Coeval versus reciprocal mixed carbonate–siliciclastic deposition, Middle Devonian Baltic Basin, Eastern Europe: implications from the regional tectonic development

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ABSTRACT

The Middle Devonian Narva succession in the Baltic Basin represents a significant turnaround in the history of the basin. The detailed study of core and outcrop sections and the three-dimensional correlations across the Baltic Basin reveal a carbonate-dominated, mixed retrogressive succession, overlain by a siliciclastic-dominated, progradational succession. The palaeogeographic reconstructions show how the shallow, tide-influenced basin expanded from south-west to north-east and, later during the transgression, also to the north, south and east. The transgressive portion of the basin fill is dominated by carbonate-rich sabkha and supratidal to intertidal deposits on the basin margins, and subtidal carbonates in the basin centre. Siliciclastic material was derived by tidal currents and storm waves from the south-west through a tidal inlet and flood-tidal delta complex. This initial transgressive phase is characterized by the lack of subsidence or even episodic uplifts in the northern/north-western part of the basin margin, shown by convergence of timelines and the thin (30 m) transgressive succession. In contrast, on the southern margin, the facies associations stack vertically into a 70 to 80 m thick succession, indicating significantly higher subsidence rates. The upper part of the transgressive phase indicates subsidence across the whole basin. The upper, progradational portion of the basin fill is dominated by coarse, siliciclastic, tide-influenced deltaic deposits that rapidly prograded from north-west to south-east. This detailed study on the Narva succession shows that siliciclastic and carbonate deposition was coeval and that mixing occurred at different temporal and spatial scales. The mixing was controlled by grain-size, volume and location of siliciclastic input rather than relative sea-level changes as suggested in widely used reciprocal mixing models. It is suggested that the forebulge of the Scandinavian Caledonian fold-and-thrust belt migrated to the north-western margin of the Baltic Basin during the earliest Eifelian, as indicated by the lack of subsidence and probable uplift in the northern/north-western margin during the early transgressive phase. The forebulge migration ceased although the forebulge had already started to subside during the later stages of the transgressive phase. The deltaic progradation is interpreted to be associated with the orogenic collapse and uplift in the Scandinavian Caledonides that caused the erosion of the foreland basin fill and the coarse sediment transport into the Baltic Basin.

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Keywords Baltic Basin, coeval carbonate–siliciclastic deposition, Devonian, mixed carbonate–siliciclastic deposition, reciprocal carbonate–siliciclastic deposition, shallow marine.

INTRODUCTION

According to conventional models of reciprocal sedimentation for tropical mixed siliciclastic–carbonate systems, accumulation of carbonates dominates during relative sea-level highstand, whereas siliciclastics are deposited preferentially during lowstands (Handford & Loucks, 1993). This observation implies that the carbonate factory shuts down when siliciclastics are introduced and is rejuvenated as the siliciclastic input stops (Tucker & Wright, 2001). This paper reports a whole basin study of the Middle Devonian Narva succession, where coeval deposition of carbonate (dolostone) and siliciclastic mudstones occurred across the whole basin. It is argued that the coeval deposition of muddy carbonates (dolostone) and siliciclastics occurred due to microbial carbonate production in peritidal hypersaline environments (Vasconcelos et al., 1995; Perri & Tucker, 2007).

Mixed carbonate–siliciclastic deposition is discussed widely in the literature (Walker et al., 1983; Elrick, 1995; Betzler et al., 1997; Coffey & Read, 2004). However, most of these studies focus on the environmental aspects of mixed shelf carbonate wackestones and grainstones, and siliciclastics (Purser et al., 1987; Halfar et al., 2004; Córza et al., 2006) and their sequence stratigraphy (Martin-Chivelet, 1995; Osleger & Montanè, 1996; McLaughlin et al., 2004). Much less is known about mixed carbonate and siliciclastic mudstones in shallow epeiric seas, for example, the shallow cratonic sea of the Baltic Basin (BB).

The Narva succession occurs across the whole BB over an area of ca 160 000 sq km (Fig. 1). This paper focuses on the spatial and temporal relationships of carbonate–siliciclastic mixing on a whole-basin scale. This study documents a critical time in the evolution of the basin, where a retrogradational, carbonate-dominated, mixed sedimentary system changed into a progradation, siliciclastic-dominated system during the Middle Devonian Narva time. This retrogressive to progradational turnaround coincides with the maximum extent of the basin.

This study focuses on documenting: (i) the lateral and vertical distribution of facies associations (FAs); (ii) different styles of mixed carbonate–siliciclastic deposition; (iii) basin evolution; and (iv) the potential relationship of siliciclastic sediment input to the orogenic events in the Scandinavian Caledonides.

GEOLOGICAL BACKGROUND

The Baltic Basin developed in the western part of the East European Platform (EEP) on the Baltica...
plate. From Ediacaran times up to the Late Ordovician, the Baltica was a separate plate that drifted from high to moderate latitudes on the southern hemisphere towards the equator. The equatorial position of Baltica was reached by Silurian–Devonian times. Following the Ediacaran to Early Cambrian opening of the Tornquist and Iapetus oceans and the break-up of the Rodinia supercontinent, the Baltica began to converge during Middle and Late Cambrian times with Avalonia as well as the Laurentia-Greenland plates, to which it was finally sutured during Late Ordovician and Silurian times, respectively, along the Trans-European Suture Zone and the Artic-North Atlantic Caledonides (Nikishin et al., 1996; Torsvik & Rehnström, 2003).

From the end of the Silurian and during the Early Devonian, episodic and dominantly continental siliciclastic sedimentation occurred in the BB (Kuršs, 1992; Kleesment, 1997; Plink-Björklund & Björklund, 1999). During Early Devonian times, the northern part of the BB was uplifted and most of the basin experienced subaerial erosion (Kuršs, 1992; Paškevičius, 1997). The uplift has been attributed to propagation of stress from the Baltica to Laurentia-Greenland collision (Plink-Björklund et al., 2004). At the end of the Early Devonian and during the Emsian, the basin started to subside anew (Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004).

A phase of coarse siliciclastic deposition occurred in the BB from the latest Early Devonian (Pragian) until the end of the Middle Devonian (end of Givetian). During Narva time (Eifelian), however, deposition of the coarse siliciclastics was interrupted by an episode of retrogradational to progradational, mixed carbonate–siliciclastic accumulation (Fig. 2; Kuršs, 1992; Kleesment, 1997; Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004).

The Narva succession is exposed in a 10 to 30 km wide belt at the northern margin of the basin in Estonia and North-western Latvia (Fig. 1). Only a few small outcrops of the Narva succession are available. Thickness of the Narva succession is variable and increases generally southwards from the north-east in Estonia (ca 30 m) to the south-west in Latvia (ca 180 m; Paškevičius, 1997). The thickness increase towards the western-central part of the basin is rapid and the average thickness of the Narva succession in the BB is ca 100 m (Paškevičius, 1997).

