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Middle Devonian Narva deposits in the Baltic Basin: sedimentary environments and sequence stratigraphy

MSc thesis

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Content

Abstract

The sediments deposited during the Narva time are widely distributed in East-European Platform and particularly in Baltics. These deposits belong to the Narva Regional Stage (RS) and are composed of two lithologically different units: carbonate and siliciclastic sediment. The carbonate sediments are characterized by mixed carbonate-siliciclastic lithology. The siliciclastic deposits are composed of silty and fine-grained sandstone. In the Baltic Devonian Basin from investigated cross-sections 14 facies, 7 subfacies were separated and 11 facies associations were distinguished in Narva RS. Based on the lateral and vertical trends the facies association successions are defined. The analysis of successions and facies association suggests at least three sedimentary sequences within the basin. The relatively thin successions in the first sequence indicate the sea-level dependence of the deposition. The relatively thick succession in the second sequence, particularly in the middle and the southern part of the basin indicate the influence of the additional accommodation space given by subsidence.

The beginning of the sedimentation in the Narva time is marked with the carbonate deposition, which compromises the first sequence. During the second sequence the influx of silty and sandy material to the basin increased. At the end of sequence the basin was significantly affected by siliciclastic sedimentation. The third sequence indicates the turnaround from transgressive basin to the regressive basin, where the deltaic environments prevailed.

The siliciclastic sediments were transported into the basin by rivers and wind. The relatively coarse, up to gravel size grains indicate the river input. The fine-grained sediments mixed with carbonates in peritidal deposits indicate the aeolian transport. Most probably the terrigenous sediments were most probably derived from two emerged land areas - the Caledonian folded thrust belt in the north and the Voronez-Mazurian anticline in the south.

1. Introduction

The Narva deposits, which accumulated during the Narva time are widespread almost in all Baltic (Fig. 1) and in the neighborhood areas (Narbutas, 1964; Valiukevičius, 1986; Kleesment *et al*., 1987; Valiukevičius & Kruchek, 2000). These sediments were first described by Karl Orviku in 1930 (Orviku, 1930). From this time the lithology and sedimentology of the Narva deposits is throughout studied by several authors (etc. Tamme, 1962; Viiding, 1962; Tamme, 1964; Kuršs, 1975; Kuršs, 1992; Kleesment & Mark-Kurik, 1997 among many others).

The sediments of the Narva RS were deposited during a wide transgression that occupied the whole East European Craton. This transgressive cycle is characterized dominantly by carbonate sedimentation (Nikishin *et al*., 1996). However, the transgressive part of the Narva RS is characterized with the carbonate deposits and the regressive part with the siliciclastic sediments.

The carbonate dominated part of the Narva RS is divided into two parts, (1) the siliciclastic mud-carbonate and (2) the siliciclastic mud-mixed carbonate siliciclastic shallowing-upward cycles.

The aims of this work are, (1) to describe the architecture and depositional environments in Narva RS, (2) to give an overview of the sequence stratigraphy in the Narva basin, and (3) to reconstruct the basin evolution on the basis of the facies association and the sequence startigraphy interpretation.

This work is based on the detailed investigations of the drill-cores, which are selected from the different areas of the Baltic basin (Fig. 1). Based on these data, the facies and facies associations were defined.

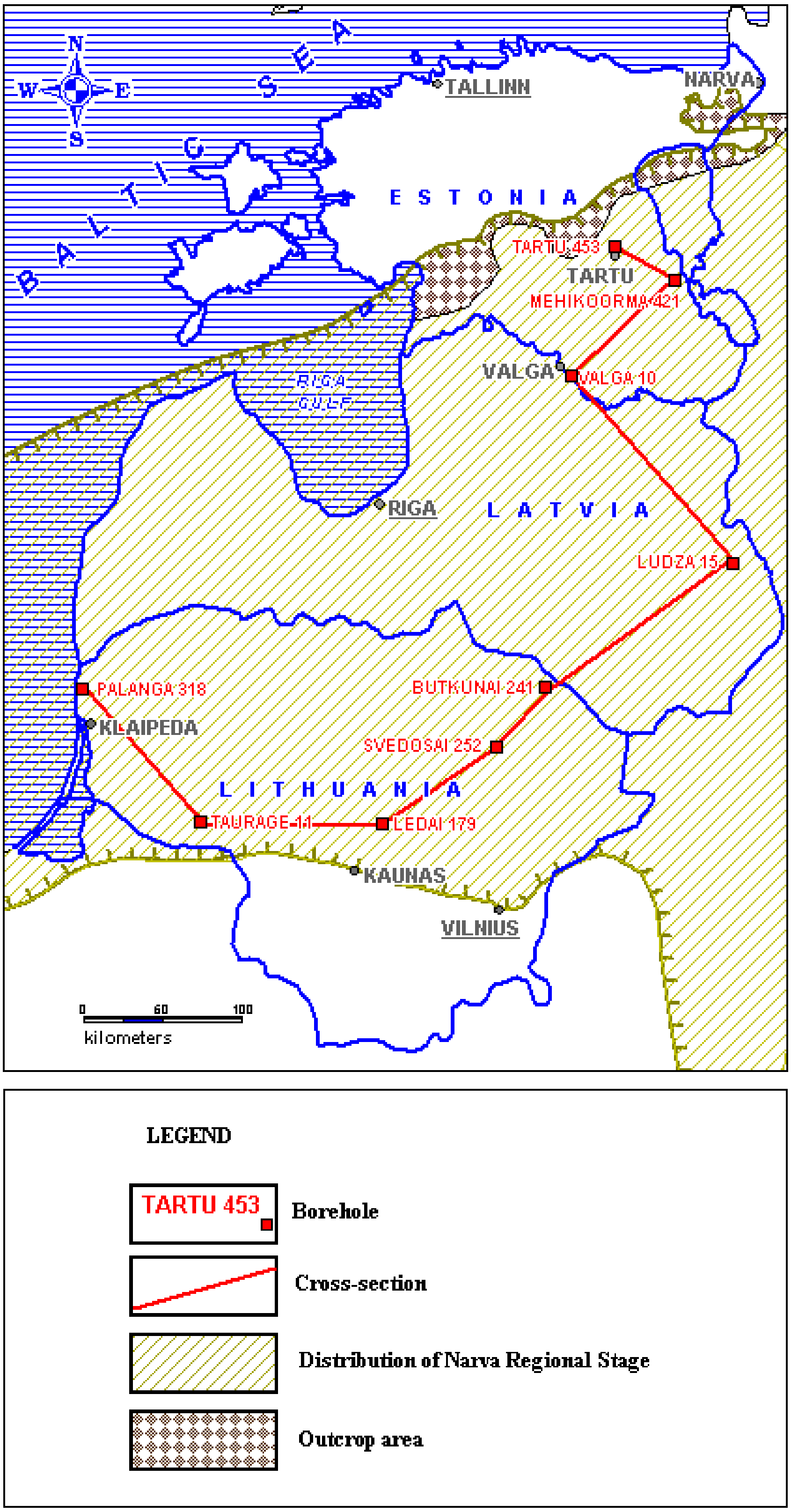

Figure 1. The distribution and the outcrop area of the Narva RS, with investigated boreholes and cross-section.

2. Sequence stratigraphy and depositional features of the mixed carbonate-clastic systems

2.1. Sequence stratigraphy

Sequence stratigraphy is the analysis of generally related depositional units within a cronostratigraphical framework, bounded by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner *et al*., 1988; Reading & Levell, 1996). The fundamental unit of sequence stratigraphy is sequence, which is bounded by unconformities and their correlative conformities (Van Wagoner *et al*., 1988).

A sequence is divided into system tracks, deposited during specific intervals of the relative sea-level curve (Hunt & Tucker, 1992). System tracks are named in their position relative to the sea level cycle, comprising (1) a highstand (HST – highstand system track), (2) a major sea level fall (FRST – forced regressive system track), (3) a lowstand (LST – lowstand system track) and (4) a sea level rise (TST – transgressive system track). Sea level change causes the unconformities that are called sequence boundaries (SB) and their correlative conformities. The maximum rise of sea-level marks the maximum flooding surface (mfs) in the basin (Reading & Levell, 1996) (See Fig. 2).

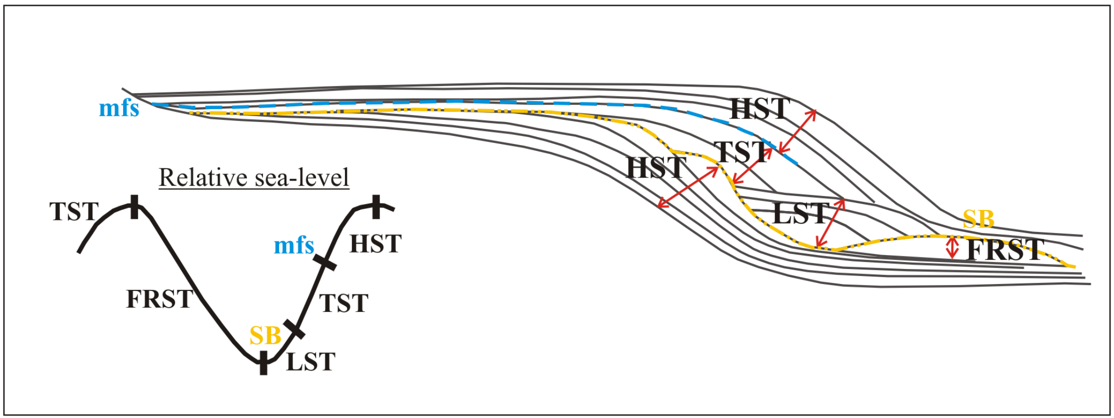

Figure 2. System tracks and their position in the basin and on the relative sea-level curve.

Sequence stratigraphical model for carbonates was developed later than for siliciclastic sediments and it is not so well defined (Reading & Levell, 1996). The main reason for that lays in the principal difference of the carbonate production, distribution and deposition from siliciclastic sediments. Those are (1) the carbonates production can be organic or inorganic, it may occur in shallow water in tropic or subtropical areas, (2) carbonate deposits (organic buildups) can build the wave resistant structures with steep slope, and (3) they undergo extensive diagenetic alternation and induration/cementation soon after the deposition, particularly where subaerally exposed (Reading & Levell, 1996). The carbonate deposition is strongly controlled by environmental variables that depend on latitude and climate. Specifically the absence of clastic input, salinity, temperature, nutrient supply, water depth and turbulence, sea-level change and tectonics, are the most important (Tucker, 2003).

Because the bulk of carbonate sediments production occur in the top of 100 m of the water column, with by far the highest production rates at depths of less than 20 m, carbonate production is very sensitive to the sea-level changes (Wright & Burchette, 1996). Because of that on most carbonate platforms the sediment production is the greatest during the HST. Relative sea-level fall, even for few meters, may expose the whole interior of flat-topped platform and shut down the deposition. The proximity to the siliciclastic source area often causes the deposition of mixed carbonate-siliciclastic systems, where the carbonate depositional systems dominate during the relative sea-level highstands and siliciclastic sedimentation dominates during the lowstand of relatively sea-level (Wright & Burchette, 1996).

2.2. Mixed sediments

Mixed carbonate siliciclastic sediments are deposited mostly in carbonate basin with remarkable siliciclastic input. There are many factors which determine the nature of a carbonate formation, two the most important are (1) geotectonics, and (2) climate, which together control the other important variable - sea-level. The geotectonic is of primary importance. It controls one of the prime requisites for carbonate sedimentation - the lack (or low) of siliciclastic material input by determining the hinterland topography and river drainage (Tucker, 1990). For example - a proximal clastic marine shelf with a linear source versus distal tectonically active, uplifted source terrain with a fluvial, point-source input (Goldhammer, 2003).

The climate also influences the supply of clastic sediments to a sedimentary basin. In a humid regime the mud-rich sediments prepared by intense chemical weathering (Tucker, 2003) and transported by fluvial-deltaic clastic input onto a carbonate shelf (Goldhammer, 2003) prevail. In arid climate sand/gravel-rich systems, suggests more physical type of weathering (Tucker, 2003) with aeolian influx domination (Goldhammer, 2003).

The sea-level affects the position of base-level, gradients and sediment supply to the shoreline. Falling sea-level leads to river entrenchment and down cutting, resulting in more clastic input to the basin; rising sea-level causes deposition in higher reaches of the fluvial systems and consequently, less sediments are reaching the basin (Tucker, 2003). The rates and magnitudes of relative sea-level changes will determine the amount and style of the mixing between carbonate and siliciclastic sediments (Goldhammer, 2003). There are many other factors, which affect mainly the carbonate sedimentation and cause the mixed sediments deposition. For example, the transport mode – episodic storm mixing versus lowstand-induced sediment by-pass of a carbonate shelf; structure of the shelf - carbonate ramp, distally-steepened carbonate ramp, reef rimmed high-relief platform, etc.; oceanographic factors, such as prevailing wind – and storm driven currents, tidal range etc. (Goldhammer, 2003).

Mixed sediments consist primarily of four components: (1) siliciclastic sand (2) siliciclastic mud (3) carbonate sand, and (4) carbonate mud (Mount, 1985).

There are two types of mixed deposits: (1) mixtures due to spatial variability, deposited at the same time, and (2) mixtures due to temporal evolution in sedimentation (Goldhammer, 2003).

In the first case, mixing occurs by lateral facies mixing of coeval sedimentary environments. In cross-sections these sediments are related with each-other. Mount (1984) divided those sediments into the four groups. This subdivision is basically same today.

(1) Punctuated mixing – sporadic storms and other extreme, high intensity periodic events that transfer sediment across contrasting environmental boundaries. For example erosion from peritidal carbonates or nearshore belt and tidal flat siliciclastics and deposition to the subtidal, carbonate or terrigeneous mud-dominated environments below fairweather wave base.

(2) Facies mixing – sediments are mixed along diffuse borders between contrasting facies. For example nearshore clastic belts and offshore carbonate reefs or oiid shoals or eolian sands mix with nearshore and tidal flat carbonates.

(3) In situ mixing – carbonate fraction consist of the autochthonous assemblages of calcareous organisms that accumulated on or within clastic substrates, for example foram-mollusc assemblages within subtidal clastic shelf.

(4) Source mixing – admixtures of carbonates into clastic-dominated settings are generated in response to uplift and erosion of proximal carbonate terrains. They occur in marginal or nearshore environments, which are proximal to exposed carbonate source terrain (Mount, 1984; Goldhammer, 2003).

The most widely is found the second type, where the mixing is caused by the temporal evolution of the sedimentation pattern. This is induced by sea-level changes and/or variations in sediment supply, causing a vertical variation in the stratigraphic successions. These mixed-litology cycles are developed where carbonate platforms are attached to terrigeneous source-areas or where there is an axial supply of clastic material to the basin. There are a two possibilities; (1) lower carbonate – upper sandstone cycles, or (2) lower mudrock – upper carbonate cycles (Tucker, 2003).

Mixing of sediments can occur to trough a wide scale ranges, from millimeters to kilometers. The mixing trend can vary from coastal environments to the deep basinal settings (Goldhammer, 2003).

3. Geology and Stratigrapy of the Narva Regional Stage

3.1 Tectonics and sedimentary background

Baltic Basin is a Late Proteorozoic - Phanerozoic polygenetic sedimentary basin, which is developed in the western part of the East European Platform in Baltica plate (Poprowa *et al*., 1999).

