). Mud pebbles up to 25 cm in diameter occur on erosional surfaces.

Paleocurrent directions derived from cross strata and ripples are bidirectional. The dominant group of paleocurrents varies between 90 and 170°, with most currents between 130 and 170°. The subordinate group varies between 320 and 30°, with most currents between 10 and 30°.
The paleocurrent directions derived from the master surfaces vary between 140 and 230°, with most currents between 140 and 200°.

**Interpretation.**—The flaser-, wavy-, lenticular-bedded deposits, bidirectional cross strata, reactivation surfaces, sigmoidal bedding, and abundant mica and mud drapes indicate deposition from tidal currents with fluctuating current speed and direction, and suggest deposition in a high-energy tidal environment (Reineck and Wunderlich 1968; Nio and Yang 1991a, 1991b; Willis 2005). Cyclic thickening and thinning of foresets within cross sets indicates rhythmic changes of neap and spring tides (Nio and Yang 1991b). Large-scale inclined master surfaces with superimposed cross strata indicate deposition in large macroforms. The large difference of dip azimuth between the master-surface dip directions and the migration directions of superimposed macroforms suggests lateral migration and deposition in delta-front tidal bars (Dalrymple 1992; Dalrymple and Choi 2007) that occur as more discontinuous deposits present across the basin.

The heterolithic stratification, relatively high mud content, flood-dominated paleocurrents, and the more seaward position of Facies Association 5.1 compared with Facies Association 5.2 indicates lower-energy conditions and suggests deposition in distal tidal bars.

The coarser grain size and ebb-dominated paleocurrents of Facies Association 5.2 compared with Facies Association 5.1 suggests more significant fluvial influence (Dalrymple and Choi 2007). Therefore Facies Association 5.2 could also be a mouth bar. However, due to the dominance of tidal signatures, such as sigmoidal bedding, cyclic thickening and thinning of foresets within cross sets, and high occurrence of single and double mica and mud drapes, Facies Association 5.2 is interpreted as proximal tidal bar.

**Facies Association 6: Prodelta**

Facies Association 6 is present only in cores, and occurs southward (basinward) of Facies Association 5, primarily in the western and southern parts of the basin. Facies Association 6 consists of interbedded homogeneous (Facies 1; Fig. 5F), planar-laminated and ripple-laminated mudstone and siltstone (Facies 2) depositional units 0.4–4.6 m thick that stack vertically, forming successions up to 20 m thick. Very fine- to fine-grained structureless (Facies 6) or ripple-laminated sandstones (Facies 7) layers and interbeds, 0.05–0.42 m thick, occur within the mudstones and siltstones. Structureless carbonate (Facies 16) beds 0.06–0.35 cm thick, and thin millimeter thick mica interlayers, occur locally. In places, shell fragments occur on bedding planes. Facies Association 6 grades upward into Facies Association 5 (see cross section in Fig. 8).

**Interpretation.**—The dominantly laminated mudstones and siltstones with coarser-grained sandstone layers and beds, together with the seaward position from Facies Association 5, suggest deposition in a prodelta environment. Fine-grained sandy layers are interpreted as occasional fluvial input (Reading and Collinson 1996). Current-rippled sandy beds and shell fragments suggest occasional fair-weather wave influence. The structureless character of mudstone and siltstone beds may indicate a high degree of bioturbation (Enos 1998).