**STRATIGRAPHY**

The Narva succession in Estonia and Latvia includes three formations: Vadja, Leivu and Kernave (Fig. 2; Kleesment & Shogenova, 2005). In Lithuania, only two formations are defined: Ledai and Kernave (Fig. 2; Paškevičius, 1997). The Vadja, Leivu and Ledai Formations are characterized by interbedded dolomite and dolomitic marl mudstones with gypsum and anhydrite interlayers, and siliciclastic mudstones. The Kernave Formation is formed dominantly by siliciclastic mudstone, siltstone and up to fine-grained sandstones. The subdivision of the Narva succession into formations is somewhat unclear and is based on a combination of palaeontological, mineralogical and lithological data (Kleesment, 1999).

In this paper, the Narva succession is subdivided into a lower, retrogradational, carbonate-rich part

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**Fig. 2.** Middle Devonian stratigraphy of the Baltic Basin (modified after Paškevičius, 1997; Kleesment & Shogenova, 2005). Absolute ages after Kaufmann, 2006.

<table>
<thead>
<tr>
<th>Global scale</th>
<th>Regional stage</th>
<th>Estonia, Latvia Formations</th>
<th>Lithuania Formations</th>
<th>Dominated lithology and environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3837 Ma</td>
<td>Givetian</td>
<td>Amata</td>
<td>Amata</td>
<td>Fine-grained delta plain sandstones</td>
</tr>
<tr>
<td>3881 Ma</td>
<td>Middle Devonian</td>
<td>Butniki</td>
<td>Butniki</td>
<td>Fine to medium-grained delta plain sandstones</td>
</tr>
<tr>
<td>3919 Ma</td>
<td>Eifelian</td>
<td>Aruküla</td>
<td>Aruküla</td>
<td>Fine to coarse-grained delta plain sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kernave</td>
<td>Sventoji</td>
<td>Fine-grained delta plain sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Butunai</td>
<td>Mudstones to very fine-grained marine sandstones</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Narva</td>
<td>Ledai</td>
<td>Mixed carbonate and siliciclastic marine deposits</td>
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<tr>
<td></td>
<td></td>
<td>Leivu</td>
<td>Vadja</td>
<td>Fine to coarse-grained delta plain sandstones</td>
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<td></td>
<td></td>
<td>Pärnu</td>
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</tbody>
</table>

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and an upper, progradational, siliciclastic-rich part (Figs 2 and 3). Due to uncertain formation boundaries, the correlation between the core sections is based on the detailed FA study. It is argued that, in numerous places, the formation boundaries follow changes in depositional environments and sediment input, which are diachronous, instead of representing actual timelines.

**FACIES ASSOCIATIONS**

The present study is based on detailed sedimentological descriptions of 15 drill-cores from the Estonian Academy of Science, the Estonian Geological Survey, the Department of Geology at the University of Tartu in Estonia, the Latvian Geological Survey and the Museum of Geology of Lithuania, and six outcrops, combined with previously published core descriptions from Estonia, Latvia and Lithuania (Fig. 1). Thirteen FAs have been identified from studied sections and have been defined by sedimentary structures, textures and composition (carbonate–siliciclastic ratio, evaporite content) (Tables 1 to 3). Sedimentary rocks have been classified into three groups by carbonate content: dolomite (with more than 66% of carbonate, predominantly dolomite); dolomitic marl (with 33% to 66% of carbonate, predominantly dolomite); siliciclastic rocks (claystone, calcareous or dolomitic clay, siltstone, sandstone with < 33% of calcite or dolomite). Defined FAs are organized into three genetically related groups: (i) carbonate-rich FAs, where carbonate deposits dominate (Fig. 4 and 4A); (ii) mixed FAs, where siliciclastic deposits dominate (Fig. 5); and (iii) siliciclastic-rich FAs, which consist mainly of siliciclastic material (Fig. 6).

**Carbonate-rich facies associations**

**FA 1.1: Carbonate sabkha**

Facies Association 1.1 is found over the whole basin (Fig. 3). The occurrence of brecciated beds, interbedded with crinkled, thinly laminated carbonate and siliciclastic mudstones with concave-up structures, desiccation cracks and evaporite fabrics (Fig. 4B and C; Table 1) suggest deposition in an arid, supratidal environment (Warren & Kendall, 1985; Demicco & Hardie, 1994; Pratt, 2002). The broken-up beds of carbonates and contorted, soft-sediment deformed siliciclastic clasts in breccia, as well as crinkle lamination and evaporite fabrics, refer to the salt growth sedimentation deformations and to the solution-collapse features (Goodall et al., 2000). The breccia is thus interpreted as solution-collapse breccia formed through evaporite dissolution processes (Goodall et al., 2000; Schreiber & El Tabakh, 2000). Such breccias commonly occur in karst-related and in sabhka environments (Warren & Kendall, 1985; Pomoni-Papaioannou & Karakitsios, 2002). However, the fact that deposits formed in the basin margin during transgression (Fig. 3) suggests that deposition occurred in sabkha environments. The breccias in the northern part of the basin lack evaporitic features, but they are also interpreted as sabkha deposits because they are otherwise similar to the breccias in the rest of the basin.

**FA 1.2: Intertidal to supratidal carbonate tidal flats**

Facies Association 1.2 occurs in the northern and southern part of the basin (Fig. 3) and forms highly variable depositional units with current ripple-laminated siliciclastic mudstones and nodular-bedded, thinly laminated or massive carbonate mudstones (Fig. 4D; Table 1). These deposits, together with desiccation cracks and a large amount of mud drapes (Fig. 4D), indicate deposition in intertidal to supratidal tidal flat environments (Elrick, 1995; Osleger & Montañez, 1996; Lehrmann et al., 2001). The occurrence of brecciated deposits and carbonate mudstone clasts in the deposits are interpreted to have formed under the influence of occasional storms or tidal currents (Pratt et al., 1992; Seguret et al., 2001; Horbury & Qing, 2004).