During Cambrian and Ordovician and up to the end of Silurian time the Baltica was a separate plate, which in a general manner drifted from high-to-moderate latitudes on the southern hemisphere in Ediacara-Cambrian time towards equator. The equatorial position of Baltica was reached for Silurian-Devonian time. Following the Early Cambrian opening of the Tornquist and Iapetus oceans and the breakup of the Rodina (super) continent, the Baltica began to converge during Middle and Late Cambrian times with Laurentia-Greenland plates to which it was finally sutured at the end of the Silurian along the Arctic-North Atlantic Caledonides (Nikishin *et al*., 1996). The tectonic activity, rifting, along the southern margin of Baltica continued till the early Carboniferous time intermittent back-arc rifting and compression governed the evolution of the Variscian ‘geosynclinal system’ (Nikishin *et al*., 1996).

Formation of the Caledonides has significantly influenced the Late Silurian and Devonian development of the Baltic basin. During the Ordovician and Early Silurian, the marginal areas of Baltica were characterized by the carbonate-dominated shelves (Nikishin *et al*., 1996). However, from the Late Silurian the flysch series, derived from the rising Caledonides, were deposited in a foreland basin along the Caledonian front (Nikishin *et al*., 1996), whereas the still carbonate-dominated marine Baltic basin gradually deceased in size to south-southwest. By the end of Caledonian orogen, from the end of Silurian to the Early Devonian period, episodic continental siliciclastic sedimentation in Baltic Basin area started (Kuršs, 1992; Kleesment & Mark-Kurik, 1997; Plink-Björklund & Björklund, 1999). The sediments deposited during the Caledonian or post Caledonian times are specially characterized by widely distributed reddish-yellowish-to-white sandstone lithologies. These sandstones, known as Old Red Sandstones, and similar rocks have been found in all continents (Hartz, 2000). The Old Red Sandstones (ORS) have been long considered as a stratigraphic response to major Paleozoic (Caledonian) mountain-building, and particularly as a late-or post-orocenic (molasse) magnafacies. The ORS are widely distributed on the lands bordering the North Atlantic Ocean ranges in age from Mid-Silurian to Carboniferous time. It provides the fill for many basins, which range in present day location from the Appalachians at 40° N, to Spitsbergen, at 80° N, a distance of some 4500 km (Friend *et al*., 2000).

Devonian Baltic Basin (DBB) forms the northwestern part of the Main Devonian Field, which occupies the most part of the northern and northwestern East-European platform (Kleesment, 1997). The main phase of the siliciclastic deposition within the DBB was from the Emsian time until the end of the Middle Devonian (Fig. 3). In Upper Devonian, carbonate and evaporite sedimentation prevailed (Kuršš, 1992; Kleesment, 1997).

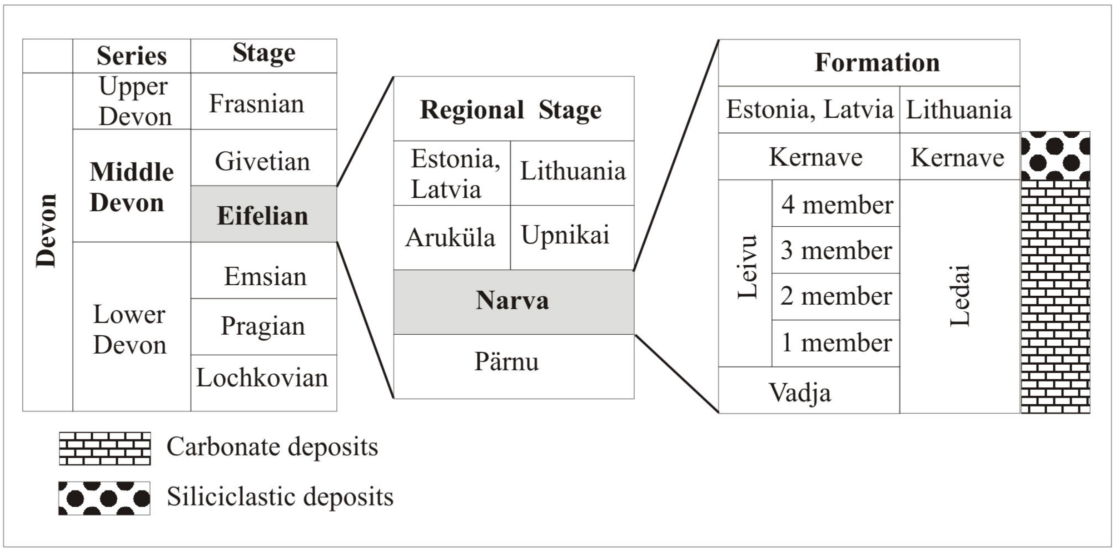

Figure 3. The generalized Devonian subdivision and studied stratigraphical interval with the mainly distributed deposits.

The siliciclastic deposition in the Middle Devonian occurred mostly in shallow water marine deltas, whereas the sediment supply/accumulation rates and sedimentation style varied considerably through time. The major change in the sedimentation style occurred in Narva time when DBB changed from the deposition of sandstones and clay conglomerates on the subaqueous delta plains in the Pärnu time, to the deposition of mudstones and domerites (siliciclastic-rich domerites) in shallow marine conditions (Plink-Björklund & Björklund, 1999). This event is well correlated with the units of neighboring areas in Belarus, in Central Devonian Field – on the eastern part of Moscow syneclise and in Timan - Pechora (Narbutas, 1964; Valiukevičius, 1986; Kleesment *et al*., 1987; Valiukevičius & Kruchek, 2000). The deposition of domerite and mudstone deposition contrast with all the other Middle Devonian periods that are characterized with the input of very fine-grained siliciclastic material. The sedimentation style in succeeding Aruküla and Gauja times was again clearly dominated by the progradiational and siliciclastic type (Plink-Björklund & Björklund, 1999).

3.2. Narva Regional Stage

Narva Regional Stage (RS) was stratigraphically defined by Karl Orviku in 1930, when the first cross-section of Narva RS was described (Orviku, 1930). First biostratigraphical work was made by W. Gross in 1933 (Gross, 1933). The name of the RS was given by Obrutšev in the same year as ´´narovskie sloji´´ (Obrutšev, 1933). The name for RS came from the place were the sediments were first described - in area around the Narva River (Orviku, 1948).

After definition of Narva RS, detailed and systematic investigations started. In 1942 Gross names the Narva beds as *Pterichtys concate*natus Unit. Already in 1956, the Narva unit was named as a separate Stage (D_2nr), which was in 1962 correlated to the Eifelian Stage. In 1970 the Narva RS (horizont) was correlated to the zone *´´Schizosteus striatus´´* of the Efelian Stage (Polivko, 1981).

Most of the earlier studies of the Narva RS have been focused in lithological-mineralogical and palaeontological studies (Tamme, 1962; Viiding, 1962; Tamme, 1964; Kleesment *et al*., 1980; Kleesment, 1998).

Narva RS is spread almost in whole DBB except north Estonia and south Lithuania (Fig. 1). Narva RS consist with two different litological units – carbonate and siliciclastic (see Fig. 3). The carbonate part forms the down and middle portion of Narva RS. It is the thickest part of Narva RS. The total thickness of carbonate sediments of Narva age reaches up to 136 m (Narbutas & Uginčius, 2001). Upper siliciclastic rich part is thinner, with the maximum thickness of 36 m (Narbutas & Uginčius, 2001). The maximum thickness for both – carbonate and siliciclastic parts is found in the Baltic Syneclise (Kuršs, 1975; Kuršs, 1992; Narbutas, 1994; Kleesment, 1997; Narbutas & Uginčius, 2001).

Thickness of the Narva sediments is variable and it increases from NE Estonia, where the sedimentary pile is about 30 m to maximum 184 m in SW Latvia (Kuršs, 1975; Kleesment *et al.,* 1981). The thickness increase from NE to S and SE is rapid and the average thickness of RS ~100 m is reached already in south Estonia and it stay's the same over large areas in DBB (Valiukevičius *et al*., 1981).

The Narva RS outcrop area in DBB is a 10-30 km wide belt that extends from Ruhnu Island in SW Estonia to Peipsi Lake and the separated area in NE Estonia near to the Narva River (Kleesment & Mark-Kurik, 1997) (Fig. 1). Sediments belong to the Narva RS are exposed mainly in NE Estonia, near to the Narva River and its distributaries Borovnja and Gorodenka Brooks. There are also some outcrops on the river brooks in the middle Estonia (Orviku 1948; Tamme, 1964; Kleesment & Mark-Kurik, 1997). Most of outcrops belongs to the upper part of Narva RS and represent its siliciclastic unit. However, the thickness of outcrops is up to 3 m and most of them are very badly preserved and affected by vegetation. The only outcrops of the carbonate unit are the Narva and Sirgala quarries, where the Narva sediments overlay in up to 25 m thickness the Ordovician organic rich shale (oil-shale) that is mined there (Fig.4).

In Estonian and Latvian part of the DBB the Narva RS is divided on the basis of paleontological, mineralogical and lithological characteristics into three formations - Vadja, Leivu and Kernave (Fig. 3) (Valiukevičius *et al*., 1986; Kleesment *et al*., 1987; Kleesment, 1995; Kleesment & Kurik, 1997). Leivu Formation is divided into mineralogical and litological criteria to the four members, which are marked with numbers (Fig. 3) (Valiukevičius *et al*., 1986; Kleesment & Mark-Kurik, 1997). In Lithuanian part of the basin only two formations are distinguished: Ledai and Kernavė (Fig. 3) (Narbutas, 1994; Paškevičius, 1997).

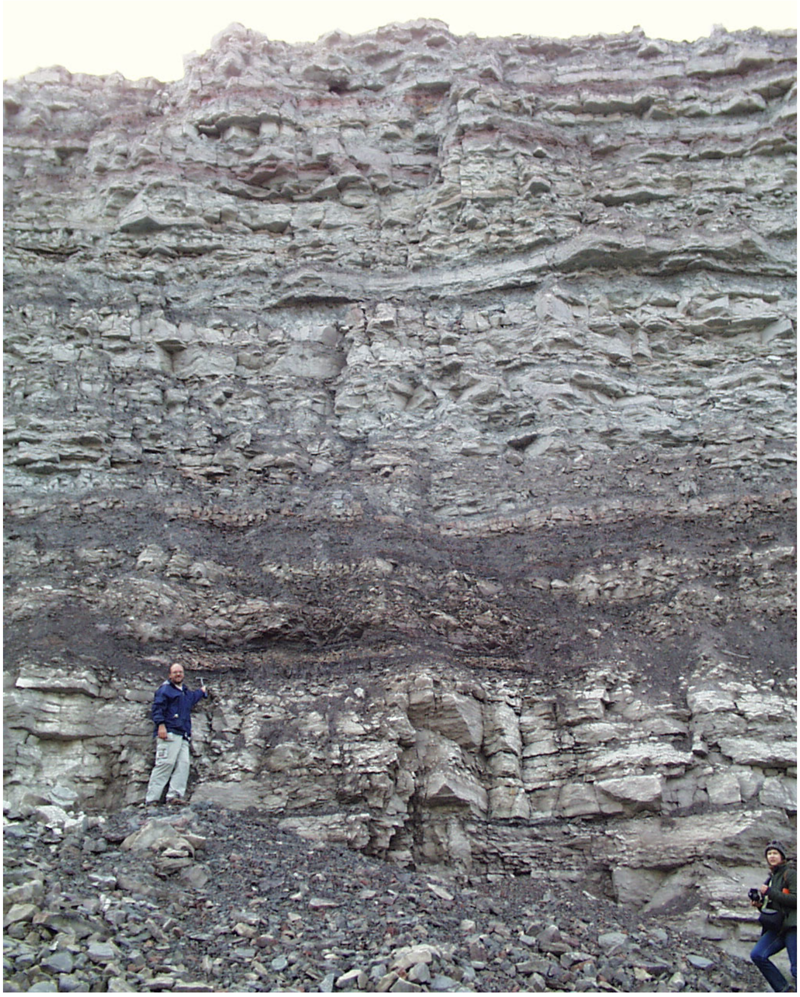

Figure 4. The carbonate deposits in Narva RS in Narva quarry in NE Estonia (pointed on the boundary separating Narva RS from blelow lying Ordovician deposits).

The Substages/Formations are correlated with acanthodians zones. Three following zones based on *Cheiracanthoides estonicus*, *Ptychodictyon rimosum* and *Nostolepis kernavensis*, are established within the Narva RS. Each of them is related to respective Formation of the Narva – Vadja, Leivu and Kernavė, respectively (Valiukevičius, 1998; Kleesment 1999; Valiukevičius & Kruchek, 2000).

The lower boundary of Narva RS, corresponding to the lower boundary of Vadja in Estonia and Latvia and Ledai in Lithuania. It is in places marked with carbonate breccia or dolomitic marl or dolomite. The breccia is 0.2-10 m thick and overlays the sandy dolomite or sandstone of the Pärnu RS (Kleesment, 1999). Breccia consist of dolomitic marl with unsorted irregular pebbles of dolomite, dolomitic marl, clay and siltstone are common. In some places breccia may form several layers.

Vadja Fotrmation is defined in Estonian-Latvian part of the basin. This Formation is characterized by a thin-bedded complex of dolomitic marl, dark-grey to black silty clay and pale yellowish-grey dolomite, which often includes crystalline dolomite, chalcedony, pyrite or sphalerite filled vugs (Kleesment *et al*., 1981; Valiukevičius *et al*., 1986; Kleesment *et al*., 1987; Kleesment, 1995; Kleesment & Mark-Kurik, 1997). In the western Latvia and in western Lithuania the formation contains interbeds of sandstones and admixture of sands (Kuršs, 1975; Kuršs, 1992).

Leivu Formation has a highest carbonate proportion in Estonia-Latvian part. The prevailing sediment type is dolomitic marl. The formation is divided into four members:

1. Member – contains remarkable amount of dispersed silty-sandy particles with a diameter up to 2 mm.

2. Member – grey thin-bedded complex of intercalacting dolomitic marl, dolomite and dolomitic clay.

3. Member – increased the amount of interlayers of grey silt- and sandstone.

4. Member – consist of reddish-brown, purplish-grey and grey mottled massive arcillaceous dolomitic marl (Valiukevičius *et al*., 1986; Kleesment *et al*., 1987; Kleesment, 1995; Kleesment & Mark-Kurik, 1997).

The lowermost bed of the Leivu Formation is commonly represented by grey dolomitic marl. It contains remarkable amount of silty-sandy particles with diameter up to 1-3 mm. In western part of Latvia up to 19 m thick dolomite-cemented layers of sandstone and siltstone occur in this level (Kleesment, 1999).

Ledai Formation is defined in Lithuania and it is similar to the above mentioned Vadja and Leivu Formations. In the lower part of Ledai Formation clay with dolomite marl and dolomite interlayers, sandstone, sandstone with gypsum cement and gypsum with dolomite and clay interlayers. In the upper part of Ledai sediments clay, dolomite, dolomite marl with fine dolomite clay interlayers prevail. On the top of formation variegated, greenish and violet grey dolomite marls with red-brown ferrigeneous spots and selenite veins occur (Narbutas, 1981a; Narbutas, 1981b; Narbutas, 1994; Paškevičius, 1997).

The boundary between Leivu and Kernave Substages, as well as between Ledai and Kernavė, is marked with reddish-brown, purplish-grey and grey mottled massive argillaceous dolomitic marl (Kleesment, 1999).

Kernave Formation consists of brownish-red, lilac and grey loose and dolomite-cemented silty sandstone with intercalations of siltstone, dolomitic marl and clay. In Lithuania in this Formation clay with marl, aleurolite and clayley dolomitic limestone interlayers occur. The complex consists with homogeneous, horizontal, rarely cross-bedded silt and fine-grained sandstones (Narbutas, 1981a; Narbutas, 1981b; Narbutas, 1994; Kleesment & Mark-Kurik, 1997; Paškevičius, 1997).