**ARCHITECTURE**

The vertical and lateral relationships of facies associations is based on the detailed facies descriptions from described cores and outcrops, and core descriptions from literature (see Fig. 2). Described facies and facies-association successions occur as three progradational vertically stacked packages each 20–40 m thick (see Stratigraphic Units 1–3 in Figs. 10–12). Bounding surfaces between stratigraphic units are inferred from distinct vertical grain-size changes and facies trends in cores. In outcrops the bounding surfaces tend to be covered. In cores, stratigraphic units generally start with thin mudstone or siltstone beds and grade upward into coarser-grained deposits. Each of these stratigraphic packages consists of two characteristic portions. The lower portions consist of an upward-coarsening succession from prodelta mudstones (FA 6) to distal and proximal tidal bars (FA 5), which are interpreted to form in a delta front. The upper portions consist of an upward-finining sandy to mixed and muddy tidal-flat succession (FA 2) and supratidal muds (FA 4) with occasional channel deposits (FA 3). The latter succession is interpreted as tide-dominated delta plain. No river-dominated delta plain occurs other than the occasional channel deposits. As seen in outcrops, the lower,
Fig. 8.—Representative stratigraphic section and photos of proximal tidal bar (FA 5.2). A) Cross-stratified sandstones. Note pebble-size mud clasts on the erosional boundaries (Outcrop 5). B) Trough cross-stratified sandstones with mud clasts on bedding planes. Location of outcrop is shown in Figure 2.
upward-coarsening portion has characteristically inclined (7–15°) master surfaces (Fig. 6) that dip generally southwards (basinward). In the upper, upward-fining portion, bedding surfaces are flat-lying. The progradation of the tidal bars (FA 5) shown in Figures 10–12 is based on the dominant paleocurrent directions, as well as grain-size decrease southward and the measured inclination of the master surfaces in outcrops. The thickness of stratigraphical units decreases upward. The lower portions of the three stratigraphic packages are thicker (10–30 m thick) than the upper portions (5–20 m thick; Figs. 10, 11).

**Stratigraphic Unit 1**

Stratigraphic Unit 1, 40 m thick, is the thickest of the three units (Figs. 10–12). The prodelta deposits (FA 6) occur at the base of the stratigraphic unit, and are very thin (up to 1 m thick) in the northern part of the basin (Tartu (1) and Mehikoorma (2) cores in Fig. 10). The thickness of the prodelta deposits increases considerably towards the southern and western part of the basin (up to 20 m; Ledai (7), Taurage and Nida (15) cores in Figs. 11 and 12). In the western part of the basin, the distal tidal-bar (FA 5.1) deposits are up to 4 m thick only (Talsi (12), Dobele (13) and Palanga (14) cores in Figs. 11 and 12), whereas in the northern and eastern part, prograding distal to proximal tidal-bar successions (FA 5) are up to 30 m thick (Tartu (1), Mehikoorma (2), Valga (3), Ludza (4), and Svedasai (5) cores in Figs. 10 and 12).

The tidal-bar (FA 5) deposits are overlain by tidal-flat (FA 2) deposits in the eastern and central part of the basin, whereas the proximal tidal-bar (FA 5.1) deposits occur at the top of the Unit in the western part of the basin (Figs. 10–12). In the northern and central parts of the basin, tidal gullies and distributary channels (FA 3) occur within the tidal-flat (FA 2) deposits (Tartu (1), Valga (3), Ludza (4), and Kriukai (8) cores in Figs. 10 and 11). In the southern part of the basin paleosols (FA 1) occur at the top of Unit 1 (Svedasai (5), Butkunai (6), Kunkojai (9), and Taurage (11) cores in Figs. 10–12).

Carbonate beds and interbeds occur within the prodelta (FA 6) and tidal-bar (FA 5) deposits in Stratigraphic Unit 1. The number and density of these carbonate beds decreases upward through Stratigraphic Unit 1 and throughout the whole deltaic succession.

Paleocurrent directions derived from cross strata and ripples are bidirectional. Dominant paleocurrent directions within Stratigraphic Unit 1 are towards 10–40° and 120–160°.

Paleocurrent directions and lateral and vertical facies transitions indicate general southward and southeastward progradation of the delta.
of Stratigraphic Unit 1 (Figs. 10, 11). Paleocurrent directions indicate both ebb-influenced and flood-influenced deposits, but the dominant paleocurrent directions are ebb-dominated (Fig. 11). The high proportion of prodelta (FA 6) deposits that grade upward into thin tidal-bar (FA 5) deposits and the lack of river-dominated delta-plain deposits in the western part of the basin compared to the central and eastern parts of the basin. Paleosols (FA 1), tidal-flat (FA 2), and channel (FA 3) deposits at the top of Stratigraphic Unit 1 mark temporal infilling of the basin, except in the western part of the basin (see Figs. 10–12).