**FA 1.3: Intertidal to supratidal shoals**

Facies Association 1.3 is found in the central and southern part of the basin (Fig. 3). The combination of lenticular, wavy-bedded, flaser-bedded carbonates and siliciclastics together with desiccation cracks and fenestral fabric (Fig. 4; Table 1) indicate deposition in intertidal to supratidal conditions (Osleger & Montañez, 1996; Lehrmann et al., 2001). The higher occurrence of sand-rich deposits: current ripple-laminated sandstone interlayers (Fig. 4E), up to gravel-sized quartz grains, sandy dolomites and sandstones with dolomitic cement, compared with the intertidal to supratidal carbonate tidal flats (FA 1.2) suggest that deposition occurred in high-energy environments in the tidally influenced bars, or storm-influenced and tide-influenced shoals (Brooks et al., 2003; Rankey et al., 2006).
Fig. 3. Schematic cross-sections of the Baltic Basin during the Narva time. Based on detailed sedimentological descriptions, (A) and (B) three north–south (A–A', B–B', C–C'), and (C) two west–east (D–B–D', C–B'–A') sided cross-sections are presented. For a better understanding of basin evolution 15 time slices (depositional unit boundaries, marked with red lines) were chosen across the basin (see Fig. 7 for palaeogeographical maps). The position of the cross-sections is located on the map (inset). The vertical scale slice of cross-sections is 10 m. The horizontal scale for a single core is seen in Figs 4 to 6.
Coeval versus reciprocal mixed carbonate–siliciclastic deposition
Table 1. Summary of carbonate-rich facies associations.

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Lithology</th>
<th>Sedimentary structures</th>
<th>Depositional units</th>
<th>Evaporite features</th>
<th>Biogenic features</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Carbonate sabkha</td>
<td>Breccia with angular to sub-rounded carbonate (dolomite, dolomitic marl) and siliciclastic mudstone clasts (up to 8 cm in diameter), with carbonate and siliciclastic mudstone, and sand grain matrix Non-brecciated carbonate and siliciclastic mudstones</td>
<td>Brecciated: primary thin lamination preserved in clasts, desiccation cracks and fenestrae are common. Sandstone grains form interlayers in siliciclastic clasts Non-brecciated: thin laminated, wavy, crinkle-bedded deposits with desiccation cracks, locally massive carbonates and homogeneous, planar-laminated siliciclastics</td>
<td>Brecciated beds (0.2 to 2.7 m thick) are interbedded with non-brecciated beds (0.1 to 5.1 m thick); form successions 1.3 to 20 m thick</td>
<td>Anhydrite and gypsum rosettes, nodules, interlayers and vug ﬁlls. Halite crystals and pseudomorphs. Carbonates contain veins and cavities (4 mm deep)</td>
<td>Organic-rich lamina (up to 5 mm thick)</td>
<td>Along the basin margins, pass laterally to the tidal flat deposits (FA 1.2; 2.2; 2.3) and subtidal carbonates (FA 1.4)</td>
</tr>
<tr>
<td>1.2. Intertidal to supratidal carbonate tidal flats</td>
<td>Carbonate (dolomite, dolomitic marl) and siliciclastic mudstones and siltstones with occasional sub-angular to sub-rounded carbonate mudstone clasts (up to 6.5 cm in diameter)</td>
<td>Carbonate mudstones are thinly laminated, nodular-beded or massive with mud drapes and lenses, and desiccation cracks. Siliciclastic mudstones are planar and current ripple-laminated or homogeneous</td>
<td>Siliciclastic mudstones grade upward into carbonate mudstones within 0.2 to 2 m thick units; such units stack as 1.2 to 13.6 m thick successions</td>
<td>Anhydrite and gypsum rosettes and interlayers. Carbonates also contain cavities (4 mm deep)</td>
<td>Brachiopod shell fragments and fish scales</td>
<td>Laterally associated with carbonate sabkha (FA 1.1) and subtidal carbonates (FA 1.4); vertically associated with tidal flat deposits (FA 1.3, 2.3)</td>
</tr>
<tr>
<td>1.3. Intertidal to supratidal shoals</td>
<td>Carbonate (dolomite, dolomitic marl) and siliciclastic mudstones, siltstones, sandy dolomites, sandstones with dolomite cement, sub-rounded and rounded quartz grains (up to 6 mm in diameter) and lenses of quartz grains</td>
<td>Carbonate mudstones are flaser, wavy, nodular-beded with up to fine-grained sandstone lenses and interlayers, desiccation cracks, fenestrae and locally with tepee structures. Siliciclastic mudstones are thinly laminated, lenticular, wavy-beded and ripple-laminated. Sandy dolomites and sandstones with dolomitic cement are structureless or planar-laminated with mud lenses</td>
<td>Siliciclastic mudstones grade upward into carbonate mudstones, sandy dolomites or sandstones with dolomitic cement within 0.2 to 2 m thick units; such units stack as 0.75 to 21 m thick successions</td>
<td>Anhydrite and gypsum rosettes, interlayers. Carbonates also contain cavities (3 mm deep)</td>
<td>Few brachiopod shell fragments</td>
<td>Vertically associated with subtidal shoals and channels (FA 1.5), and subtidal carbonates (FA 1.4)</td>
</tr>
<tr>
<td>Facies Association</td>
<td>Lithology</td>
<td>Sedimentary structures</td>
<td>Depositional units</td>
<td>Evaporite features</td>
<td>Biogenic features</td>
<td>Occurrence</td>
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<tr>
<td>1.4. Subtidal carbonates</td>
<td>Carbonate (dolomite, dolomitic marl) and siliciclastic mudstones and siltstones with occasional sub-rounded carbonate mudstone clasts (up to 6 cm in diameter)</td>
<td>Carbonate mudstones are massive, and locally nodular and wavy-bedded. Siliciclastic mudstones are homogeneous or current ripple-laminated. In places rolling grain ripples occur</td>
<td>Siliciclastic mudstones grade upward into carbonate mudstones within 0.2 to 0.9 m thick units</td>
<td>Carbonates also contain cavities (4 mm deep). In places anhydrite and gypsum rosettes, interlayers occur</td>
<td>Vertical, simple trace fossils; fish scales, and brachiopod shell fragments</td>
<td>Subtidal carbonates are spatially and volumetrically the most common deposits; they occur in the central parts of the basin</td>
</tr>
<tr>
<td>1.5. Subtidal shoals and channels</td>
<td>Sandstones with dolomite cement and sandy dolomites with thin layers, lenses or aggregations of sub-rounded and rounded quartz grains (up to 6 mm in diameter) Siliciclastic mudstones, siltstones and carbonate mudstones (dolomite, dolomitic marl)</td>
<td>Sandy dolomites and sandstones with dolomitic cement are structureless or planar-laminated with mud lenses. Siliciclastic mudstones and siltstones are homogeneous or planar-laminated. Carbonate mudstones are massive and in places nodular or wavy-bedded</td>
<td>In places sandstones and sandy dolomites grade upward into the carbonate or siliciclastic mudstones in fining-up units, 0.4 to 1.9 m thick. In other places siliciclastic or carbonate mudstones grade upward into sandstones or sandy dolomites in coarsening-up units, 0.5 to 1.1 m thick. Form successions 0.8 to 6.9 m thick</td>
<td>Anhydrite, gypsum rosettes and interlayers</td>
<td></td>
<td>Vertically associated with subtidal carbonates (FA 1.4) and intertidal to supratidal shoal deposits (FA 1.3)</td>
</tr>
</tbody>
</table>
Table 2. Summary of mixed facies associations.