The boundary between Narva and the overlying Aruküla RS is often unclear. In general, the boundary is marked with the lowermost occurrence of the first significant uncemented reddish-brown sandstone bed above the dolomitic siltstone or dolomitic marls of the Narva RS. The topmost part of the Narva RS contains often a distinctive greenish-grey siltstone layer. The boundaries of Narva RS are established on the basis of lithological criteria whereas the above–observed units of the Narva RS, which correspond to the biozones (Kleesment *et al*., 1981; Narbutas, 1981; Kleesment, 1995; Kleesment, 1999).

4. Material and Methods

This study is based on the detailed investigation of borehole sections and available outcrops of the Narva RS. The examined boreholes were chosen to by their locality and preservation to get the most complete and representative vertical and lateral variation of the sediments. Altogether 11 boreholes were chosen to investigate the sediments of Middle Devonian Narva time. From these eleven boreholes three were chosen from Estonia, three from Latvia and five from Lithuania (Fig. 1). The quality and preservation of Jelgava and Jurmala drill-cores was, however, not sufficient for detail sedimentological analysis and these two were not used in further work.

This study included (1) detail description and documentation of drill-core sections, (2) definition and description of characteristic facies and facies associations, (3) analysis of facies association distribution in Narva RS, and (4) establishment of the sequence stratigraphical framework of the DBB development in Narva time.

The detailed investigations from all nine boreholes were made. All sections from selected boreholes were described in cm-scale. The carbonate content in carbonate lithologies was estimated visually or by field methods. The carbonate component in Narva sediments is represented by dolomite and only (very) rarely with calcite (Narbutas, 1994; Paškevičus, 1997). Only dolomitic sandstone rock types were investigated in laboratory for carbonate content by dissolution in 3% HCl. It was important to differ this facies from other siliciclastic sediments. Clay and calcareous/dolomitic clay, with less than 33% of calcite/dolomite was taken as a single group. The second group of carbonaceous sediments with 33 to 66% of dolomite was taken as dolomitic marl. Sediments with >66 % of dolomite were taken to the group, named dolomites.

The mean grain-size of the sediments was estimated visually by comparison with standard palette. All data's were drawn to the logs. The sections were described from the lowermost part upwards. The caps in the boreholes, caused mainly by incomplete preservation of rocks during drilling, are marked with hole. No reductions were made.

Described sections were composed both of carbonate and siliciclastic part. The sediments composition was drawn in two columns. First column, in the left, shows the carbonate-terrigenous material (mostly clay) ratio. The graph shows generalized scale that is divided into three parts – siliciclastic mud (Sm), dolomitic marl (Dm) and dolomite (D). Second column, at the right, shows the texture and structure of described sediments. For all carbonate lithologies the grain size is taken equal with the mud, except the silty and sandy dolomites. The siliciclastic beds, which matrix consists of wide range of grain sizes is showed on the log with the box of diagonal side. The grain size is showed with the diagonal line from the biggest size at the bottom and smallest one at upper corner of the box. Coarser grains than that of matrix are shown with the separate grain marks. The interlayers and interlaminae with coarser grain size are marked with a separate layer. The sediment structures are shown with the marks and signs (see logs in the attached part).

By the examination of logs and beds the facies types were separated. Every bed as attributed to one of the facies types. Altogether 14 facies types/classes were distinguished (Table 1). The facies separation was based on sedimentary structure criteria. Three facies from 14 were divided to subfacies according to the carbonate content (See table 1). For each facies the specific sedimentary texture-structure pattern, content of carbonate and bedding characteristics were employed.

According to the facies analysis eleven facies associations were separated (Table 2). Every facies association is characterized with the most inherent facies and subfacies. Facies associations were distinguished in all cross-sections and according to the lateral and vertical facies association trends their spatial and temporal variation was found. Based on these data the system tracks were found and the basin evolution was investigated. For the sequence stratigraphical subdivision the model given by Hunt and Tucker is used (Hunt & Tucker, 1992; Hunt and Tucker, 1995).

5. Facies and facies associations

From the measured boreholes 14 facies and 7 subfacies was divided (Table 1). These facies are grouped into 11 facies associations on the basis of palaeoenvironmental significance (Table 2). A generalized reconstruction of the facies associations in Narva time is given in the Fig 5.

Table 1. Summary of facies from Narva RS.

Facies	*Subfacies*	Texture/Constituents	Sedimentary structures	% of carbonate	Bedding
1. Homogeneous mud	***a. siliciclastic mud***	gray, dark gray, red mudstones, silty mudstone, occasionally calcareous	homogeneous	0-33	occur interlayers of carbonate, rarely interlayers, vugs of gypsum, quarts grains
	b. dolomitic marl	light grey, grey mudstone	massive, homogeneous	33-66	occur interlayers of clay, rarely interlayers, vugs of gypsum, quarts grains
	c. dolomite	light, pinkish mudstone	massive, homogeneous	66-100	occur interlayers of clay, rarely interlayers, vugs of gypsum, occasionally crystals, quarts grains
2. Laminated muddy sediments	***a. laminated and ripple laminated mud***	gray, dark gray, red mudstones, silty mudstones	cross and parallel lamination, normally graded	0-33	Interlaminated with silty and vf to f sand layers, occur interlayers of carbonate, gypsum, shell lags, wavy, lenticular bedding
	b. nodular, wavy dolostone	light grey, grey mudstone, with darker clay, silty, sandy interlayers	nodular, wavy laminae, wave ripples, cross lamination, mudcracks	33-100	thin laminated units, undulating surfaces, wavy, lenticular bedding, lenses and interlayers of clay, silt sand, shell lags, clasts
3. Cavernous, fenestrial dolostone		light grey mudstone	homogeneous, thinly laminated beds, caverns, fenesrtriae, vugs, tepee structures, mudcracks	33-100	occur interlayers of clay, vugs and interlayers of gypsum, intraclasts, shell lags, halite pseudomorfs, anhydrite diapirs
4. Burrowed muddy sediments	***a. burrowed mud***	red, reddish-grey, lilac mudstone, calcareous mudstone and silty mudstones	homogeneous, thin-bedded mudstone, burrowed	0-33	mostly mottled, rarely silty sandy interlayers, shell lags
	b. burrowed dolostone	red, lilac mudstone	homogeneous, thin-bedded, burrowed	33-100	mottled, rarely silty sandy interlayers, shell lags, burrows
5. Sandy carbonates		light grey mudstone with silt to fine-grained sand, occur single quartz grains (size from 0.5 to 6 mm)	massive, laminated beds	40-100	occur interlayers of clay, interlayers, vugs of gypsum

6. Dolomitic silt and sand		silt to fine grained sand and single quartz grains (size from 0.5 to 6 mm)	massive, laminated beds, normally to inverse graded, mud-drapes	0-40	undulating surfaces, occur lenses and layers of clay, carbonate, biotite, flaser, wavy bedding
7. Homogeneous silt and sand		red, reddish-gray, lilac silt to fine sand, well sorted	homogeneous, thin-bedded, burrowed	<5	occur interbeds of carbonate, rarely interlayers of bigger sand fraction, shells, ooids, mottled
8. Laminated silt and sand		silt to fine grained sand	laminated, mud-drapes	<5	occur interlayers of clay
9. Current ripple laminated silt and sand		silt to medium grained sand	current-ripple cross lamination, normally graded	0	occurs interbeds of clay and carbonate
10. Wave ripple laminated silt and sand		silt to fine grained sand	wave-ripple cross lamination	0	occurs lenses, interbeds of clay and carbonate, lenticular, wavy and flaser bedding
11. Plane-parallel laminated silt and sand		very fine to fine-grained sand	plane parallel lamination	0	
12. Planar-cross laminated silt and sand		very fine to fine-grained sand	planar-cross lamination	0	
13. Trough-cross laminated silt and sand		very fine to fine-grained sand	trough-cross bedding	0	
14. Matrix supported breccia		matrix muddy, rarely gypsum, clasts up to 7 cm	undulating, wave structure	0-100	occur interlayerslayers of clay, carbonate, gypsum

Table 2. Summary of facies associations in Narva RS.

Facies associations	**Facies nr**	**Stratigraphic unit**	**Lateral trends**	**Environmental interpretation**
I Prodelta facies association	1a; 1b	The uppermost part of Kernave Formation in Butkūnai borehole	In the middle part of the basin	The distal part of delta environment, in the shallow marine contitions
II Delta front/mouth bar facies association	1a; 1b; 2a; 7; 8; 9; 13	The uppermost part of Kernave Formation. In Mehikoorma, Tartu boreholes	In the northern part of basin	Distal and proximal delta front, fluvially influenced
III Siliciclastic barrier-island facies association	1a; 1b; 2a; 4a; 4b; 6; 7; 8; 9; 10; 11; 12; 13	In the middle or upper part of Kernave formation. In all boreholes except Ledai and Palanga	The thickest part is in the northern part of basin.	Shallow marine siliciclastic barrier-island environment
IV Siliciclastic peritidal facies	1a; 1b; 2a; 4a;	Mostly mark the boundary between	In whole basin, thickness increase	Shallow marine, low energy mixed, mud

association	4b; 7; 8; 9	Leivu/Ledai and Kernave Formation. In all boreholes	to the south	tidal flat, (storm) wave influenced environment
V Peritidal carbonate facies association with freshwater influence	1a; 1b; 1c; 2a; 2b; 3; 4; 7	In the upper part of Leivu/Ledai Formation. In all boreholes except Tartu and Mehikoorma	The thickness increase to the south	Shallow marine, low energy micro tidal, (storm) wave inluenced environment with freshwater income
VI Peritidal mixed siliciclastic-carbonate facies association	1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 14	In the upper part of Leivu Formation in Valga and Ludza boreholes. In the lower and middle part of Ledai Formation Ledai and Tauragė boreholes	Thickest in southern part of basin	Shallow marine micro to meso tidal environment with strong terrigeneous material inflow
VII Peritidal carbonate facies association	1a; 1b; 1c; 2a; 2b; 3; 4a; 4b; 14	In Vadja Formation in Tartu and Valga boreholes. In upper part of Leivu Formation in Leivu borehole	Laterally prograde to basinwards into shallow subtidal environment	Shallow marine, low energy micro tidal (storm) wave influenced environment
VIII Lagoonal facies association	1a; 1b; 2a; 2b; 4a; 4b	In Leivu Formation in Valga and Ludza boreholes	Laterally prograde to basiwards into shallow subtidal environment	Shallow marine, low energy, back barrier lagoon and open lagoon
IX Shallow subtidal facies association	1a; 1b; 1c; 2a; 3; 4a; 4b; 5; 6	In Vadja and Leivu (Ledai) formations in all boreholes, except Ledai, Tauragė and Palanga	Mostly in northern and middle part of the basin, seaward from the peritidal environment	Shallow marine, carbonate and mixced siliciclastic wave influenced epheiric platform. Channel and incisised valley fills
X Deep subtidal facies association	1a; 1b; 1c; 2a; 4a; 4b	In Vadja and Leivu (Ledai) formations in all boreholes and in Kernavė Formation in Palanga borehole	Mostly in northern and middle part of basin, seaward from the shallow subtidal environment	Shallow marine, carbonate and mixed siliciclastic storm influenced, epheiric platform
XI Endocenic/exocenic breccia	1a; 1b; 2a; 3; 14	In the lower part of Vadja (in Tartu and Ludza borehole) or Ledai (Svėdasai and Ledai boreholes) Formation	No lateral trends, composed with local material	

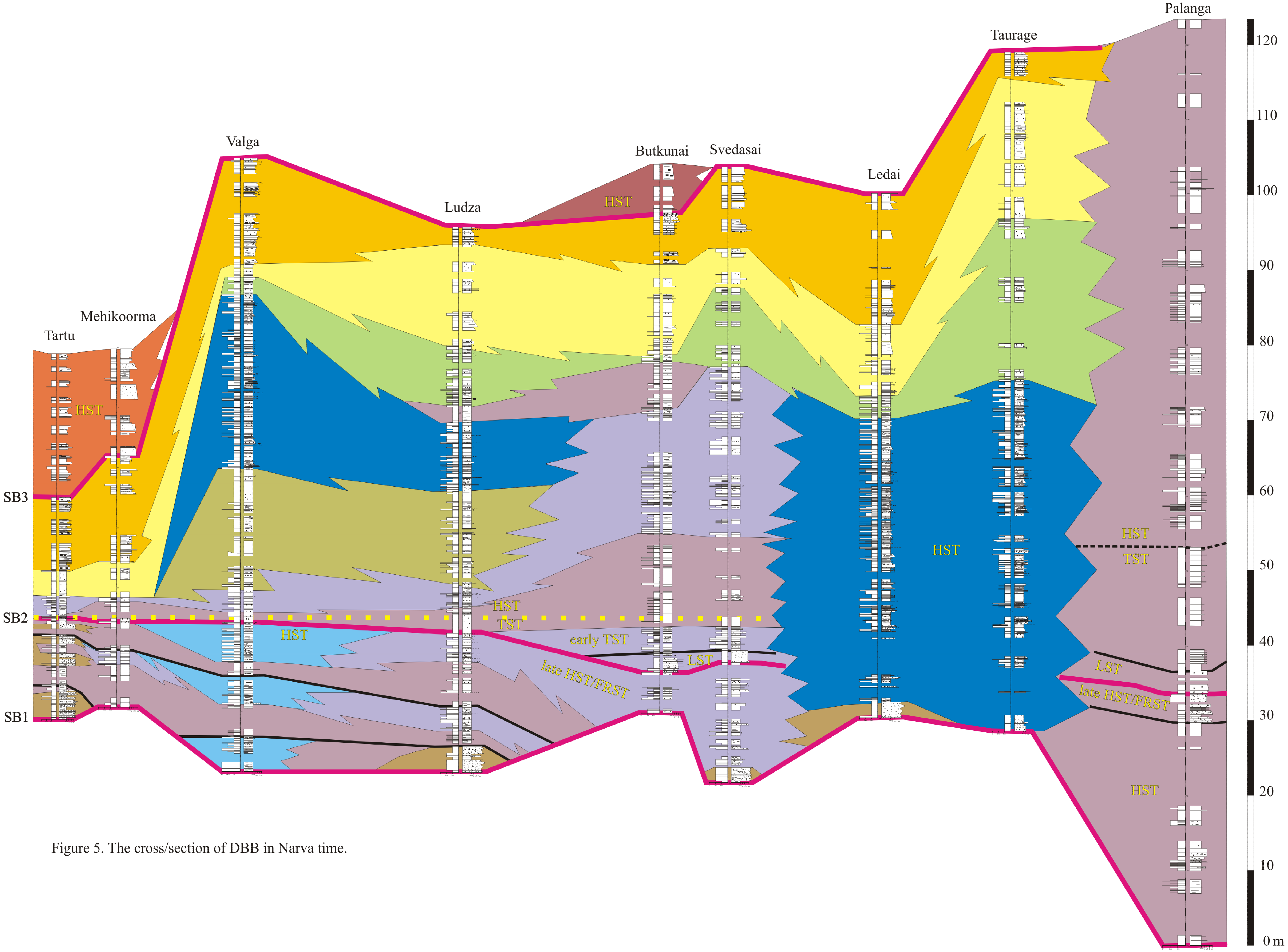

Figure 5. The cross/section of DBB in Narva time.

5.1. Prodelta facies association

Description

The prodelta facies association includes homogeneous siliciclastic mud and laminated siliciclastic mud (Appendix 5). This facies association is only represented in the Butkūnai borehole (Fig. 5) with an 8 m thick unit. There are a no cycles or clear boundaries. At the uppermost bed the mud-drapes occur.