**Stratigraphic Unit 2**

Stratigraphic Unit 2, 30 m thick, is gradationally based above Stratigraphic Unit 1 (Figs. 10, 11). The prodelta (FA 6) deposits at the base of Stratigraphic Unit 2 are thinner (up to 4 m thick; Figs. 11, 12) compared to Stratigraphic Unit 1, except in the southwestern corner of the basin (Nida (15) core in Fig. 10). Tidal-bar (FA 5) units form the main bulk of deposits in the eastern part of the basin, where they are 25 m thick (Valga (3), Ludza (4), and Svedasai (5) cores in Fig. 10). Tidal-bar thickness decreases considerably towards the central and western parts of the basin, being thinnest in the west (7 m; Talsi (12), Dobele (13), and Palanga (14) cores in Figs. 11, 12). That is in contrast to tidal-flat (FA 2) deposits that are up to 22 m thick in the western and central parts of the basin (Kriukai (8), Talsi (12), and Dobele (13) cores in Figs. 11 and 12). Tidal-flat (FA 2) deposits are thinnest in the east-central part of the basin (4 m) but reach 11 m along the northern basin margin (Tartu (1) core in Fig. 10) and 7 m in the southeastern part of the basin (Butkunai (6) and Ledai (7) cores in Fig. 10). Channel deposits interpreted as tidal gullies or distributary channels (FA 3) occur mainly along the northeastern and northwestern margins of the basin within the tidal-flat (FA 2) deposits (Tartu (1), Mehikoorma (2), Talsi (12), and Dobele (13) cores in Figs. 10 and 11).

In the western part of the basin, tidal-flat (FA 2) deposits pass southward into supratidal muds (FA 4) and prodelta (FA 6) deposits (Palanga (14) and Nida (15) cores in Fig. 11). That is in contrast to the “normal” southward (basinward) progression of facies associations in the rest of the basin, from tidal flats (FA 2) and channels (FA 3) into tidal bars (FA 5), and then into prodelta (FA 6) deposits (Figs. 10, 11). Paleosols (FA 1) occur at the top of Unit 2 in the southern, central, and northern parts of the basin (Tartu (1), Ledai (7), Vidukle (10), and Taurage (11) cores in Figs. 10–12). The main paleocurrent directions are towards 70–165° and 275–305°.

Paleocurrent directions, together with the lateral and vertical facies transitions, indicate generally ebb-influenced deposits and southeastward progradation of the delta of Stratigraphic Unit 2 (Fig. 11). Prodelta deposits (FA 6), followed by the thick sand tidal-flat (FA 2.2) deposits that were covered by the thick sandy-tidal-flat (FA 2.2) deposits in the western part of the basin (see Fig. 11), indicate higher sedimentation rates compared to Unit 1. Moreover, the transition from prodelta (FA 6) deposits into supratidal muds (FA 4) and then into tidal-flat (FA 2) deposits indicates rapid infilling of the western part of the basin with muds. The western part of the basin seems to have received much less sand than the rest of the deltaic system. This most likely implies that the main feeder channels were located farther eastward.

Thick tidal-flat (FA 2) deposits in the northern margin of the basin (Tartu (1) core in Fig. 10) that thin and then thicken towards the south (Butkunai (6) core in Fig. 10) indicate delta-plain deposition at the end of the progradation episode. Paleosols (FA 1) and delta-plain deposits at the top of Stratigraphic Unit 2 mark temporal infilling of the basin (Figs. 10–12).