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Lithology</th>
<th>Sedimentary structures</th>
<th>Depositional units</th>
<th>Evaporite features</th>
<th>Biogenic features</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Evaporite mudflat/siliciclastic sabkha</td>
<td>Siliciclastic mudstones and siltstones with occasional sub-angular to sub-rounded siliciclastic mudstone clasts (up to 3 cm in diameter), carbonate mudstones (dolomitic marl)</td>
<td>Siliciclastic mudstones and siltstones are homogeneous, planar-laminated, crinkle, lenticular, wavy-bedded or locally brecciated, and contain up to fine-grained sandstone interlayers and interbeds. Carbonates are structureless, or wavy-bedded</td>
<td>Siliciclastic mudstones and siltstones occur as 0.1 to 0.8 m thick units with carbonate mudstone (0.05 to 0.25 m thick), and breccia (0.5 to 0.95 m thick) beds; form successions 15.5 to 52.3 m thick</td>
<td>Anhydrite, gypsum rosettes, interlayers. Halite crystals and pseudomorphs</td>
<td>Vertically associated with carbonate sabkha (FA 1.1) and subtidal carbonates (FA 1.4), laterally associated with subtidal carbonates (FA 1.4)</td>
<td></td>
</tr>
<tr>
<td>2.2. Supratidal flat</td>
<td>Siliciclastic mudstones and siltstones, carbonate mudstones (dolomitic marl)</td>
<td>Siliciclastic mudstones and siltstones are homogeneous, or planar and current ripple-laminated. Carbonate mudstones are planar-laminated, flaser, wavy-bedded or gradationally laminated. Locally homogeneous or current ripple-laminated sandstone layers and lenses, and desiccation cracks occur in deposits</td>
<td>Siliciclastic mudstones and siltstones (0.1 to 3.6 m thick) grade upward into carbonate mudstones (0.07 to 0.45 m thick); form successions 20.7 m thick</td>
<td>Anhydrite and gypsum rosettes, interlayers and vug fills</td>
<td>Laterally associated with subtidal carbonates (FA 1.4) and intertidal flat deposits (FA 2.3)</td>
<td></td>
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<tr>
<td>Facies Association</td>
<td>Lithology</td>
<td>Sedimentary structures</td>
<td>Depositional units</td>
<td>Evaporite features</td>
<td>Biogenic features</td>
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<tr>
<td>2.3. Intertidal flat</td>
<td>Siliciclastic mudstones and siltstones, carbonate mudstones (dolomitic marl)</td>
<td>Siliciclastic mudstones and siltstones are homogeneous, or current ripple-laminated. Carbonate mudstones are massive or flaser, wavy-bedded, with current ripple-laminated, locally bimodal (herring bone) sandstone interlayers and desiccation cracks</td>
<td>Siliciclastic mudstones and siltstones (0.1 to 2.8 m thick) grade upward into carbonate mudstones (0.07 to 0.3 m thick); form successions 2.1-2 m thick</td>
<td>Totally or partly bioturbated, with vertical, sub-vertical trace fossils; brachiopod shell fragments, locally fish scales</td>
<td>Laterally associated with subtidal carbonates (FA 1.4) and supratidal flat deposits (FA 2.2)</td>
<td></td>
</tr>
<tr>
<td>2.4. Flood-tidal delta</td>
<td>Very fine-grained sandstones, siltstones, siliciclastic mudstones, carbonate mudstones (dolomitic marl)</td>
<td>Sandstones and siltstones are thinly bedded, planar, current ripple-laminated or structureless, locally cross-stratified, with siliciclastic mudstone interlayers and clasts (3 to 8 mm in diameter). Carbonate mudstones are massive</td>
<td>Sandstones and siltstones (0.05 to 3.5 m thick) grade upward into carbonate mudstones (0.05 to 0.15 m thick)</td>
<td>Vertically associated with the tidal inlet deposits (FA 2.5)</td>
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<tr>
<td>2.5. Tidal inlet</td>
<td>Very fine to fine-grained sandstones, siltstones, siliciclastic mudstones, carbonate mudstones (dolomitic marl)</td>
<td>Sandstones are planar and current ripple-laminated, thinly bedded, locally cross-stratified with siliciclastic mudstone interlayers and lenses. In places mudstone clasts (up to 9 mm in diameter) occur on base of sandstones. Carbonate mudstones are massive</td>
<td>In places sandstones grade upward into siltstones and siliciclastic mudstones in up to 2.5 m thick upward-fining units. In other places, siliciclastic mudstones and siltstones are capped by sandstones in up to 5.3 m thick upward-coarsening units</td>
<td>Vertically associated with the flood-tidal delta deposits (FA 2.4)</td>
<td></td>
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<tr>
<td>2.6. Subtidal mudstones</td>
<td>Siliciclastic mudstones, carbonate mudstones (dolomitic marl)</td>
<td>Homogeneous siliciclastic mudstones with siltstone and sandstone interlayers. Carbonate mudstones are massive</td>
<td>Siliciclastic mudstones (0.05 to 3 m thick) grade upward into carbonate mudstones (0.05 to 0.33 m thick); form successions 3 to 13.3 m thick</td>
<td>Laterally and vertically associated with subtidal carbonates (FA 1.4)</td>
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</table>
Table 3. Summary of siliciclastic-rich facies associations.

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Lithology</th>
<th>Sedimentary structures</th>
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<tr>
<td>Siliciclastic-rich facies associations</td>
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</tr>
<tr>
<td>3.1. Deltaic deposits</td>
<td>Very fine to fine-grained sandstones, siltstones, siliciclastic mudstones, carbonate mudstones (dolomitic marl)</td>
<td>Sandstones are uni-directional and bi-directional, planar-laminated, ripple-laminated, planar and trough cross-stratified with single and double mica and mud drapes. In places convolute bedding and mud clasts (up to 5 cm in diameter) and cemented carbonate concretions occur. Siliciclastic mudstones and siltstones are planar and ripple-laminated or homogeneous. Carbonates are massive, locally brecciated</td>
<td>In places sandstones (0.15 to 2.5 m thick) grade upward into siltstones, siliciclastic and carbonate mudstones (0.06 to 2.0 m thick), in upward-fining units, 0.9 to 2.8 m thick. In other places siltstones and siliciclastic mudstones (0.35 to 2.0 m thick) grade upward into sandstones (1.2 to 3.65 m thick) in upward-coarsening units, 1.5 to 5.6 m thick. Form successions 6 to 45 m thick</td>
<td>Root traces, brachiopod shell fragments</td>
<td>Deltaic deposits downlap carbonate-rich and mixed facies associations</td>
<td></td>
</tr>
<tr>
<td>3.2. Prodelta mudstones</td>
<td>Siliciclastic mudstones and siltstones, very fine to fine-grained sandstones, carbonate mudstones (dolomitic marl)</td>
<td>Siliciclastic mudstones and siltstones are homogeneous, or planar and ripple-laminated with sandstone grain interlayers. Structureless or planar-laminated sandstones are less common. Carbonates are massive</td>
<td>Siliciclastic mudstone units (0.2 to 4.6 m thick) are interbedded with sandstone layers (0.05 to 0.65 m thick) and carbonate mudstone layers (0.05 to 0.35 m thick); form successions 8 to 44 m thick</td>
<td>Brachiopod shell fragments</td>
<td>Vertically and laterally associated with the deltaic deposits (FA 3-1)</td>
<td></td>
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</tbody>
</table>
**FA 1.4: Subtidal carbonates**