Interpretation

This facies association is interpreted to be deposited in low energy tidal/wave influenced prodelta environment. Relatively thick mud unit is interpreted to deposited from suspension, carried by river flow. The preservation of some silt lamination marks commonly the influence of delta (Bhattacharya & Walker, 1992). Mud-drapes refer the deposition in the tidally influenced environment, but because there are no clearer evidences on tidal influence, it cannot be clearly stated.

5.2. Delta front/Mouth bar facies association

Description

The delta front/mouth bar facies association includes homogeneous siliciclastic mud and dolomitic marl, laminated and ripple laminated siliciclastic mud, homogeneous, laminated, ripple laminated, ripple cross-laminated, trough-cross laminated silt and sand (Appendixes 1; 2). This faces association consist of muddy up to fine-grained sediments. Most of the beds are homogeneous, structurless, silt and sand dominated; at the places occur mud-drapes. In Tartu borehole in this facies upward coarsening sedimentary bodies occur (Appendix 1). The lower part of this unit forms layers of muddy sediments with rare shell fragments. The upper part consists of fine grained sandstone beds. The beds consist mostly homogeneous, but also trough-cross laminated silt and sandstones. The thickness of this unit is around the 3.5 m. In Mehikoorma borehole up to 2.5 m thick structurless beds occur (Appendix 2). The grain size of those beds varies from very fine to medium sand. It also includes coarser grains with up to 2 mm in diameter.

This facies association is found only in Tartu and Mehikoorma boreholes (Fig. 5). The thickness of this unit decreases to the south from 28 m in Tartu borehole to the 20 m in Mehikoorma borehole.

Interpretation

This facies association is interpreted to be deposited in delta front/mouth bar environment. The prevalence of relatively fine-grained sediments shows that from the river system a big amount of muddy and fine-grained materials were carried out. The relatively coarse sediments which forms upward-coarsening cycles are interpreted as distributary mouth bars. They are relatively small features in deltas and are formed where basin processes are weak and fluvial processes dominate (Reading & Collision, 1996). The couple of meters thick structurless beds with different grainsize and with some bigger, up to 2 mm, grains are interpreted as gravitational deposits. The deposition of those beds is caused by mass-movement from the delta front, mainly because of the sediment instability at high accumulation rates (Reading & Collision, 1996).

5.3. Siliciclastic barrier-island facies association

Description

This siliciclastic barrier-island complex includes homogeneous siliciclastic mud and dolomitic marl, (ripple) laminated siliciclastic mud, burrowed mud and carbonates, homogeneous, laminated, current and wave-ripple laminated, plane parallel, planar- and trough-cross laminated silt and sand (Appendixes 1-8). This facies association is characterized with two different units: (a) upward-coarsening and (b) upward-fining units. The upward-coarsening units are from 1.5 to up to 6.5 m thick. This unit forms complex of superposed sandstone and mudstone beds, which show prominent reactivation surfaces within internal cross-sets, and the abundance of cross-stratification and locally reversing cross-strata (Fig. 6A). Burrowed beds are rare.

The upward-fining unit forms the sedimentary bodies with the thickness from 1.5 up to 2.5 meter. The lower part consists of laminated, trough-cross stratified beds with reactivation surfaces and mud-drapes. The upper part consists with muddy siliciclastic and carbonate or silty sediments, which at the places are bioturbated. In some beds ripple cross- and wave-lamination occurs (Fig. 6B).

This facies association extends all over the basin except in Palanga borehole (Fig. 5).

Interpretation

This facies association is interpreted to be deposited in the shallow marine siliciclastic barrier-island environment. This environment consists of several subenvironments, from which two are presented here - the barrier bar and cannel-fill complex.

The upward-coarsening (planar) laminated and small-scale cross-bedded (laminated) sedimentary bodies, which include some bioturbated beds, are interpreted as a barrier bar complex. The presence of reactivation surfaces and mud-drapes shows the tidal influence. The upward-fining sedimentary bodies with relatively coarse-grained lag and muddy top deposits with the presence of reactivation surfaces and mud-drapes are interpretive of tidal channel deposits. The superposition of channel and bar deposits is caused by channel cut through the barrier bar complexes.

5.4. Siliciclastic peritidal facies association

Description

This facies association consists of homogeneous mud and dolomitic marl, laminated and ripple laminated siliciclastic mud, bioturbated mud and carbonate, homogeneous, laminated, ripple laminated, current-ripple cross-laminated silt and sand (Appendixes 1-8). This facies association is mostly represented with muddy and fine-grained sediments. The sediments are often bioturbated and include the root traces (Fig. 6C; 6D; 6E). Some beds include shell lags and interlayers of relatively coarse-grained sediments. This facies association is characterized with mostly homogeneous beds with no clear internal structures. At the places it is only percipient. There are relatively less clear cycles, units. Most of cross-sections in this facies association are characterized with muddy, silty and fine-grained sediments. There are some intervals were fining-upward cycles prevail. Those cycles start with relatively coarse grained sediments followed with fine-grained sediments or with mixed mud-silt units. The upper part of this kind of cycles consists mostly of silicilastic rich mud or dolomitic marl, for example in Ludza and Svėdasai boreholes. In Tartu and Mehikoorma boreholes this facies association is represent only with homogeneous and laminated siliciclastic mud with the thickness 6 m.

In most cases the beginning of this facies association marks the boundary between Leivu/Ledai and Kernave formations (see Appendixes 1-4; 6-7). However, in Butkūnai and Tauragė boreholes this unit composes the upper part of Ledai Formation (see Appendixes 5; 8). In Mehikoorma borehole this facies association belongs to the Leivu Formation (see Appendix 2). This facies association is spread in whole basin and its thickness increases to the south (Fig. 5). In Tartu and Mehikoorma boreholes the thickness is around the 6 m, and it increases up to 20 m and more in the Tauragė borehole.

Interpretation

This facies association is interpreted to be deposited in the low energy shallow marine mixed and muddy tidal flat. Muddy tidal flats tend to prevail along costal plains and near mud-dominated rivers (Einsele, 1992). The high amount of mud in this unit is interpreted to be deposited at the end of the tidal current transport-paths, where both tidal current velocity and, particularly, the wave activity are relatively low. Alternatively the association was deposited at the distal end of the transport paths due to flow expansion and deceleration (Johnson & Baldwin, 1996). This interpretation is based on the evidence that the muddy sediments contain relatively little sand interbeds or separate beds. The sand beds and thinner interbeds are interpreted to be deposited during the spring tides or storm events. The small-scale fining-upward cycles with relatively coarse-grained bottom sediments in Ludza and Svėdasai boreholes are interpreted as small-scale channels. They indicate the landward portion of the meandering channels that dissect the muddy tidal flat. Those small-to-medium sized channels are usually deepening to the sea-ward (Dalrymple, 1992). In Tauragė borehole the upward-fining successions without lag or relatively coarse-grained sediments in the lower part are interpreted as a prograding tidal flat. The structurless of sediments can be caused by bioturbation, what may partially or completely obliterate the physical structures of the sediment. Burrowed sediments to not show the exact deposition environment, because they may figure on any part of tidal flat were sediment movement is not too intense (Dalrymple, 1992).

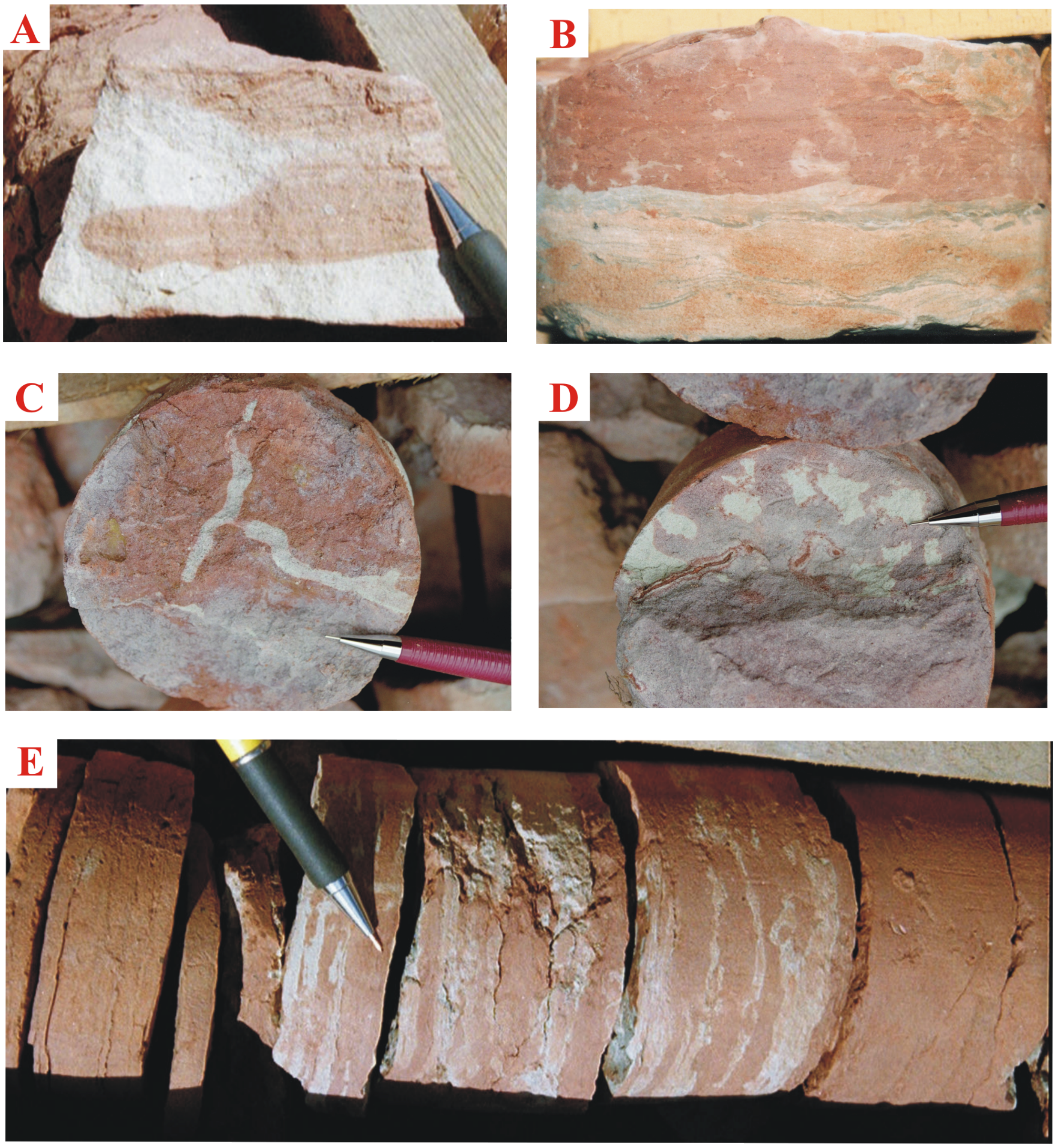

Figure 6. The examples of facies from the barrier-island and siliciclastic peritidal facies associations. 6A ripple cross-lamination, Valga borehole (made by S. Jorild). 6B wave ripple cross-lamination, Valga Borehole (made by P. Plink-Björklund). 6 C burrows, Valga borehole (d=10 cm) (made by P. Plink-Björklund). 6D root traces, Valga borehole. 6E burrowed bed?, Valga borehole.

5.5. Peritidal carbonate facies association freshwater influence

Description

This facies association includes six facies: homogeneous siliciclastic mud, dolomitic marl and dolomite, laminated and ripple laminated siliciclastic mud and carbonate, cavernous carbonate sediments, burrowed siliciclastic mud and carbonates, sandy homogeneous silt and sand (Appendixes 3-8). It consists of upward-shallowing cycles. The thickness of cycles, range from 1.9 m up to 3.7 m. The shallowing-upward cycle is formed by two parts. The cycle starts with homogeneous, (ripple) laminated siliciclastic mud and passes upward into homogeneous, cavernous or burrowed carbonates. The amount of burrowed sediments increases and the share of cavernous carbonates decreases from the down to the upper part of this facies association, except in Ludza borehole. Also the amount of dolomitic beds decreases in the upper part of complex.

This facies association is widespread in middle and southern part of the basin. The thickness is increasing somewhat to the south; the thickest complex is indentificated in the Tauragė borehole (Fig. 5).

Interpretation

This facies association is interpreted to be deposited in peritidal carbonate environment influenced by freshwater influx. Dominating structurless beds with some relatively coarse-grained interbeds indicate deeper environment, but many beds indicate also shallow water peritidal environment (See in Butkūnai borehole, Appendix 5). This phenomenon is interpreted to be caused by freshwater influx, which carry more muddy material and affect the sedimentation environment.

5.6. Mixed peritidal carbonate-siliciclastic facies association

Description

The mixed peritidal carbonate-siliciclastic complex includes homogeneous muddy sediments, laminated and ripple laminated muddy sediments, cavernous carbonate, burrowed deposits, sandy carbonates, cemented sandstones, homogeneous silt and sand, (ripple)laminated, current and/or wave ripple laminated silt and sand, and breccia (Appendixes 3, 4, 7, 8).

This facies association is characterized with shallowing upward cycles that have high structural variability. The sheared features of these facies include: (1) abundant evidence of exposure, which appear in the form of vugs, desicration cracks, caverns, fenestriaes, karstification (Fig. 7A); (2) abundant beds of silt, sand up to medium grained sandstone layers; (3) rare ooids and intraclasts.

The lower part of cycles is composed of interbedded siliciclastic mud, silt and sand layers (Fig. 7B). Silt and sand layers are thin, locally lens-shape. The sandstone beds are 5 to 17 cm thick and composed of very fine to medium grained sand. Also, ripple laminations are abundant. Occasionally wavy, lenticular bedding and mud-drapes are present.

The upper part of cycle contains dolomite, dolomitic marl and sandy carbonates of flaser, wavy, nodular bedding (Fig. 7C; 7D; 7E). Fenestria, caverns, vugs, mudcracks are abundant and also anhydrite diapirs occur (Fig. 8A-8D). The carbonate beds contain high amount of silty and sandy interbeds and lenses with abundant mud-drapes.

Some shallowing-upward cycles are recognized, which contain thick, relatively coarse-grained sediments at the cycle bottom and which pass upward to the dolomite marl or dolomite beds. The thickness of such units reaches up to 1.6 m.

Bioturbation in this facies association lacks or is rare. The amount of bioturbated beds increases to the upper part of mixed peritidal complex. Dolomitic silt and sandstone and sandy dolostone are mostly present in the lower part of Leivu and Tauragė boreholes (Appendix 7; 8; Fig. 9A). These sediments often contain quartz grains with the diameter up to 6 mm. Commonly quarts grains concentrate at the upper or lower boundary beds.

This facies association is mostly found in the southern area of basin. It forms the biggest part of Ledai Formation in Ledai and Tauragė boreholes. It is spread also in the middle and upper part of Leivu Formation in Valga and Ludza boreholes (Fig. 5).

Interpretation

This facies association is interpreted to be deposited in the mixed carbonate-siliciclastic peritidal environment. The flaser, wavy and lenticular bedding characterize tidal flat deposits deposited in intertidal environment (Dalrymple, 1992; Pratt *et al*., 1992). The shallowing-upward cycle with relatively coarse-grained bottom bed is interpreted to be the channel infill deposits. In low energy environment the tidal flat channels are typically shallow, but they may be up to 100 m wide (Wright, 1990). However, these deposits are very similar and probably confused with prograding tidal flat deposits. Therefore, genesis of these sediments/cycles is unclear and it needs more detail analysis. The presence of fenesrial fabric, vugs, dissolution cavities, desiccation cracks indicate the deposition of environment what was occasionally exposed above sea level (Pratt *et al.,* 1992). The most indicative forms for tidal flat are mudcracks, which indicate the upper intertidal or supratidal environment (Pratt *et al*., 1992; Demicco & Hardie 1994). Fenestriae is used as one of the most useful sedimentary structures for identifying subaeral exposure (Demicco & Hardie, 1994) and it is mainly formed by desiccation and shrinkage or by air and gas bubble formation in tidal flat environments (Wright, 1990). The carbonate sediments with small mm-size vugs are interpreted like a fenestiral rocks. The fenestria is defined as a primary or penecontemporaneous gap in rock framework, larger than grain supported interstices (Demicco & Hardie, 1994). The caverns in the bedsurfaces are not taken into this definition.