**Stratigraphic Unit 3**

Stratigraphic Unit 3, 20 m thick, forms the upper part of the deltaic deposits and lies gradationally on the top of Stratigraphic Unit 2.
Prodelta (FA 6) deposits are relatively thick, up to 14 m, and occur in the western and southwestern part of the basin, alternating with 4-m-thick tidal-bar (FA 5) deposits (Talsi (12), Dobele (13), Palanga (14), and Nida (15) cores in Fig. 11). The thickness of tidal bars increases towards the east, from 11 m in the western part to 17 m in eastern part of the basin (Talsi (12) and Ludza (4) cores in Figs. 10–12). Thin successions of supratidal muds (FA 4) occur in the western part of the basin and pass southward into tidal-bar (FA 5) deposits (Talsi (12) and Dobele (13) cores in Fig. 11). At the northeastern margin, thick tidal-flat (FA 2) deposits form the whole thickness of Stratigraphic Unit 3 (Tartu (1) and

(Figs. 10–12). Prodelta (FA 6) deposits are relatively thick, up to 14 m, and occur in the western and southwestern part of the basin, alternating with 4-m-thick tidal-bar (FA 5) deposits (Talsi (12), Dobele (13), Palanga (14), and Nida (15) cores in Fig. 11). The thickness of tidal bars increases towards the east, from 11 m in the western part to 17 m in eastern part of

(Figs. 10–12). Prodelta (FA 6) deposits are relatively thick, up to 14 m, and occur in the western and southwestern part of the basin, alternating with 4-m-thick tidal-bar (FA 5) deposits (Talsi (12), Dobele (13), Palanga (14), and Nida (15) cores in Fig. 11). The thickness of tidal bars increases towards the east, from 11 m in the western part to 17 m in eastern part of
Mehikoorma (2) cores in Fig. 10). Tidal gullies and distributary channels (FA 3) occur within the tidal-flat (FA 2) deposits. In the central part of the basin, tidal-flat (FA 2) deposits occur across the basin and cover the underlying tidal-bar (FA 5) deposits. In the eastern part of the basin, aggradation-based tidal-flat (FA 2) deposits pass southward to the proximal (FA 5.2) to distal (FA 5.1) tidal-bar deposits (Ludza (4), Svedasai (5), and Ledai (7) cores in Fig. 10). Thick paleosols (FA 1; 4.7 m) occur in the southern part of the basin and within the tidal-flat (FA 2) deposits in the northern part of the basin (Taurage and Valga (3) cores; Figs. 10, 11). Paleocurrent directions within Stratigraphic Unit 3 are variable. The dominant directions occur between 160 and 330°.

Paleocurrent directions and the lateral and vertical facies transitions indicate general southward and southwestward progradation of the delta of Stratigraphic Unit 3. Paleocurrent directions indicate generally ebb-influenced deposits (Fig. 11). The thick tidal-flat (FA 2) deposits at the northern margin of the basin suggest filling of the basin and delta-plain aggradation (Fig. 10). Prodelta (FA 6) deposits that alternate with tidal-bar (FA 5) deposits, as well as the lack of delta-plain deposits in the western part of the basin, suggest low sand supply, compared to the central and eastern parts of the basin (Figs. 10, 11).

DELTA EVOLUTION

The Kernave and Arukuõla deltaic succession formed in a shallow, partly closed epeiric sea that became more shallow to the south towards the Mazurian–Belarusian uplift (Kuršė 1992; Narbutas 2005). The deltaic succession consists of three gradationally based progradational to aggradational vertically stacked packages that successively thin upward (Figs. 10, 11). The overall aggradational character of the prograding delta with thick tidal-bar (FA 5) successions that are overlain with aggradational tidal-flat (FA 2) successions indicates a balance between sedimentation and relative sea-level rise. The relative sea-level rise correlates well with the worldwide eustatic sea-level rise in Middle Devonian time and more specifically with the Kačak Event (Fig. 13; Huse 2002; Buggisch and Joachimski 2006; Marshall et al. 2007; Haq and Schutter 2008). The Kačak Event occurred during deposition of the Kernave Formation (Marshall et al. 2007), which forms the main part of Stratigraphic Unit 1. The upward thinning from Stratigraphic Unit 1 to Stratigraphic Unit 3 and the progradation of the deltaic succession indicate a relative decrease in the relative sea-level rise rate through the delta evolution.
The lateral and vertical association of the facies associations indicates deposition in a tide-dominated delta. The main volume of deltaic deposits, as tidal bars (FA 5) and sandy tidal flats (FA 2.2), accumulated on the delta front and on the subaqueous delta plain (Figs. 10, 11). The subaerial deposits, paleosols (FA 1), muddy and mixed tidal flat (FA 2.1), and supratidal muds (FA 4) occur at the top of the prograding tidal bars (FA 5) and adjacent to the distributary channels. The overall subaqueous character of the deposits and the occurrence of marine fauna (see Mark-Kurik 1995) suggests that the Kernave and Arukuļa deltaic succession formed as a dominantly subaqueous, tide-dominated delta. Marine fauna commonly occur in subaqueous delta deposits (Cattaneo et al. 2003).