Facies Association 1.4 is found all over the basin (Fig. 3). The dominantly homogeneous, siliciclastic mudstones grade upwards into massive carbonate mudstones (Fig. 4A; Table 1). Locally bioturbated deposits with brachiopod shell fragments and fish scales, the lack of desiccation cracks, fenestrae and high structural variability makes this FA different from the intertidal to supratidal deposits (FA 1.2), described above. Therefore, this FA is interpreted as shallow subtidal deposits (Elrick, 1995; Osleger & Montañez, 1996; Jiang et al., 2003).

**FA 1.5: Subtidal shoals and channels**

Facies Association 1.5 occurs in the central and southern part of the basin (Fig. 3) and consists of interbedded sandstones with dolomitic cement, sandy dolomites, siliciclastic and carbonate mudstones (Fig. 4; Table 1). The coarser-grained deposits and the common occurrence of gravel-sized quartz grains compared with the above described FAs and the vertical continuation into intertidal to supratidal shoal deposits (FA 1.3; Figs 3 and 4) suggest deposition in a high-energy, subtidal shoal environment (Gonzalez & Eberli, 1997; Rankey et al., 2006).

**Mixed facies associations**

**FA 2.1: Evaporitic mudflat/siliciclastic sabkha**

Facies Association 2.1 is found only in the western part of the basin (Fig. 3). The lenticular and wavy-bedding and dominance of siliciclastic mudstones and siltstones (Fig. 5; Table 2) suggest deposition in the tidally influenced upper intertidal or lower supratidal area (Dalrymple, 1992; James & Kendall, 1992). The crinkle-bedding and brecciated deposits, together with the silicified crusts and evaporite fabrics (Fig. 5A to C), indicate deposition in the evaporitic mudflat/siliciclastic sabkha (Kendall, 1992; Schreiber & El Tabakh, 2000).

**FA 2.2: Supratidal flat deposits**

Facies Association 2.2 has been identified in the central part of the basin (Fig. 3). The planar-laminated and current ripple-laminated siliciclastics, together with flaser, wavy-bedded carbonates, gradational lamination and evaporite fabrics (Fig. 5D; Table 2), indicates deposition on arid, upper intertidal to supratidal flats (Warren & Kendall, 1985; Nio & Yang, 1991; Alsharhan & Kendall, 2003).

**FA 2.3: Intertidal flat deposits**

Facies Association 2.3 is identified in the north-eastern part of the basin (Fig. 3). The combination of siliciclastic mudstones, locally extensive bioturbation, wavy or flaser-bedding and bi-directional cross-lamination (Fig. 5E; Table 2) suggests deposition in a setting subjected to rapidly changing energy conditions, such as the intertidal flat (Dalrymple, 1992; Weimer et al., 1998).

**FA 2.4: Flood-tidal delta deposits**

Facies Association 2.4 occurs in the south-western part of the basin (Fig. 3). This FA consists dominantly of thinly bedded, planar, current ripple-laminated or structureless, very fine-grained sandstones and siltstones that grade upward into siliciclastic mudstones (Fig. 6A; Table 2). The relatively high sand content and the mixture of high-energy, sandy facies with siliciclastic mudstones suggest deposition in a tidal environment, where the sand deposition rates were high but episodic. The common occurrence of mudstone clasts and the mixture of laminated sandstones with mudstones suggest deposition in flood-tidal delta environment (see also Davis et al., 2003). The millimetre-scale sandstone units that grade up into mudstones may indicate deposition during waning storm events (Walker & Plint, 1992).

**FA 2.5: Tidal inlet deposits**

Facies Association 2.5 occurs in the south-western part of the basin (Fig. 3). FA 2.5 is similar to FA 2.4 (Fig. 6; Table 2). However, the occurrence of upward-fining and upward-coarsening bar and channel deposits, and the larger amount of coarser-grained sandy material suggests deposition in a tidal inlet.

**FA 2.6: Subtidal mudstones**

Facies Association 2.6 is found in the north-eastern and south-eastern part of the basin (Fig. 3). Predominance of homogeneous siliciclastic mudstones (Fig. 5; Table 2) indicates deposition in a low-energy environment. Such homogeneous sediments can indicate an extremely high degree of bioturbation (see Enos, 1998; Malpas et al., 2005). However, no tracks or burrows were found. The FA 2.6 is interpreted as subtidal mudstones formed between the higher-energy environments (Fig. 3; Pratt et al., 1992; Osleger & Montañez, 1996; Jiang et al., 2003).
Siliciclastic-rich facies associations

FA 3.1: Deltaic deposits
Facies Association 3.1 occurs across the whole basin (Fig. 3). The dominantly cross-laminated siltstones and sandstones, cross-stratified up to fine-grained sandstones and the occurrence of overturned ripples (Fig. 6B and C; Table 3) indicate high-energy conditions. The occurrence of bi-directional bedding, mica and mud drapes suggests deposition in a tidally influenced environment. The described sedimentary features, in agreement with the overall progradational nature of the siliciclastic succession (Fig. 3), suggest deposition in a tidally influenced deltaic environment (Willis, 2005; Pontén & Plink-Björklund, 2007).

FA 3.2: Prodelta mudstones
Facies Association 3.2 occurs in the central and southern part of the basin (Fig. 3). This FA consists dominantly of homogeneous, planar and ripple-laminated, siliciclastic mudstones and siltstones (Fig. 6D; Table 3) and is similar to the subtidal mudstones (FA 2.6). However, the occurrence of planar-laminated mudstones and siltstones with relatively coarse-grained interlayers, together with the vertical association with FA 3.1 suggests deposition in a prodelta environment (Fig. 3).