Dolomitic sandstones cemented by calcite, aragonite or dolomite, is a common feature of peritidal carbonate environments. Clasts in the sediments are interpreted to be formed during storms from desiccrated mud polygons, which commonly litter the upper intertidal and supratidal zone and can be reworked (Wright, 1990).

The silty, sandy dolomite, cemented sandstones and carbonates with high content of silty-sandy sediments represent a mixed carbonate-siliciclastic tidal flat. It is not known what may have caused the inflow of terrigeneous material. Was it carried by wind or by river? It is possible that siliciclastic silt and sand was transported to the carbonate tidal flats by wind action and reworked by tidal action (Mount, 1984; Goldhammer, 2003), particularly given well-sorted quarts and sand grains. Wind-blown particles are know to be transported hundreds to thousand of kilometers from their source areas to marine carbonate environment in the modern Persian Gulf (Alsharan & Kendall, 2003; Tucker, 2003) and are found in many ancient deposits (Osleger & Montaňez, 1996). The anhydrite diapir in Tauragė borehole and the presence of gypsum in massive sparry dolomite may indicate a saline or evaporate depositional environment (Jiang *et al*., 2003). However, the genesis of gypsum in these sediments is unclear and it is not discussed later in this work.

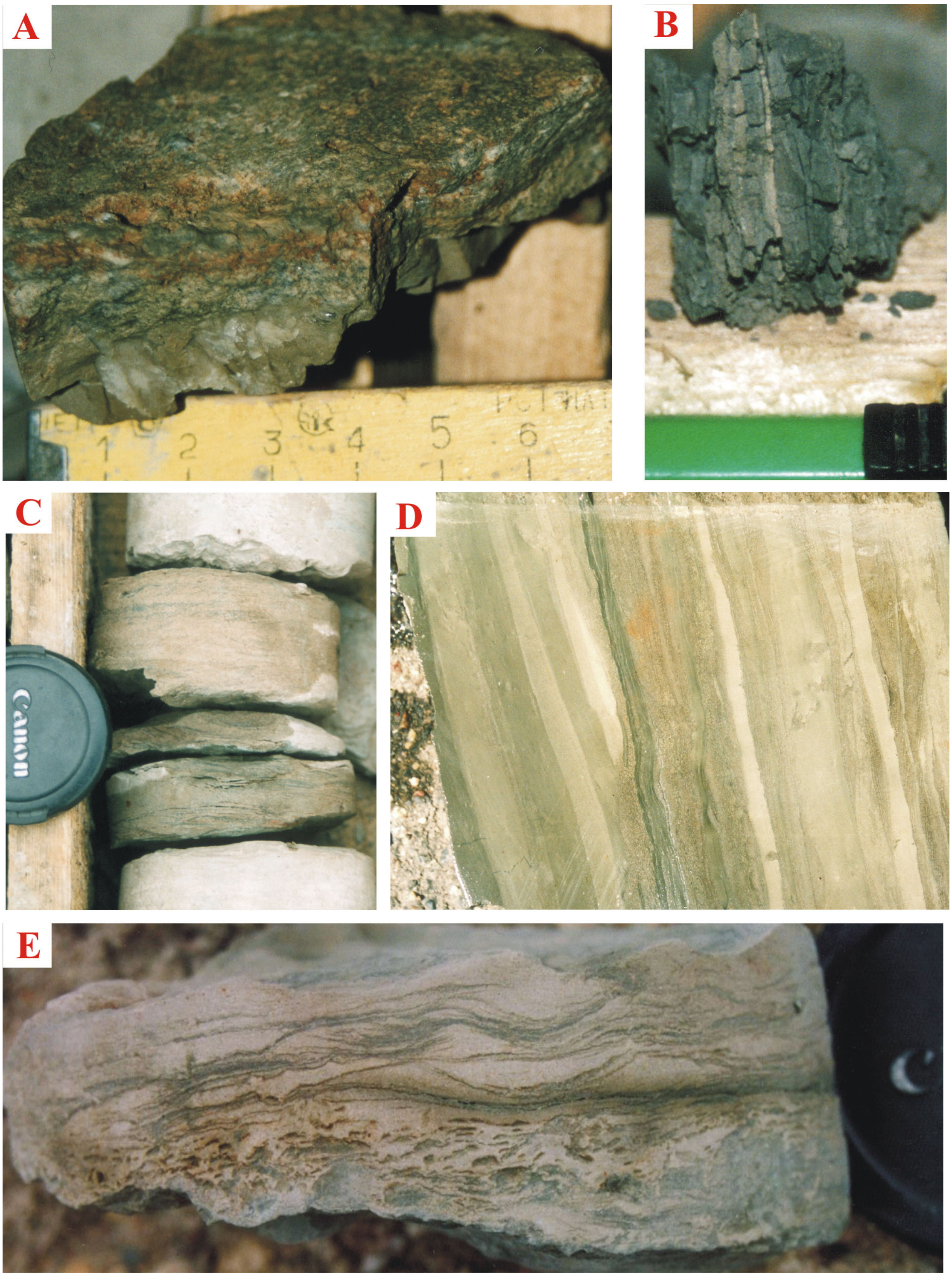

Figure 7. The examples of facies from mixed peritidal facies association. 7A carbonate bed with carstificated upper part, Ledai borehole. 7B interlaminated siliciclastic mud, Ledai borehole. 7C ripple cross-laminated dolomitic sand between the carbonate beds, Valga borehole. 7D the sandy carbonate with ripple lamination, Tauragė borehole (d= 11 cm). 7E dolomite with wavy bedding, Tauragė borehole.

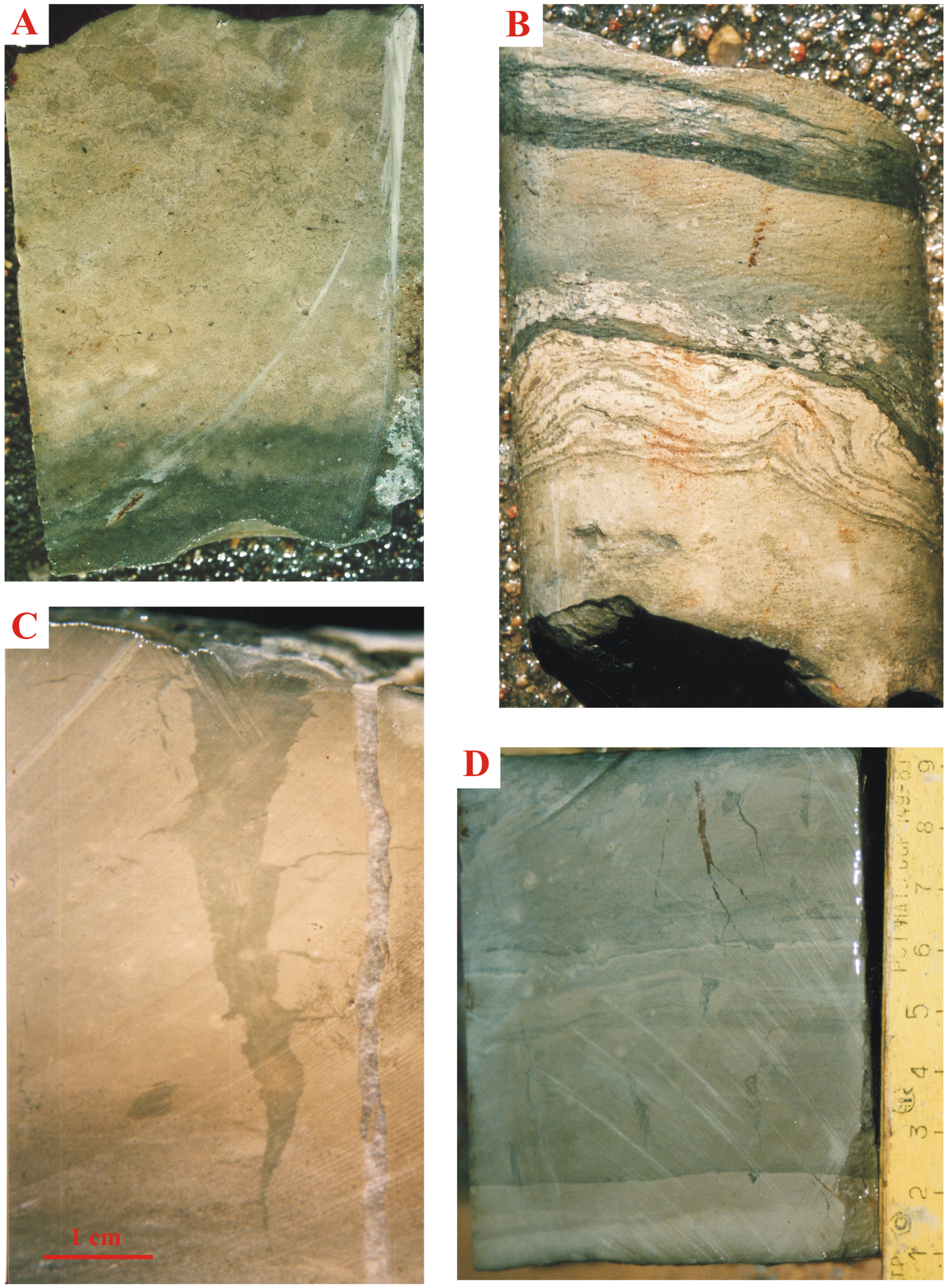

Figure 8. The examples of facies with different structures from mixed peritidal facies association. 8A fenestrial fabric, Tauragė borehole (d=11 cm). 8B anhydrite diapirs, Tauragė borehole (d=11 cm). 8C mudcrack, Tauragė borehole. 8D mudcracks, Ledai borehole.

5.7. Peritidal carbonate facies association

Description

The peritidal carbonate complex includes homogeneous siliciclastic mud, dolomitic marl and dolomite, (ripple) laminated siliciclastic mud and carbonates, cavernous carbonate, burrowed mud and carbonates, and breccia (Appendixes 1; 3). Facies form 0.2 to 1.5 m thick shallowing-upward cycles. The down part of cycle is composed of homogeneous or (ripple) laminated siliciclastic mud, with the bed thickness from 7-80 cm. Ripple lamination is composed of interlayering mud and silt layers. The upper part of cycle is composed with dolomitic marl, dolomites. This part consists mostly of wavy, nodular, thinly laminated bedded carbonates (Fig 9C). In this facies association some bioturbated beds occur. Vugs, desiccation cracks, caverns, and breccia occur in the upper part of cycle. Beds with the subangular carbonate clasts up to 2.5 cm in size also angular, subanglar intraclasts with diameter up to 1 cm, and breccia with the angular particles up to 2.5 cm in size are present (Fig 9B; 9D; 10A; 10B).

The thickness of facies association complex is up to 7 m in Valga borehole. It is widespread only in Vadja Formation in Estonia (Fig. 5).

Interpretation

This facies association is interpreted to be deposited in the peritidal (carbonate dominated) environment. The presence of shallowing-upward cycles shows the fluctuations of the sea level. Wave-, nodular, laminated and fine-scale laminated dolomite and dolomitic marl beds are interpreted being accumulated in the peritidal environment and it is generally the result from spring or storm tide deposits (Shinn, 1998). The beds tend to be thicker in the more distant or landward portion of the system and thinner in the more seaward portion. Horizontal lamination, whether graded or ungraded, thick or thin, with or without cross-bedding, are deposited both in present and past environments and indicate the peritidal environment (Shinn, 1998). The intraclast are interpreted to have formed in storm-influenced settings, in which intraclasts were reworked from lithified or partially lithified sea floor (Pratt *et al*., 1992; Demicco & Hardie, 1994; Shinn, 1998). The breccia is interpreted being redeposited during the storm event. The desiccation in the peritidal flat is marked with mudcracks.

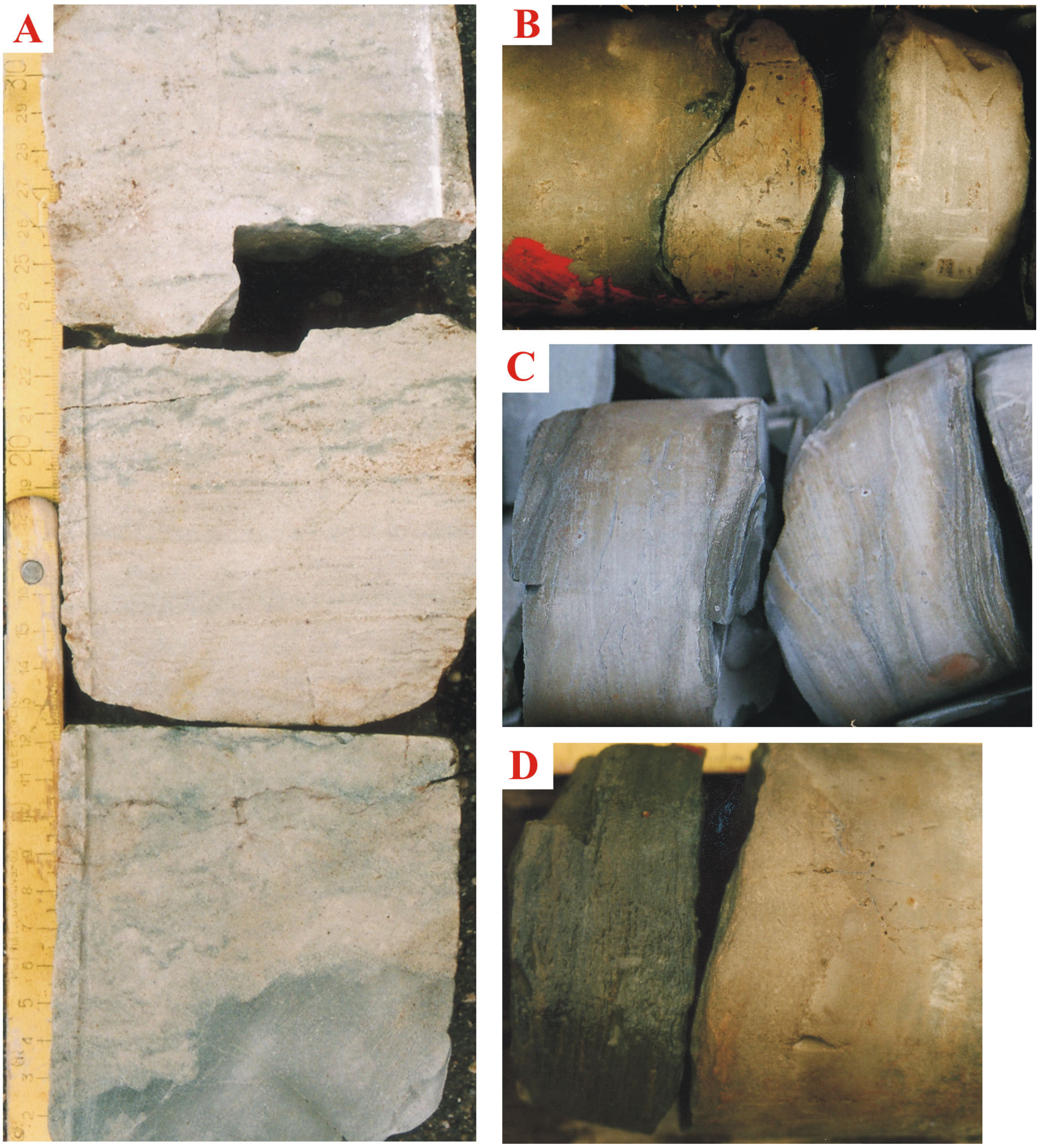

Figure 9. The examples of facies from mixed peritidal and carbonate peritidal facies associations. 9A dolomitic sandstone, Tauragė borehole. 9B tempestite layer, Ludza borehole (d=8 cm). 9C thin bedded nodular lamination, Valga borehole. 9D tempestite layer, Ludza borehole (d=8 cm).