Reconstructions of the evolution of the Kernave and Arukuļa deltaic succession (Fig. 14) are based on detailed analysis of facies and facies associations and on tectonic background. The exact position of rivers is not known. However, areas with higher sand content are interpreted to have been closer to the river input than the areas that have higher mud content. The position of facies associations is based on the core descriptions; cores from the literature are used to clarify the boundaries between facies associations. The orientations of tidal bars (FA 5) are based on the paleocurrent data. The position of the shoreline is approximate and follows existing facies models of tide-dominated systems.

During delta evolution, the depositional architecture and delta morphology changed from Stratigraphic Unit 1 through 3, including lateral changes between eastern and western parts of the basin. In the beginning of the delta evolution, prodelta (FA 6) deposits were gradually covered with distal tidal-bar (FA 5.1) deposits that formed in the main part of the basin. Proximal tidal-bar (FA 5.2) deposits occurred in the northeastern part of the basin (Fig. 14 T1; Tartu, Mehikoorma, Valga, and Ludza cores). Large delta lobes formed in the eastern part of the basin (Fig. 14 T1). At the end of deposition of Stratigraphic Unit 1, proximal tidal bars (FA 5.2) prograded southward and tidal-flat (FA 2) deposits occurred in the northern part of the basin (Fig. 14 T2). Thick aggrading prodelta (FA 6) to distal tidal-bar (FA 5.1) deposits indicate lower sand input into the western part of the basin, whereas the thick sandy tidal-bar (FA 5) deposits in the central and eastern parts of the basin suggest that the main sand inflow was directed to those parts of the basin (Fig. 14 T1, T2). The occurrence of tidal flats (FA 2) and paleosols (FA 1) in the southern part of the basin is interpreted to be related to the Mazurian–Belarusian uplift (Narbutas 2005) south of the Baltic Basin, due to shallower water depths at the southern basin margin.

Sediment input from the Mazurian–Belarusian uplift to the Baltic Basin is, however, unlikely, because of documented paleocurrent directions as well as paleogeographic reconstructions (see also Pontén and Plink-Björklund 2007; Tänavsu-Milkeviene et al. 2009). Therefore, we suggest the tidal bars (FA 5) in the southern part of the basin filled the accommodation space due the lower water depths and were capped by the tidal-flat (FA 2) and paleosol (FA 1) deposits.

In Stratigraphic Unit 2, sediment input increased dramatically. Sand was mainly dispersed to the eastern part of the basin, and input of finer-grained silts and muds dominated the western and central parts of the basin (Fig. 14 T3). Large volumes of fine-grained sediments transported to the western and central parts of the basin formed thick tidal-flat (FA 2) and supratidal-mud (FA 4) deposits and filled the basin rapidly (Fig. 14 T3, T4). At the end of Stratigraphic Unit 2 time, thick paleosol (FA 1) deposits formed in the southern and central parts of the basin.