BASIN EVOLUTION

Palaeogeography
The Baltic Basin during the Middle Devonian Narva time was a shallow sea in the western part of the East European Platform. It was periodically connected with seas to the west, east and possibly also to the south towards the margin of the EEP (Kuršs, 1992; Nikishin et al., 1996).

The Narva time marks an abrupt change in the development of the BB, as well as in most areas across the EEP, from siliciclastic (sandstone) dominated sedimentation to the mixed carbonate-rich deposition (Nikishin et al., 1996). In previous studies, the carbonate-rich deposits in the BB during Narva time were interpreted to have accumulated either in a lagoonal environment (Paškevičius, 1997) or in shallow marine, tidally influenced environments (Kleesment, 1997; Plink-Björklund & Björklund, 1999; Narbutas, 2005).

These palaeogeographic reconstructions (Fig. 7, T1 to T15) indicate a north-east to south-west oriented basin, with shallow (up to intertidal) water at the basin margins and gradually deeper (subtidal) water towards the middle of the basin. The lateral and vertical distribution of FAs suggests that the basin was open to the south-west during the early stages of the retrogradation, whereas the northern and eastern parts of the basin were subaerially exposed (Fig. 7, T1). This initial BB was dominated by deposition on carbonate sabkha (FA 1.1) and intertidal to supratidal carbonate tidal flats (FA 1.2; Fig. 7, T1). Carbonate sabkha (FA 1.1) and intertidal to supratidal carbonate tidal flats (FA 1.2) flanked the basin margins during an initial transgression, and subtidal carbonates (FA 1.4) occurred in the middle part of the basin (Fig. 7, T1 to T4). In the south-west, flood-tidal deltas (FA 2.4) occurred (Fig. 3B and C, Nida (15); Fig. 7, T2 to T4), suggesting a rather restricted connection to the ocean, and deposition in protected lagoonal environments. The flood-tidal deltas were the main input of siliciclastic sandy material into the basin at that time. During the continued transgression, the basin gradually expanded to the north, east and south. In the western part of the basin, carbonate sabkha deposits (FA 1.1) covered a shallow north–south oriented area [Fig. 3B and C, Dobele (13) and Nida (15); Fig. 7, T4 to T7]. The main siliciclastic input remained through the flood-tidal delta and tidal inlet complex [FA 2.4 and 2.5; Fig. 3B and C, Vidukle (10) and Nida (15); Fig. 7, T2 to T13]. Basinward from the tidal delta and inlet deposits intertidal to supratidal shoal (FA 1.3), and subtidal shoal and channel

Fig. 4. Representative photographs and measured sections of the carbonate-rich facies associations. (A) Representative depositional units for carbonate-rich facies associations; the planar-laminated, homogeneous siliciclastic mudstones grade upward into massive carbonate mudstones (subtidal carbonates, FA 1.4). (B) Broken-up carbonate beds with gypsum nodules and interlayers (carbonate sabkha, FA 1.1). Note fenestrae and desiccation cracks in carbonate clasts. (C) Crinkle-laminated, thinly bedded carbonates (carbonate breccia, FA 1.1). (D) Wavy-bedded carbonate mudstone (intertidal to supratidal carbonate tidal flat, FA 1.2). (E) Bi-directional and ripple-laminated sandstone lenses in carbonates (intertidal to supratidal shoals, FA 1.3). 'C' tidal flat – intertidal to supratidal carbonate tidal flats, ‘S and C’ – subtidal shoals and channels, ‘S’ – intertidal to supratidal shoals. The legend for core-sections is given in Fig. 6.
Input of siliciclastic sediment

The presence of fine siliciclastic material in mixed FAs (FAs 2.1 to 2.6; Table 2) and also in the carbonate-rich FAs (FAs 1.1 to 1.5; Table 1) indicates variable, but relatively continuous, influx of terrigenous material throughout the retrogradation. The siliciclastic mudstone composes the basal parts of the small-scale depositional units. The silty and sandy material occurs as interlayers and lenses in both siliciclastic and carbonate mudstones (Tables 1 and 2).

Fluctuations of carbonate-dominated to siliciclastic-dominated deposits could be caused by climate changes from arid to humid. However, correlative successions elsewhere suggest the arid, semi-arid climate during Narva time (Marshall et al., 2007); this is also supported by the occurrence of evaporite-rich deposits in the BB and the neighbouring areas (Kuršs, 1992; Alekseev et al., 1996). The evaporite fabrics are found mainly in the southern and central part of the basin as anhydrite and gypsum rosettes, interlayers, vug fills, and halite crystals and pseudomorphs throughout the retrogradational part. The amount and frequency of the evaporites decreases rapidly in the upper portion of the retrogradational section. This upward decrease in evaporite features in the Narva succession is probably related to the increasing river and freshwater influence, supplied from the northern part of the basin.

The distinct differences in FAs and their distribution in the basin suggest that two siliciclastic sediment delivery systems existed during Narva time. During retrogradation, the silt-rich and sand-rich deposits occurred mainly in the southern part of the basin, and muddy deposits in the central and northern part of the basin (Figs 3 and 7). The coarse siliciclastic input at that time was supplied by tidal currents and perhaps also by storm waves through the tidal inlet and tidal delta complexes in the south-west (Fig. 7, T1 to T13). This effect is indicated by the occurrence of silt and sand in tidal delta and tidal inlet complexes (FA 2.4 and 2.5), as well as in the intertidal to supratidal shoal (FA 1.3) and subtidal shoal and channel deposits (FA 1.5). During
Fig. 6. Representative photographs and measured sections of the mixed facies associations and siliciclastic-rich facies associations. (A) Siliciclastic mudstone clasts (flood-tidal delta, FA 2.4). (B) Ripple laminated sandstones with mica drapes (Deltaic deposits, FA 3.1). (C) Convolute bedding in sandstones (deltaic deposits, FA 3.1). (D) Siliciclastic mudstone with sand grain interlayers (prodelta mudstones, FA 3.2).
Fig. 7. Palaeogeographical reconstructions, to illustrate the evolution of the Middle Devonian Eifelian Baltic Basin. The reconstructions indicate shallow, tide-influenced basin expansion from south-west to north-east, and the carbonate-dominated transgressive infill (T1 to T13) that was followed by coarse-siliciclastic-dominated progradational infill (T14 to T15). Black circles mark cores; stars mark outcrops; grey circles mark cores described in literature; the time slices locations are shown in Fig. 3.
later stages of the retrogradation, the amount of siliciclastic material increased in the northern and central parts of the basin (Fig. 7, T8 to T13). This increase is indicated by the appearance of intertidal to supratidal shoals (FA 1.3) and siliciclastic-rich tidal flat deposits (FAs 2.1 to 2.3) in the northern part of the basin during the second part of retrogradation and the subtidal deposits (FA 2.6) at the end of retrogradation (Figs 3 and 7).