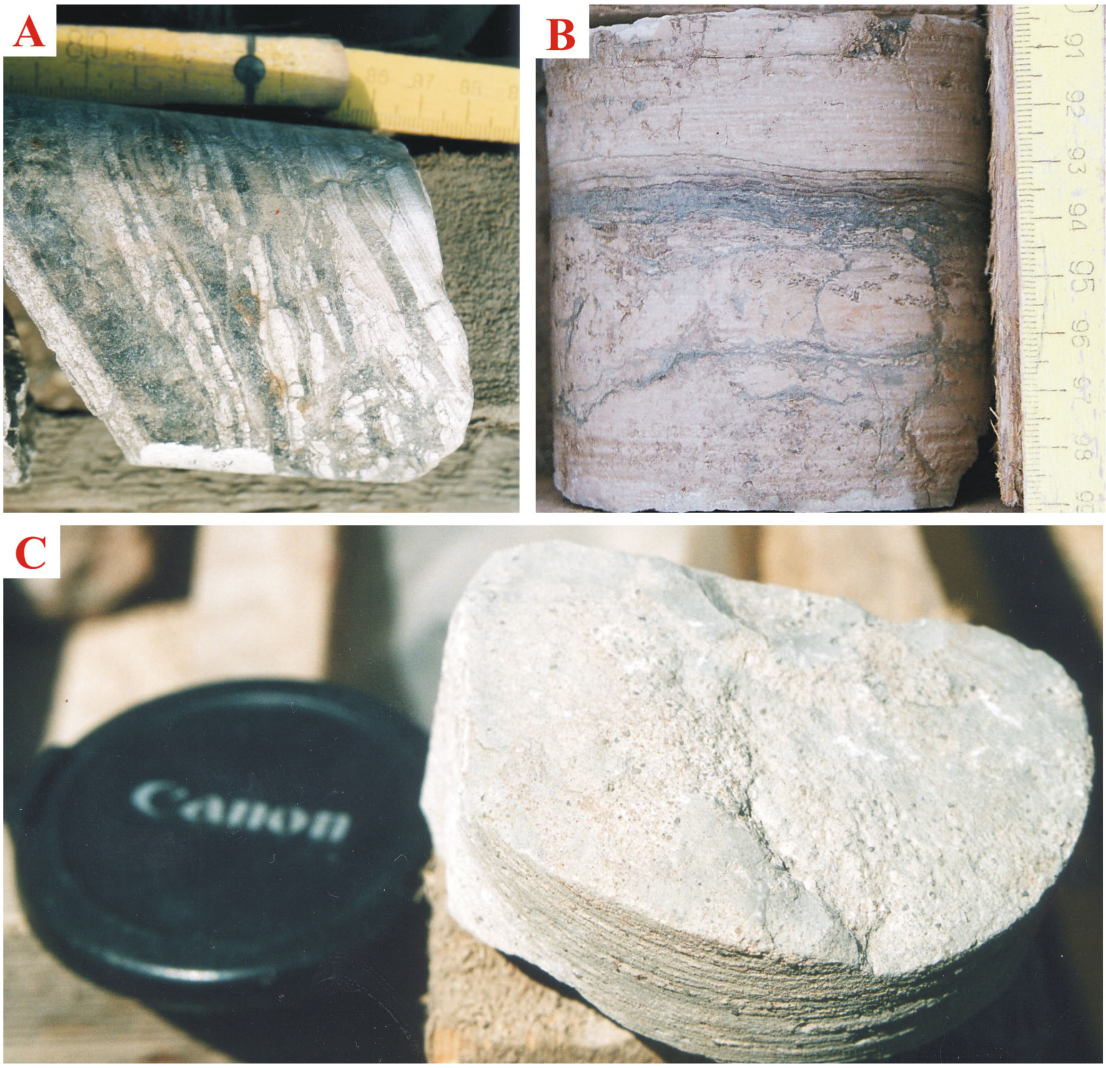

Figure 10. The examples of facies from the peritidal and shallow subtidal facies associations. 10A breccia, Ludza borehole. 10B carbonate bed with storm layer, Valga borehole. 10C dolomitic sandstone with subangular and subrounded quarts grains, Ludza borehole.

5.8. Lagoonal facies association

Description

The lagoonal facies association includes homogeneous siliciclastic mud and dolomitic marl, laminated and ripple laminated siliciclastic mud and carbonates, burrowed siliciclastic mud and carbonates (Appendixes 3;4). The facies association is represented only in Valga and Ludza boreholes (Fig.5). It is composed mostly of alternate (ripple) laminated and bioturbated or homogeneous siliciclastic mud's with silty, sandy interlayes. Also, shell fragments are abundant. Some homogeneous dolomitic marl beds with shell and fish fragments occur rarely.

Interpretation

This facies association is interpreted to be deposited in a restricted lagoonal environment in the Valga borehole and in open lagoonal environment in Ludza borehole. The open lagoonal environment is suggested by a lack of bioturbation, but high amount of laminated sediments and the relatively coarse-grain sizes. The lack of sedimentary structures and high bioturbation in Valga borehole suggest the deposition in a low energy environment, probably in subtidal lagoonal environment. The silty interlayers and shell lags indicate deposition during the storm periods in both boreholes. The wavy, ripple cross-bedded sediments in Ludza borehole are probably caused by tidal events.

5.9. Shallow subtidal facies association

Description

The shallow subtidal facies association includes homogeneous siliciclastic mud, dolomitic marl and dolomite, (ripple) laminated siliciclastic mud, cavernous carbonate, burrowed siliciclastic mud and carbonate, silty, sandy carbonates and dolomitic sand (Appendixes 1-6). The facies association is composed of shallowing-upward cycles, starting with mud and passing upward into dolomitic marl or dolomite. The mud rich part is composed of fluctuating homogeneous or (ripple) laminated siliciclastic mud. At the places with up to 4 cm thick carbonate interlayers occur. The carbonate-rich part is composed mostly of homogeneous carbonate sediments. Occasionally silty, sandy carbonates and dolomitic sandstone prevail. Those beds are widespread in the lower part of Ledai Formation in Butkūnai, Svėdasai and Palanga boreholes and contain subrounded and rounded quarts grains (Fig. 10C). Quarts grains up to 6 mm in diameter are also abundant in all facies, which are situated in the upper part of Vadja Formation or in the lower part of Leivu Formation in Estonia and Latvia, and in the lower part of Ledai Formation in Lithuania. In the carbonate beds some relatively coarse grained interlayers with shell fragments and at the places angular carbonate clasts up to 0.7 cm and rounded elliptical carbonate clasts up to 4 cm in diameter occur.

This facies association is spread almost in all boreholes. However it is not identified in Ledai, Tauragė and Palanga boreholes (Fig. 5). The thickest units of this association are situated in the middle part of DBB and it reaches up to 26 m in Svėdasai borehole.

Interpretation

This facies association is interpreted to represent shallow subtidal environment near fair-weather wave base. The presence of ripple lamination and minor erosional surfaces in the beds indicate wave action. The lithology of sediments and high content of mud shows the low level of wave action. Relatively coarse grained interlayers and shell fragments indicate storm wave action and are interpreted being carried into the deposition environment during the storm events. The angular carbonate clasts were probably derived from the cemented crusts on the upper part of shallow subtidal environment and were destroyed/redeposited during the storms. Rounded carbonate clasts are interpreted to be also of tempestite origin. The locally bioturbated beds show low sediment supply and are indicative of shallow subtidal to lower intertidal zone (Pratt *et al*., 1992).

This lithofacies is not interpreted as an intertidal deposit because the mudcracks, caverns, fenestraes, high structural variability or other distinguishing features of tidal flat deposits are completely absent here.

The presence of silty, sandy (inter) layers and lamination indicates that environment was not far from the fair-weather wave base and it is different from deep subtidal facies association described below. The bigger rounded quarts grains indicate the presence of source area. With high diameter, up to 6 mm, they could not have been transported by wind, but were probably transported from the area next to the basin by current/wave action. These quartz grains are in most cases found in dolomitic sandstones or in silty-sandy dolomites, but they can be found also in the siliciclastic mud sediments as well. The amount and relative distribution of grains is variable, but all grains are characterized by textural and compositional maturity.

Up to 2 m thick dolomitic sandstone beds in Butkūnai and Svėdasai boreholes are interpreted deposited in incised valleys or in tidal channels during the FRST and LST (See Appendixes 5; 6; Fig. 5).

5.10. Deep subtidal facies association

Description

Deep subtidal facies association includes homogeneous siliciclastic mud, dolomitic marl and dolomite, (ripple) laminated siliciclastic mud, burrowed siliciclastic mud and carbonates (Appendixes 1-6; 9). This facies association is composed mostly of muddy sediments with thin carbonate interlayers. The most common are homogeneous or thin parallel, ripple laminated mudstones, which are occasionally bioturbated. At the places beds include rippled silty sandy layers or quartz grains. Carbonate beds in facies association are relatively thin, homogeneous, locally bioturbated and less abundant to compare with other facies associations.

In Palanga borehole this facies association includes homogeneous dolomitic sandstones, up to the three meters thick unit.

This facies association is spread in whole basin except in Ledai and Tauragė boreholes (Fig. 5). It is spread mostly in northern and middle part of the DBB, seaward from the shallow subtidal environment.

Interpretation

Facies association is interpreted accumulated in shallow marine subtidal environment, below fair-weather wave base. The presence of occasional (inter-)beds of ripple-laminated silt and sandstones and quarts gains may indicate storm-wave activity. In general, sedimentary structures indicative of the storm deposition are uncommon. However horizontal lamination in mud beds is mostly caused by storm or spring tide deposition (Shinn, 1998). Occasional quartz grains in beds are interpreted being derived from proximal areas of the platform and transported seawards by storm induced currents. Locally occur burrow-mottled nature indicate slow deposition during the time.

The sandy beds in Palanga borehole are interpreted to be deposited during LST. Thick sandy intervals may represent the time when the surrounded area was still exposed and the incisised valleys were formed. The large amount of sandy material was carried in, probably with river input. The siliciclastic mud with silty sandy interlayers may represent the deeper water environment during the TST and HST. The silty sandy interbeds are probably transported to the basin with flow lofting or with storm wave action.

5.11. Endogenic/exogenic breccia

Description

The endogenic/exogenic breccia facies association consists with homogeneous silicilastic mud and dolomitic marl, (ripple) laminated siliciclastic mud, cavernous carbonate and breccia (Appendixes 1; 4; 6; 8). This facies association is up to 6 m thick. Breccia is composed of matrix supported breccia and interlaminated siliciclastic and carbonate sediments. Breccia contains up to 7 cm thick angular and subangular particles-clasts (Fig. 10A). In some boreholes this facies association occurs in several levels (Appendix 1). In most cases the lowermost layer consists of the highest amount of dolomitic clasts and in the upper levels the amount of more muddy clasts increases.

Breccia is widespread in four boreholes studied in this work – Tartu, Ludza, Svėdasai and Ledai (Fig. 5). It is known from literature that in Mehikoorma and Butkūnai boreholes breccia was present too (Vaitonis *et al.*, 1972; Põldvere *et al.,* 2000), but this part of the drill-core is not preserved.

Interpretation

This facies association does not have clear depositional interpretation. There are many possibilities how this facies association, in literature described as megabreccia, could form. (Tucker, 1991; Obrador *et al*., 1992; Pedley *et al*., 1992; Hunt & Tucker, 1995; Spence &Tucker, 1997; Seguret *et al*., 2001). Also, the orgin of the Narva breccia has been interpreted in different ways: as due to sliding (Kleesment, 1997), as a result of asteroid impact (Masaitis, 2002), for example.

Traditionally the megabreccia deposits have been interpreted as the product of catastrophic collapse of high-angle metastable carbonate seafloor slopes (Spence & Tucker, 1997). However, during the last years there are several works on the different mechanisms forming the megabreccias, they are interpreted to be deposited by storm activity (Serguet *et al*., 2001) or because of carstification during the in low seal level (Wright & Burchette, 1996). Megabreccias are found in various settings - from very steep slopes to very low angle slope aprons even less than 1° (see Spence & Tucker, 1997). The factors controlling the megabreccia formation can be divided into two parts: (1) endogenic processes linked to the depositional systems, such as sedimentation rate, relative sea-level change and depositional slope angle, (2) exogenic processes which are independent from the depositional system, such as seismicity and storms. Endogenig triggers may occur in a predictable, cyclical way, exogenic triggers, being inherently random in occurrence, may produce an irregular pattern of resedimentation (Spence & Tucker, 1997).

The geological context of Narva breccia does not agree clearly with any of these possible mechanisms. Because the lack of material and due to the different goals of this work this question is not discussed further. However, the lack of the transport signatures in breccia supports the *in situ* collapse of the sediment.

6. Depositional environmental groups

The intent of this section is primarily descriptive - it provides an overview of the regional stratigraphic framework together with the interpreted facies associations and the distribution of facies associations.

During this investigation 11 facies associations were discovered from where four depositional environmental groups were distinguished: exogenic/endogenic breccia, carbonate prevailing tidally influenced shallow marine, siliciclastic tidally influenced shallow marine and delta environmental groups. The breccia group is not discussed here, as its origin and the correlation with other depositional systems is not clear.

6.1. Carbonate prevailing tidally influenced shallow marine environmental group

The deposition of this group starts with muddy deep subtidal facies association, where only rare storm events with coarse-grain layers are present. During the accommodation of the basin and relative sea-level fall, the facies association is prograding seaward. During the progradiation the carbonate rich and structurally more variable sediments start to prevail. Sea-level fall what increases terrigenous sediment supply from the basin margins, is reflected in the more silty and sandy material that is carried into the basin at this time.

The deposits in deep and shallow subtidal and peritidal environments in the geological record commonly occur in cyclic or rhythmic packages containing a few to hundreds of individual shallowing-upwards or more rarely deepening-upwards cycles (Wright, 1990). These environments are called successions (Pratt *et al*., 1992; Reading & Levell, 1996).

In this environmental group many shallowing-upward successions are discovered. They are represented with two different kinds of successions; (1) deep subtidal – shallow subtidal – carbonate peritidal, and (2) deep subtidal – shallow subtidal – mixed peritidal. Because of nondeposition or erosion it is not unusual that some parts from the succession are missing. The first kind of succession is widespread in the

Vadja Formation in Estonia and Latvia (Tartu, Mehikoorma, Valga and Ludza boreholes) and in the lower part of Ledai Formation (Butkūnai and Svėdasai boreholes) in Lithuania. The second kind of succession is spread in the Leivu Formation in Estonia and Latvia and in the Ledai Formation in Lithuania (see Fig. 5).

6.2. Tidally influenced shallow-marine siliciclastic environmental group

This environmental group consists of two facies associations – siliciclastic peritidal and barrier-island complex. The depositional group starts with mixed and/or muddy tidal flat sediments. Some channel-like sediment was discovered. These channels are in the distal part of the tidal flat depostis and they carried some silt and sand sediments to the muddy flat. Muddy coastlines, to where the muddy tidal flat belongs are mostly close to major river systems debouching large quantities of suspended sediments into the sea (Tucker, 2001).