In Stratigraphic Unit 3, the occurrence of tidal-flat (FA 2) deposits in the central part of the basin and prograding-tidal-bar (FA 5) deposits in eastern and western part of the basin suggest two well-developed input areas to the Baltic Basin. However, prograding-prodelta (FA 6) to tidal-bar (FA 5) deposits indicate somewhat lower sand input to the western part of the basin, whereas the thick tidal-bar (FA 5) deposits in the eastern part indicate main sand inflow to the eastern part of the basin (Fig. 14 T5). The occurrence of tidal-flat deposits (FA 2) in the northern margin of the basin throughout Stratigraphic Unit 3 indicates formation of locally subaerial delta-plain deposits (Fig. 14 T6).

**DISCUSSION**

**Differentiating Tide-Dominated Deltas Versus Tide-Dominated Estuaries**

Tide-dominated deltas have been considered to be very similar to tide-dominated estuaries, so that even their very existence has been questioned (see Walker 1992). However, deltas, including tide-dominated deltas, are fundamentally different from estuaries (see discussions in Dalrymple et al. 1992; Boyd et al. 2006; Dalrymple 2006; Dalrymple and Choi 2007). The studied tide-dominated Kernave and Arukuļa deltaic succession clearly shows some fundamental differences. (1) The studied successions indicate overall basinward (southward) fining, as it was fed by river systems to the north and northeast. An estuarine system, in contrast, would show coarser grain size at either end of the system, due to a fluvial and marine sediment source (see Dalrymple et al. 1992; Boyd et al. 2006; Dalrymple 2006; Dalrymple and Choi 2007). (2) In the studied Kernave and Arukuļa system, the prodelta and delta-front tidal-bar succession consists of gradationally based, upward-coarsening mudstones to sandstones (FAs 6 and 5) that prograded basinward (southward). Similar gradational prodelta to tidal-bar deposits have been documented in other tide-dominated deltas, such as the Frevens sandstone in Wyoming (Willis et al. 1999). In estuaries, tidal bars are based by tidal ravinement surfaces or are underlain by estuarine and fluvial facies in more landward positions (Dalrymple et al. 1992; Dalrymple and Zaitlin 1994; Plink-Björklund 2005; Boyd et al. 2006; Dalrymple and Choi 2007). (3) The tide-dominated delta system described in this paper shows bidirectional paleocurrent directions. However, the dominant paleocurrent directions are ebb-dominated, i.e., basinward, even in the most basinward tidal bars. In a tide-dominated estuary, a landward sediment flux from the marine end of the system would favor flood dominance in estuarine tidal bars (Friedrichs and Aubrey 1988). In conclusion, we...
suggest that the overall basinward fining, overall ebb-dominated paleocurrent directions, and gradational upward coarsening from prodelta muds to sandy tidal bars, in concert with their overall regressive vs. transgressive character, are useful and distinct criteria for differentiating tide-dominated deltas from tide-dominated estuaries (see discussions in Dalrymple et al. 1992; Boyd et al. 2006; Dalrymple 2006; Dalrymple and Choi 2007).

**Differentiating Tide-Dominated Versus Tide-Influenced Deltas**

Tide-dominated deltaic deposits are defined as progradational sedimentary bodies where tidal currents redepone more sediments than river or wave currents, change significantly the geometry of sediment bodies, and include high amounts of tidal bundles, reactionation surfaces, mud drapes, heterolithic stratification, and bidirectional stratification (Nio and Yang 1991b; Willis et al. 1999; Willis and Gabel 2001; Hori et al. 2002b; Willis 2005; Bhattacharya 2006; Dalrymple and Choi 2007). However, the presence of tidal features does not necessarily ensure correct identification and interpretation of tide-dominated deltas from tide-influenced deltas or from other tide-dominated environments, especially in ancient successions where the abundance of tide-dominated facies is not enough to indicate tidal dominance of the larger environment due erosion during transgression (Dalrymple and Choi 2007).