During progradation, the coarse siliciclastics were derived fluvially from the north/north-west, and gradually transported south-eastward, as seen by the south-eastward progradation of the deltaic system (Figs 3 and 7, T14 and T15). Replacement of carbonate-rich deposits by mixed deposition in the northern part of the BB during the later stages of retrogradation suggest initial freshwater input into the basin from the north/north-west, later followed by deltaic deposition during the progradation (Figs 3A and 7).

Controls on deposition
The retrogradational part of the basin infill is coeval with the overall transgressive trend in the EEP (Riding, 1984) and correlates with the Choteč Event in Middle Devonian episodes of marine dysoxia/anoxia with associated extinctions (House, 2002). However, the rapid progradation during the end of the Narva time does not correlate with any globally recognized sea-level fluctuations. It corresponds to a time of well-defined world-wide sea-level rise, named the Kačak Event, that marks a significant environmental change, which was identified close to the Eifelian–Givetian boundary (House, 2002; Buggisch & Joachimski, 2006; Marshall et al., 2007). The turnaround in the BB from retrogradational carbonate-dominated to progradational siliciclastic-dominated infill suggests that the progradation occurred due to changes in tectonic or climate regime in the hinterland that caused the increase in siliciclastic input rates which exceeded the rates of relative sea-level rise. During the final part of the retrogradational stage and the following progradation, the BB was connected with other basins further to the west and east, as indicated by the distribution of the deposits of the same age and similar lithology in the adjacent areas (Nikishin et al., 1996; Bjerkeus, 1999; Valiukevičius & Kruchek, 2000).

Implications for regional tectonic setting
The cross-section and the palaeogeographic reconstructions of the Narva deposits indicate saskha and supratidal to shallow intertidal FAs on both the northern and the southern basin margin throughout the retrogressive phase (Fig. 7, T1 to T13). However, the convergence of the time slices (depositional unit boundaries) in the north indicates no subsidence or even episodic uplift in the northern part of the basin, whereas on the southern margin, these shallow facies stack vertically onto a 70 to 90 m thick succession (Fig. 3A). The total thickness of the retrogressive part of the Narva succession in the northern part of the basin is ca 30 m (Fig. 3A). This difference suggests higher subsidence rates on the southern basin margin compared with the northern margin. The T9 time slice (Fig. 7) indicates a significant change in the subsidence pattern, as the upper part of the retrogressive phase appears to have uniform subsidence across the whole basin.

The turnaround from retrogradation to progradation during the Narva time additionally marks a significant change in the compositional and textural properties of the siliciclastic input into the BB (Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004). The Emsian (latest Early Devonian) and earliest Eifelian (earliest Middle Devonian) coarse siliciclastic succession, underlying the Narva succession, is characterized by poor sorting, a high proportion of angular or sub-angular grains, as well as a relatively high content of weakly resistant minerals, like feldspars and micas (quartz content roughly 75% to 85%; Kuršs, 1992; Kleesment, 1997). In comparison, the coarse siliciclastic succession from upper Narva (Eifelian) to Givetian deposits is texturally and compositionally mature (consists of up to 99-9% of quartz). Moreover, the textural and compositional maturity increases upward from the upper Narva to Gauja successions. Plink-Björklund & Björklund (1999) and Plink-Björklund et al. (2004) suggested that the compositional and textural maturity changes in the BB were caused by reorganization of hinterland in the Scandinavian Caledonides. These authors suggested that the Emsian and early Eifelian deposition occurred in a back-bulge depocentre to the Scandinavian Caledonian foreland basin and that the coarse siliciclastic material was derived from the erosion of the forebulge or the adjacent Precambrian terranes (Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004). In contrast, the upper Eifelian and Givetian deposits are interpreted to be cannibalized mainly from the Scandinavian foreland basin (Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004). The end of the Eifelian coincides with the main
phase of orogenic collapse and uplift in the Scandinavian Caledonides (see Roberts, 2003) that reduced loading on the foreland, and the foreland basin was uplifted. As a result, the forebulge ceased and the sediment supply into the BB was opened from the uplifted foreland basin to the north-west and west (Plink-Björklund & Björklund, 1999; Plink-Björklund et al., 2004).

The present study confirms the above interpretation and suggests that the forebulge may have migrated to the north-western margin of the BB during the earliest Eifelian, as indicated by the lack of subsidence and probable uplift in the northern/north-western margin during T1 to T9 (Fig. 7). It is suggested that the forebulge migration ceased and the forebulge started subsiding at the transition from T9 to T10 (Fig. 7). In agreement with the latter, the siliciclastic mud input into the northern and western part of the basin increases from T8 to T13 (Fig. 7).

### Mixed Carbonate-Siliciclastic Deposition

#### Style of carbonate–siliciclastic mixing in the Baltic Basin

Based on lithological characteristics, two types of mixed carbonate–siliciclastic deposits are distinguished in the BB: (i) mixtures due to the temporal evolution in sedimentation, induced by sea-level changes and/or variations in sediment supply, causing a vertical variation in the stratigraphic succession; and (ii) mixtures due to spatial facies mixing/variability (Goldhammer, 2003). The reciprocal model is commonly used to explain temporal facies mixing due to the changes in relative sea-level. The siliciclastics are interpreted to have invaded the basin during the relative sea-level lowstands, whereas carbonate sedimentation dominated during the highstands (Tucker, 1991; Garzanti, 1999; Bauer et al., 2003). The spatial facies mixing occurs by lateral facies mixing in coeval depositional environments. The spatial mixed-lithology units are developed mostly where carbonate platforms are attached to terrigenous source areas, or where there is an axial supply of clastic material to the basin as, for example, in the north-western Red Sea during its quaternary development (Purser et al., 1987), the Upper Cretaceous basin in Spain (Martin-Chivelet, 1995) and the late Viséan (Mississippian) sedimentary basin in South-western Spain (Cózar et al., 2006).

In the Narva succession, the mixing occurs on different temporal and spatial scales. On a small scale (1 to 10 cm), the mixing occurs within individual depositional units where siliciclastic (mudstone, siltstone, sandstone) deposits grade upward into carbonate (dolomite, dolomitic marl) deposits (see core sections in Fig. 4). The siliciclastic–carbonate ratio is environment-specific and the thickest carbonate-rich parts occur in the carbonate-rich FAs (FAs 1.1 to 1.5) and the thinnest parts occur in the siliciclastic-rich FAs (FAs 3.1 and 3.2). These siliciclastic to carbonate depositional units are interpreted to reflect retrogressive depositional units, where the siliciclastic-rich mudstones accumulated higher up on the tidal flats compared with the carbonate-rich mudstones.