The mixed, muddy tidal flat sediments change to the relatively coarse-grained coastal barrier-island complex. This environment indicates higher energy depositional system than that of muddy tidal flat. Barrier-island complex is characterized with stacking barrier channel complexes.

This tidally influenced siliciclastic environmental group is widespread all over the basin. It covers completely the above laying shallowing-upward successions (Fig. 5). The beginning of this environmental group is marking the boundary between Leivu/Ledai and Kernave formations, except in Tartu and Butkūnai boreholes, where the boundary is drawn between the tidal mud flat and barrier bar complexes and in Mehikoorma, where this environmental group belongs completely to the Leivu Formation.

6.3. Delta environmental group

This environmental group consists of two environments – prodelta and delta front/mouth bar. The prodelta sediments are founded only in Butkūnai borehole. The delta front/mouth bar deposits founded in Tartu and Mehikoorma boreholes (Fig. 5). The deposits in Tartu borehole are characterized by mouth bar sediments. Probably the sediments deposited in the proximal part of delta front, near to the level of delta plain. The deposits in Mehikoorma borehole are characterized with relatively fine grained sediments and with three up to 2 m thick homogeneous units. The sediments probably deposited in the distal part of delta front, what indicate the relatively fine grained sediments. The homogeneous sedimentary units indicate the gravitational deposits - mass movement, what is probably caused by the high sediment accumulation in the delta front.

This environmental group belongs entirely to the Kernave Formation, except Mehikoorma borehole, where the boundary between Leivu and Kernave formations are in the middle of delta front sediments.

7. Sequence stratigraphy

The sequence stratigraphical interpretation is based on the analysis of the facies associations lateral and vertical variation in the studied sections. Three major sequence boundaries are discovered in the Narva sediments. First sequence boundary is on the boundary between Pärnu and Narva RS. Second sequence boundary appears at the boundary of Vadja and Leivu Formation or in the boundary between lower and upper Ledai Formation. Third sequence boundary is recognized in Kernave Formation. In relation to the unconformities two full sequences and one uncompleted sequence in Narva RS distinguished (see Fig. 5).

The lateral and vertical variations of facies associations indicate clear difference between the north (Tartu and Mehikoorma boreholes), middle (Valga, Ludza, Butkūnai, Svedasai and Palanga boreholes) and southern (Ledai and Taurage boreholes) parts of basin during the first sequence. At the end of second sequence the depositional environments were changing and were getting more similar all over the entire basin. Because of that, there is no clear correlation within the first sequence. The mixed peritidal deposits in the Ledai and Tauragė boreholes are considered to belong to the second sequence.

First sequence

The first sequence is distinguished in northern and middle parts of the basin. It starts with the dolomite or breccia layers on the top of Pärnu RS. However the TST is not seen in the sediments and it can be eroded. HST deposits are characterized with prograding tidal deposits. Three successions are defined. The FRST is definided in Butkūnai, Svėdasai and Palanga boreholes with sandy rich deposits: sandy dolomite and dolomitic sand. The lowest sea-level is indicated in Palanga borehole with meter thick dolomitic marl with the very fine-grained sand content.

Second sequence

The sequence boundary (SB) is marked with the sedimentary cap in the shallower parts of basin. In carbonate beds the vugs and caverns occur (see Appendixes 1-3), and in the places carbonate beds with high terriceneous material occur. LST is marked clearly in Butkūnai, Svėdasai and Palanga boreholes. This sytem track is characterized by 2 m thick upper-medium grained sandy beds. These beds are interpreted as incised valleys or channels cut into the sediments during the low sea-level periods.

In Butkūnai, Svėdasai boreholes clear early transgressive sytem tract deposits are recognized. In Butkūnai and Svėdasai boreholes the beds are marked with shallow subtidal/peritidal deposists. This shows the slow sea-level rise at still relatively low sea-level conditions. The siliciclastic mud beds with silty interlayers in Palanga borehole belong to the TST, but the transition between TST and HST is unclear TST is marked with burrowed siliciclastic mud in Ludza and Valga boreholes.

No beds which could mark the maximum flooding (msf) boundary were distinguished. This boundary is most probably in the mudstones lying just above the SB. The HST is marked with prograding facies associations that reach from deep subtidal to shallow subtidal and lagoonal environments up to the mixed peritidal sediments.

The upper portion of this sequence is gets progressively more muddy in composition. These sediments are interpreted deposited in a peritidal environment with freshwater influence. The input of terrestrial material (esp. clay) changes the system from carbonate to the siliciclastic dominated all over the basin and is was probably accompanied with some sea-level rise. The uppermost deposits in the sequence are the same in all basin – siliciclastic mixed, mud peritidal sediments covered by barrier-island sediments.

Third sequence

In this sequence only HST is discovered. This system track is characterized by delta sediments, which start to deposit in the northern part of the basin. This sequence is not closed and probably the above lying deposits from the lower part of the Aruküla RS close the sequence.

8. Basin evolution

The deposition in the Narva time started with carbonate prevailing transgression, this event is widely distributed and correlated over large area on the East European Platorm. During the Narva time in the DBB shallow marine conditions prevailed. The deposition in Narva time started with carbonate sediments, which slowly turned off to the siliciclastic sedimentation in the end of Narva time.

The Narva deposits are characterized by the mixed carbonate-siliciclastic sediments with tidal and storm features. The tidal influence in deposits indicates flaser, wavy, lenticular bedding, fenestria, caverns, vugs and mudcracks. The (storm) wave affection mark tempestites, carbonate clasts, etc. in the sediments. Following these features we successt, that the sedimentation in the Narva time occurred in the tidally influenced low energy shallow marine conditions with (storm) wave affection. This environmental condition is common for shallow epeiric seas (Slingerland, 1986).

The sediments in Narva RS represent classical mixed carbonate-siliciclastic deposits. Following the classification given by Tucker (2003), the Narva RS mixed deposits were formed in both ways: (1) by temporal and (2) spatial facies mixing. The temporal facies mixing characterize the swallowing-upwards cycles with siliciclastic mud lower part and carbonate upper part. In bigger scale, the mixing is represented by siliciclastic rich carbonates and dolomitic silt- and sandstones in FRST and LST deposits. The spatial facies mixing indicate mixed carbonate-siliciclastic peritidal sediments, deposited during the HST. Following the Mount classification (1984), the mixed sediments are supposed to be deposited by punctuated and facies mixing.

Based on the facies analysis several facies associations were distinguished. The lateral and vertical variation of the facies associations was used to restore the basin evolution and the sequence stratigraphical interpretation. Based on facies association's three sequences in Narva RS were indentificated. Each of them represents a distinct Stage in the basin evolution and the relative sea-level fluctuation.

First sequence characterizes the beginning of the Narva time and it consists with relatively thin successions thickening to the basinwards. The successions evolution and the lateral progradation to the basinward during the first sequence are caused by relative sea-level changes: the infill of accommodation space during the relative sea-level still-stand or falling sea-level.

During the last stage of this sequence large amount of sand with gravel sized quarts grains were carried into the middle part of the basin (See Butkūnai, Svėdasai and Palanga boreholes in appendixes 5; 6; 9). These beds are interpreted to be incisised valley or channels fills deposited during the FRST. Most probably the relative high amount of silciclastic deposits is carried to the basin by river(s), cutting the previous carbonate platform, during the low sea-level. Based on these data's we successt that the relative sea-level drop in the end of first sequence was quite a high.

The beginning of the second sequence was affected by continued siliciclastic input to the basin during LST. During the relative sea-level rise the retrogradation of the facies started. The second sequence is characterized by one succession. The sediment accumulation during the second sequence is higher than during the first one. Most probably the thickness of the second sequence is given by the subsidence which gave more accommodation space.

The first part of the second sequence is characterized by the high difference of sediments deposited in the basin. In the southern part of basin mixed peritidal sediments deposited. In the northern and middle part of the basin the sedimentation started with the subtidal deposits, during the sequence the amount of silty and sandy material slowly increase. Finally in northern and southern part of the basin the mixed peritidal deposits prevailed (in Ludza, Valga, and Ledai, Tauragė boreholes). The deposits in the Butkūnai and Svėdasai boreholes indicate somewhat deeper depositional system.

The mixed peritidal sediments are mostly indicated with thin silty and sandy interlayers or interbeds. Most probably the sediments are carried to the basin by the wind from the siliciclastic source area near to the basin. Because there are no mixed carbonate sediments with silty and sandy interlayers founded from the Butkūnai and Svėdasai boreholes, we suggest that there were two source areas one in the north another somewere in the south. From the northern side the silty, sandy sediments from the exposed area near to the Caledonian massive were carried into the basin. From the southern side of basin wind blown sediments are expected to be carried into the carbonate prevailing system from the massive somewhere south, most probably from Ukrainan-Voronezh anticline.

In the end of the second sequence the income of the terrigenous material to the basin increased and the sediments turned muddier once – freshwater influenced sediments prevailed. This facies association composes the thickest unit in the Tauragė borehole. Probably the freshwater income and sedimentation of this facies association started from the southern side of the basin. The siliciclastic deposits lying on the carbonate once are widespread in the entire basin. Most probably during the basin turned off to the siliciclastic once the small relative sea-level rise occurs. The relative sea-level rise indicate the deposition in the Narva Brook; the most northern sedimentation part of the DBB.

The third sequence is characterized only by deltaic deposits. The deposition probably started from the northern side of the basin. The prodelta sediments in the Butkūnai borehole indicate the deltaic depositional system. However the presence of second deltaic system is not clear, because the lack of the data's.

Because the unclearity with the boundary between Narva and Aruküla RS (Kleesment, 1999), some of the sediments in the third cyclotherm may belong already to the Aruküla RS.

9. Conclusion

The deposits in Narva RS are composed with two different litholocical units – carbonate and siliciclastic. The carbonate part in Narva RS is characterized by mixed carbonate-siliciclastic sediments, in the siliciclastic part silty and mostly fine-grained sediments prevailed. In carbonate sediments two mixing ways occur (1) temporal and (2) spatial facies mixing. The temporal facies mixing is characterized by the shallowing-upward cycles and by the dolomitic sand and sandy carbonates deposited during the FSRT and LST. The spatial faces mixing is characterized by punctual and facies mixing in peritidal deposits during the HST.

In Narva RS 14 facies, 7 subfacies were distinguished and 11 facies associations were separated. Based on the lateral and vertical variation of the facies associations the sedimentary successions were distinguished. Two types of succession: (1) deep subtidal - shallow subtidal - carbonate peritidal and (2) deep subtidal – shallow subtidal – and mixed peritidal were indentificated. First one dominated during the Vadja/Lower Ledai time in the northern and middle part of the basin. The second succession formed during the Leivu/ (Upper) Ledai time in whole basin. Based on the successions and the facies association variation three sequence boundaries and sequences were indetificated.

During the first sequence the carbonate deposition prevailed. On the boundary between first and second sequence the sea-level drop was relatively high and the siliciclastic input by river(s) occur during the FSRT and in LST. In the second sequence the mixed peritidal sediments dominated caused by aeolian income. The sediment bulk during the second sequence was relatively high, probably caused by subsidence. In the end of the second sequence the siliciclastic income to the basin increased and basin turned to the siliciclastic once. The third sequence marks the closing of the basin.

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Kesk-Devoni Narva ealised setted Balti Basseinis: settekeskkonnad ja sekvents stratigraafia

Kokkuvõte

Narva ealised setted on levinud kogu Balti Basseinis, samuti ulatuslikul alal Ida Euroopa platvormil. Narva lademe setteid kirjeldati esmakordselt Karl Orviku poolt 1930 aastal. Lade on nimetatud Narva jõe järgi, mille kallastel kirjeldati esmakordselt selle ealiseid setteid.

Narva lademe setted koosnevad kahest litoloogiliselt erinevast osast – karbonaatsest ja silikaat-purdsettelisest. Põhilise osa Narva lademe setetest moodustavad karbonaadid, silikaat-purdsetteid esineb kogu basseini läbilõikes ainult lademe ülemises osas.

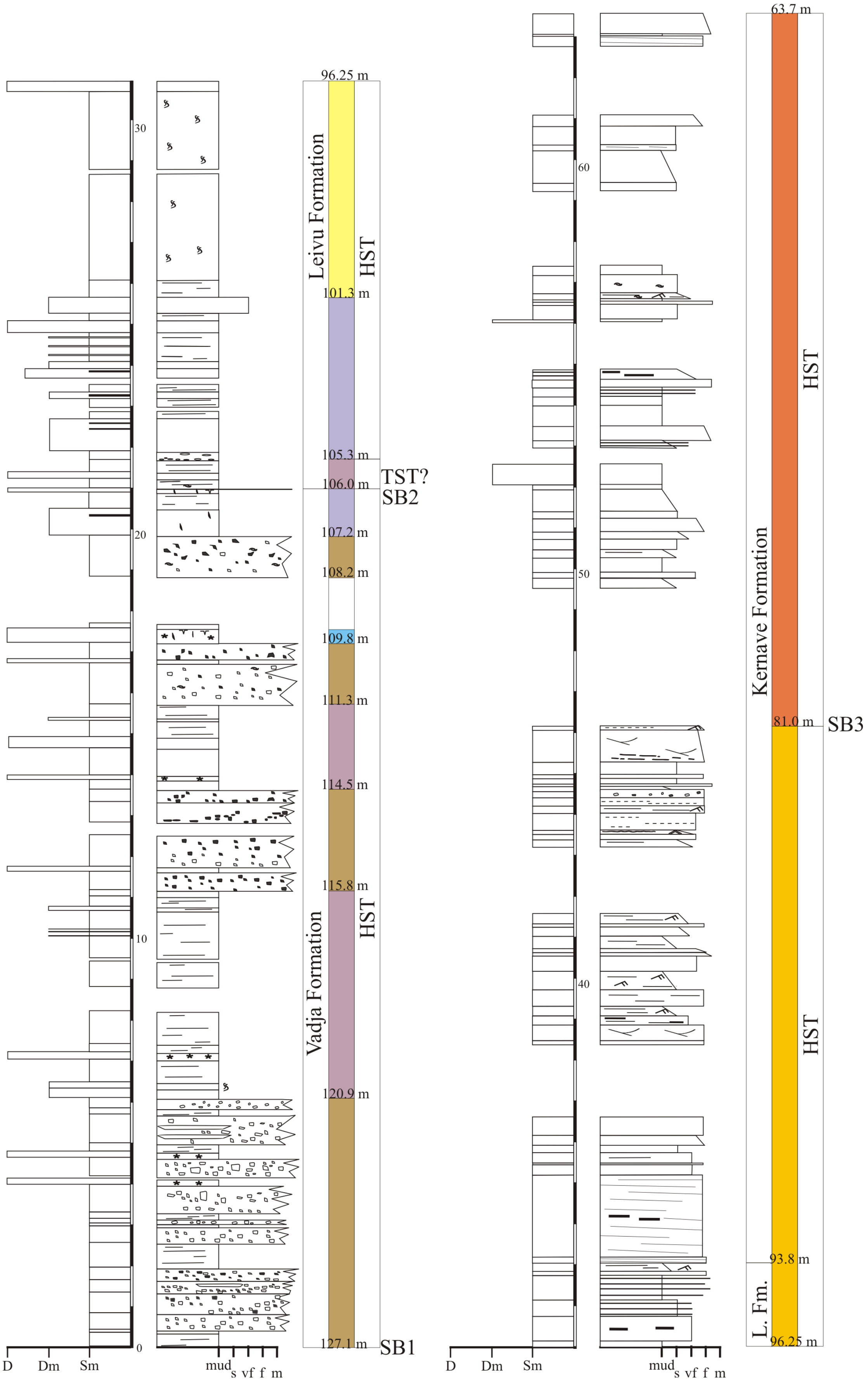
Narva lademe karbonaatse kompleksi moodustavad karbonaat- ja silikaat-pursettelised segakooslused. Need setted on moodustunud kahel viisil: (1) ajalise ja (2) ruumilise faatsieste leviku tulemusena. Ajaliselt varieeruvad segakooslused esinevad ülespoole madalduvate (shallowing-upwards) tsüklitena. Pikemas ajalises persepktiivis on nende settimine seotud langevaseisulise kulu (FRST) ja madalseisulise kulu (LSST) jooksul setinud dolomiitsete liivakivide ja silikaat-purdsetteliste karbonaatidega, mis vahelduvad kõrgseisulise kulu (HSST) ajal settinud karbonaatidega. Ruumilist fatsiaalset segunemist iseloomustavad Narva ladmes kahte tüüpi setted: punkt (punctuated) ja faatsieste (facies) segakooslused, settinud enamuses HSST ajal.