The delta succession described here contains ubiquitous mica and mud drapes, tidal bundles, and reactionation surfaces, and lacks major regional erosion surfaces. The subaqueous nature of deposits and lack of a well developed river-dominated delta plain suggests that the tidal currents were strong enough to rework most river-supplied sediments (see also Table 2). Thus, the Kernave and Aruku deltaic succession is interpreted as a tide-dominated delta. Similar ancient tide-dominated delta deposits have been identified in the upper Cretaceous Frontier Formation in the Frewns sandstones in central Wyoming, USA (Willis et al. 1999). The Fly River delta has been used as a modern example of tide-dominated deltas (Dalrymple et al. 2003). However, the concept above presented would not work at the presence of major erosion surfaces, e.g., removal of wave-built barrier and preservation of back-barrier tidal facies.

Tide-influenced delta deposits should also include signs of tidal reworking, such as tidal bundles, mud drapes, and heterolithic stratification, but vertical and lateral density of these features is low, and the fluvial, unidirectional current features dominate the succession, e.g., the Middle Devonian Gauja Formation in the Baltic Basin (Pontén and Pink-Björklund 2007). Moreover, tidal signatures have been documented to occur mainly on the delta front, whereas the delta plain is river-dominated with some tidal influence in the lower-delta-plain reaches, such as seen in the Middle Devonian Gauja Formation (Pontén and Pink-Björklund 2007), or in the Mahakam River delta in Indonesia (Storms et al. 2005; see also Table 2).

In many modern tide-influenced deltas, tidal currents reach far upstream only during extreme spring tides and storm surges, or when river discharge is low. For example, tidal currents reach 20 km upstream from the delta apex in the Mahakam River tide-influenced delta (Storms et al. 2005), and up to 50 km from the river mouth in the Huang He (Yellow River) delta (Saito et al. 2001). In contrast, in modern tide-dominated deltas, tidal currents reach up to 120 km inland in the Rajang River delta (Staub et al. 2000), 290 km upstream in the Changjiang (Yangtze River) delta (Hori et al. 2002a), and up to 400 km upstream in the Fly River delta (Dalrymple et al. 2003).

**Controls on Formation of Tide-Dominated and Tide-Influenced Deltas**

Modern tide-dominated deltas form mainly on macrotidal coasts, whereas tide-influenced deltas occur generally on microtidal and mesotidal coasts. However, it is difficult to document tidal range in ancient deposits. In the shallow epeiric Middle Devonian Baltic Basin, the high degree of tidal reworking throughout the Middle Devonian succession could be assigned to macrotidal conditions, but could alternatively be explained by the basin configuration, since the Baltic Basin was a restricted basin with low wave energy. Moreover, the tidal range may partially be a function of coastal configuration. The funnel shape of a tide-dominated delta would magnify the tidal effect due to lateral confinement. As a delta prograded to the mouth of this funnel-shaped bay, the confinement effect would disappear, and the tidal range might change.