On a larger scale (10 to 50 m), the mixing occurs as the retrogradational carbonate-rich succession changes upward into a progradational siliciclastic-rich succession (Fig. 3). However, this change is interpreted as a dramatic increase in siliciclastic sediment supply into the basin, rather than caused by a relative sea-level fluctuation.

The small-scale mixing of carbonates and siliciclastics occurs in two different ways: (i) relatively coarse siliciclastic material (sand to gravel size) occurs as interlayers or distinct beds within carbonate mudstone sequences (Figs 4 and 5); and (ii) lateral transition of mainly muddy, siliciclastic-rich FAs into carbonate-rich FAs. These types of mixing are also known as punctuated and facies mixing (after Mount, 1984). The punctuated mixing occurs in the tidal flat and shoal FAs (FAs 1.2, 1.3, 1.5, 2.2 and 2.3), where the siliciclastic material is carried into the carbonate units by tidal currents or episodic storm wave action. The amount of siliciclastic material carried to the carbonate deposition system is variable. The relative importance of siliciclastic material is highest in areas adjacent to the siliciclastic inflow, as in the south-western part of the basin during early stages of retrogradation (Fig. 7, T3 to T9), and mainly in the northern part of the basin during later stages of retrogradation (Fig. 7, T9 to T11). The facies mixing, however, occurs across the whole basin as the lateral transition from the marginal mixed FAs (FAs 2.1 to 2.6) into the carbonate-rich (FAs 1.1 to 1.5) basin (Figs 3 and 7).

#### Analogues

The best Holocene analogue for the depositional environments in the Narva succession occurs on
the coast of the United Arab Emirates, where the interbedded carbonate–evaporite units are formed in lagoon, tidal flat and sabkha settings (Alsharhan & Kendall, 2003). However, these deposits are formed mainly of carbonate mudstones and sandstones with evaporite fabrics, the opposite situation to that seen in the Narva succession where the mixed carbonate–siliciclastic depositional units occur (Tables 1 and 2). Therefore, this does not explain the coeval mixed carbonate–siliciclastic deposition in the Middle Devonian BB. Different scales of mixing also occur in the Upper Permian Delaware and Midland basins in Texas and New Mexico (Barnaby & Ward, 2007). However, these deposits are composed mostly of skeletal grainstones, abraded molluscs, corals, etc., and pelleted carbonate and oolitic sands, and mudstones are found in the lower energy environments as lagoons and tidal flats. In the BB, however, the siliciclastic and carbonate mudstones dominate (Tables 1 and 2) and the coarse-grained deposits occur only in shoals (FA 1.3 and 1.5) and tidal inlet-delta system (FA 2.4 and 2.5), in the restricted areas close to the siliciclastic inflow (Figs 3 and 7).

Muddy depositional environment analogues to the BB occur in the Upper Permian Zechstein basin in North-east England and adjoining North Sea, where nodular, thin-bedded and laminated carbonate and mudstone deposits with evaporite interbeds were deposited in nearshore areas (Tucker, 1991). However, this is not an analogue for the whole depositional system in the BB. No extensive beds of evaporites occur in the Narva succession and the proportion of evaporates decreases northward in the basin and upward through the succession. Extensively muddy deposits occur in the Mississippian Appalachian basin in West Virginia (Wynn & Read, 2008). These muddy deposits accumulated during a highstand in restricted lagoonal conditions. Lack of open marine fossils and periodically hypersaline settings are similar to the BB. In the Mississippian succession, the periodically increased inflow of fine-grained siliciclastic material has been interpreted to be controlled by changes in climate from semi-arid to humid (Wynn & Read, 2008). However, the occurrence of evaporite fabrics throughout the regressive phase of the Narva succession and the suggested arid or semi-arid climate for the whole duration of deposition from adjacent areas (Marshall et al., 2007) do not explain the increase of siliciclastic material into the BB, as caused by climate changes.

Therefore, it is suggested that the input of siliciclastic material during coeval deposition of mixed carbonate and siliciclastic deposits in the BB was controlled by the hinterland tectonics in the Scandinavian Caledonides. The occurrence of siliciclastic material in small-scale depositional units, and the lateral and vertical facies variations indicate relatively continuous fine siliciclastic input through the retrogradational phase. Towards the later stages of retrogradation, the fine siliciclastic input increased from the north/north-west and, finally, the input of coarse siliciclastic material exceeded the rate of carbonate production and the siliciclastic-dominated deposition occurred in the whole basin.

CONCLUSIONS

The detailed and systematic study of the cores and outcrops allowed a three-dimensional reconstruction of the shallow, tide-influenced Middle Devonian Narva Basin in the Baltic. The vertical and lateral facies transitions and the palaeogeographic reconstructions show an early, carbonate-dominated mixed transgressive infill and a later, coarse-siliciclastic-dominated progradational infill of the basin. The transgressive fill consists of marginal carbonate and siliciclastic sabkhas and supratidal to intertidal flats, with subtidal carbonate muds in the deeper parts of the basin. A tidal inlet-flood-tidal delta system occurred in the south-western part of the basin and provided a connection with an open ocean for the restricted basin. The coarser siliciclastic input was provided through the tidal inlet and, towards the later stages of retrogradation, the fine siliciclastic input increased from the north/north-west. The progradational part consists of siliciclastic tide-influenced prodelta and deltaic deposits that prograded south-eastward across the basin. This work shows that coeval siliciclastic and carbonate deposition in the Baltic Basin (BB) occurred at different temporal and spatial scales. The mixing was controlled by tectonic movement in the hinterland and the location of siliciclastic input rather than relative sea-level changes. Based on detailed facies associations analysis, it is suggested that the BB experienced differential subsidence, in the form of southward tilting during the early transgressive phase, interpreted as forebulge migration into the western margin of the basin. The even subsidence across the basin during the later stages of the transgression and the input of coarse-grained, mature siliciclastics during the
progradational phase suggest forebulge subsidence and input of sediment from the Scandinavian foreland basin. The forebulge subsidence is interpreted to be related to the documented orogenic collapse and uplift of the Scandinavian Caledonian foreland basin.

ACKNOWLEDGEMENTS

This work was financed by grant 2090/2002 from the Swedish Institute, by grant 2003-3391 from the Swedish Research Council, and by grant scheme from the IAS. This paper has benefited greatly from the critical reviews and valuable comments made by anonymous reviewers, Prof Peter Swart and Dr John Anderson. We thank Anne Kleesment, Girts Stinkulis, Kristine Tovmasjana and the Lithuanian Geological Survey, the Institute of Geology and Geography of Lithuania and the Museum of Geology of Lithuania who provided help concerning the regional geology and core data.

REFERENCES


Manuscript received 1 November 2007; revision accepted 8 October 2008.