The development of tide-dominated vs. tide-influenced deltas must at least partially be controlled by differences in fluvial sediment supply and deposition rates, as tide-dominated deltas are suggested to form where tidal currents are able to rework most of the river-derived sediment (Dalrymple and Choi 2007). This could be supported by high subsidence rates or eustatic sea-level rise to create conditions where river supply is not high enough to ensure river-dominated delta plain aggradation. However, many tide-influenced deltas form in areas with high subsidence rates, like the Mahakam River delta (Roberts and Sydow 2003) or deltas in Brunei Bay (Lambiasi et al. 2003). This indicates that high subsidence rates alone are not sufficient to generate tide-dominated deltas if the accommodation increase is balanced by increased sediment supply, or if tidal energy is not high enough. One of the effects of tidal reworking might be an efficient removal of fluvially derived sediment from the river mouth, and this may prevent mouth-bar buildup and formation of a subaerial river-dominated delta plain. In places where the fluvial sediment supply is high enough to overwhelm the capacity of the tidal currents to rework the sediment, a river-dominated subaerial delta plain develops. In contrast, in the delta complex described here, tidal currents were able to rework most of the river-derived sediment, and delta-plain deposits consist mainly of partially subaqueous tidal-flat deposits. No extensive river-dominated delta plain formed (see Fig. 14). Similarly, in the Fly River delta, the delta-plain deposits consist of distributary channels, islands, and tidal flats on the tops of the islands (Dalrymple et al. 2003). In the tide-dominated Changjiang (Yangtze River) delta, the subaqueous delta plain is characterized by subtidal- to lower intertidal flats, upper intertidal flats, and surface soil deposits, and there is no extensive subaerial river-dominated delta plain (Hori et al. 2002b). Also, in the Amazon delta, the relatively small delta plain consists of islands (Warne et al. 2002). All of these deltas have been forming during the last 8–6 thousand years, during decreasing rates of sea-level rise in the Holocene, and prograde across filled incised valleys or estuaries (Hori et al. 2002b; Dalrymple et al. 2003). Similarly, the tide-dominated delta succession documented here prograded across the transgressive Eifelian shallow marine succession and formed during a rise in relative sea level (see Fig. 13). This is in contrast to the younger, tide-influenced-delta deposits of the Middle Devonian Gauja Formation, which developed extensive subaerial, river-dominated delta plains, tide-influenced lower-delta-plains, and delta fronts (see Pontén and Pink-Björklund 2007).
The Gauja Formation deltas prograded across earlier deltaic deposits of the Kernave and Arukuła formations documented here, as well as the Burtnieki Formation. Similarly, the Mahakam delta is built on the top of an older delta succession that formed earlier in the Holocene. Following the deltaic evolution in the Middle Devonian Baltic Basin, we suggest that tide-dominated deltas tend to evolve with time into tide-influenced deltas, when they prograde to the mouth of their restricted bay, in basins where the rate of fluvial sediment supply exceeds the rate of accommodation increase (see also Table 2).

### CONCLUSIONS

Detailed sedimentological study of the Middle Devonian Kernave and Arukuła deposits in the Baltic Basin documents three gradationally based stratigraphical units that thin upwards. Each stratigraphical unit consists of progradational and aggradational successions that form two characteristics portions. The lower upward-coarsening portion consists of prodelta to distal-tidal-bar and proximal-tidal-bar deposits. The upper upward-fining portion consists of tidal flat, supratidal muds, occasional tidal gully and distributary channel, and palaeosol deposits. The muddy prodelta, tidal-flat, and supratidal mud deposits in the western part of the basin indicate lower sand input compared with the central and eastern part of the basin, where thick sandy tidal-bar deposits formed. The overall high occurrence of tidal signatures, such as mica and mud drapes, tidal bundles, heterolithic stratification, and bidirectional paleocurrents, as well as dominance of subaqueous depositional environments, indicates deposition in a tide-dominated delta.

We suggest here that tide-dominated-delta deposits form where tidal currents are able to efficiently remove and rework the fluvially derived sediment and result in a deltaic succession that lacks significant volumes of fluvial deposits. Such deltas are subaqueous with no extensive river-dominated delta plain and lack river- or wave-dominated deposits. Tide-dominated-delta deposits are limited to the restricted and, in many cases, microtidal bays. In such deltas, tidal signatures occur throughout the deltaic succession. During delta evolution, the tide-dominated deltas tend to develop into tide-influenced deltas when they prograde to the mouth of the restricted or funnel-shaped bay, at the point where the rate of fluvial sediment supply exceeds the rate of accommodation increase. Tide-influenced deltas form a well developed subaerial delta plain; tidal signatures occur mainly in the delta-front and lower-delta-plain deposits, whereas the upper delta plain is river-dominated. Due to the progradation of the delta, the confinement effect disappears, and the tidal range might change into microtidal or mesotidal.

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### REFERENCES


Dalrymple, R.W., and Zaitlin, B.A., 1994, High-resolution sequence stratigraphy of a complex, incised valley succession, the Cobequid Bay-Salmon River estuary, Bay of Fundy, Canada: Sedimentology, v. 41, p. 1069–1091.