Käesoleva magistritöö käigus eraldati uuritud läbilõigete alusel 14 faatsiest, 7 alamfaatsiest ning 11 fatsiaalset kooslust (facies assocication). Fatsiaalsete koosluste lateraalse ja vertikaalse leviku põhjal eraldati välja kahte tüüpi litokehi (sedimentary successions): (1) alumine subakvaalne – ülemine subakvaalne – karbonaatne subaeraalne tõusu-mõõna tsükkel, ja (1) alumine subakvaalne – ülemine subakvaalne – karbonaat- silikaat purdsetteline subaeraalne tõusu-mõõna tsükkel. Esimene litokeha domineerib basseini põhja-ja keskosas, Vadja ja alumise Ledai kihistu piirides. Teine litokeha levib Leivu ja (ülemise) Ledai kihistus, üle kogu basseini. Litokehade ja fatsiaalsete koosluste alusel eraldati kolm sekventsi.

Esimese sekventsi ajal settisid basseinis karbonaatsed setted. Esimese ja teise sekventsi piiril esines arvatavasti küllaltki suur veetaseme langus. Seda sündmust markeerib ulatuslikul alal esinevad õhukesed liiva kihid või suuremad liivakate karbonaatide, dolomiitsete liivakivide kompleksid. Need kihid on arvatavasti settinud FRST ja LSST ajal. Teist sekventsi iseloomustab märgatavalt paksem settekeha võrreldes esimese sekventsiga. Seetõttu arvatakse, et teise sekventsi ajal toimus märgatav basseini vajumine, mis tingis suurema hulga setete kuhjumise basseinis. Teise sekventsi lõppu tähistab silikaat-purdsettelise materjali hulgaline sissekanne basseini, mille tulemusena muutus settekeskkond basseinis, levisid silikaat-purdsettelised tõusu-mõõna lainetusest mõjutatud rannikulähedaste keskkondade setted (siliciclastic peritidal and barrier-island facies associations). Kolmanda sekventsiga algas basseinis deltaline settimine, mis ühtlasi märgib ka basseini sulgumis ja täitumis setetega.

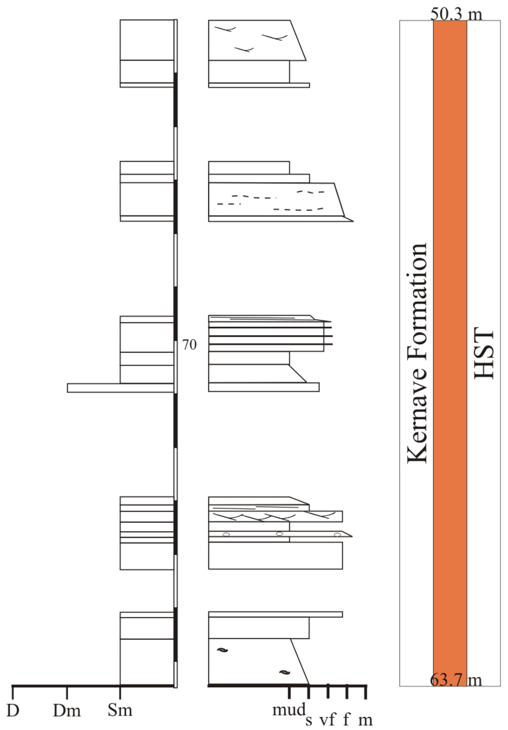
Appendix 1

Tartu-453/1

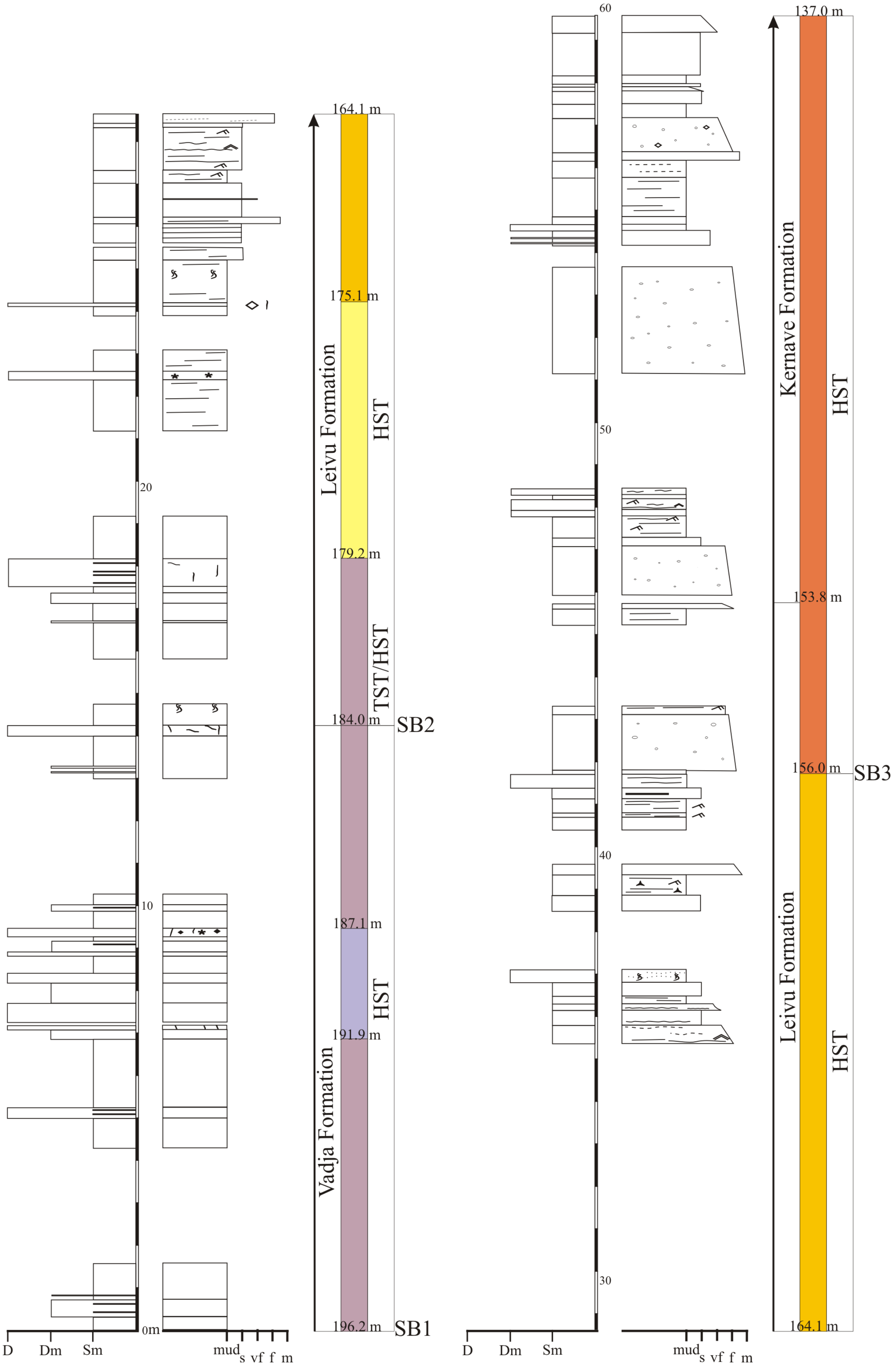


(For the legend and explanation in all boreholes look the Appen dix 10.)

Tartu-453/2

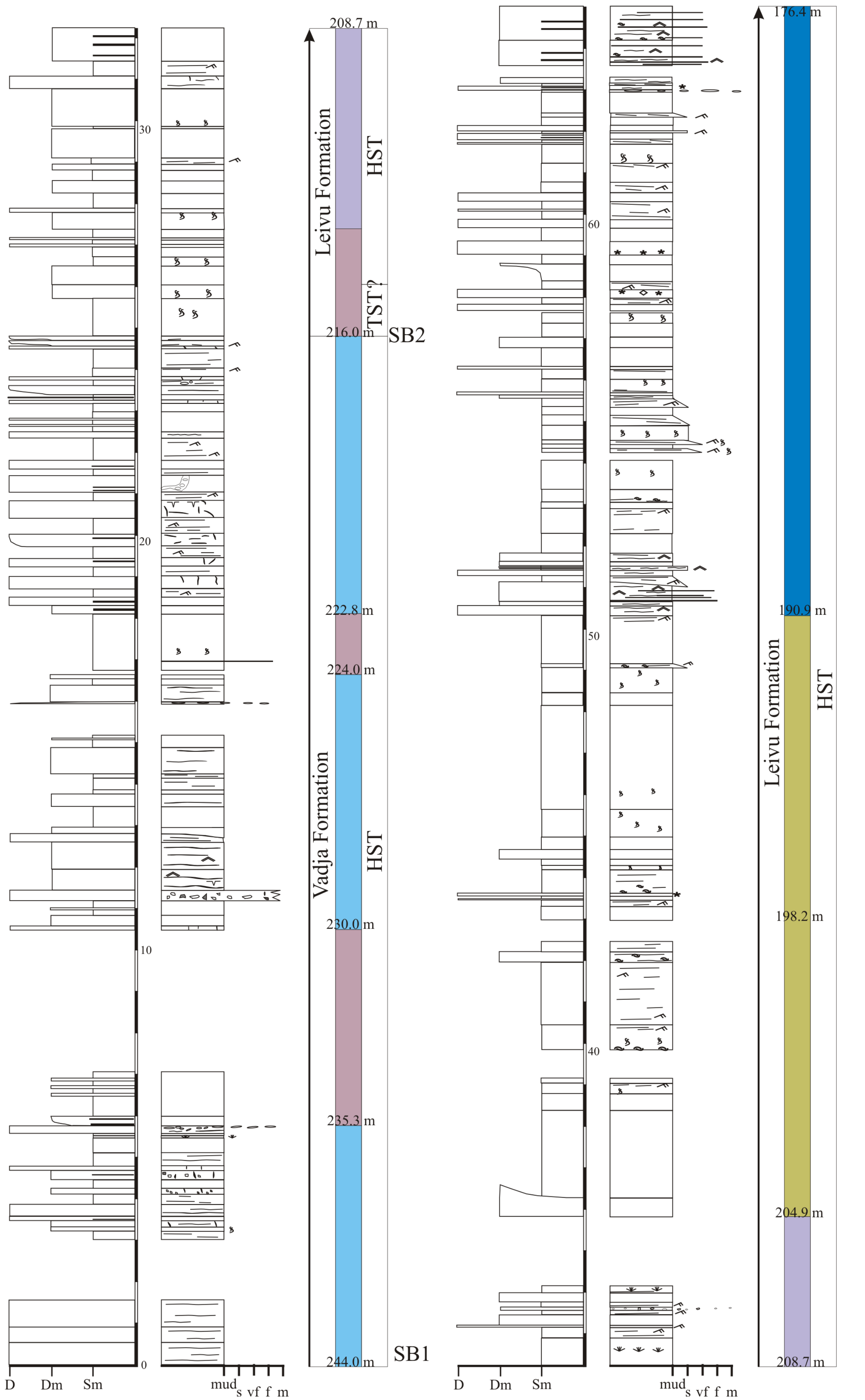


Mehikoorma-421

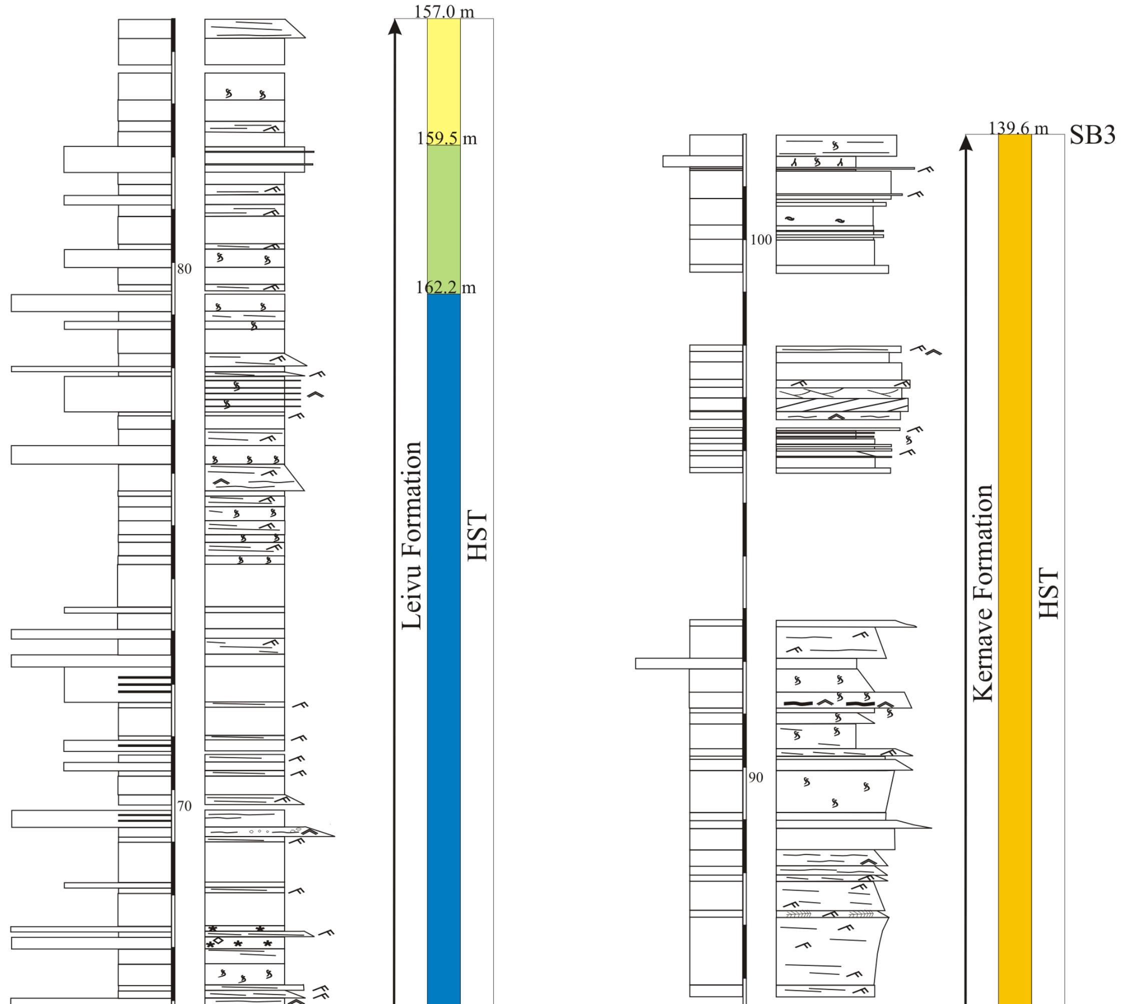


Appendix 3

Valga-10/1

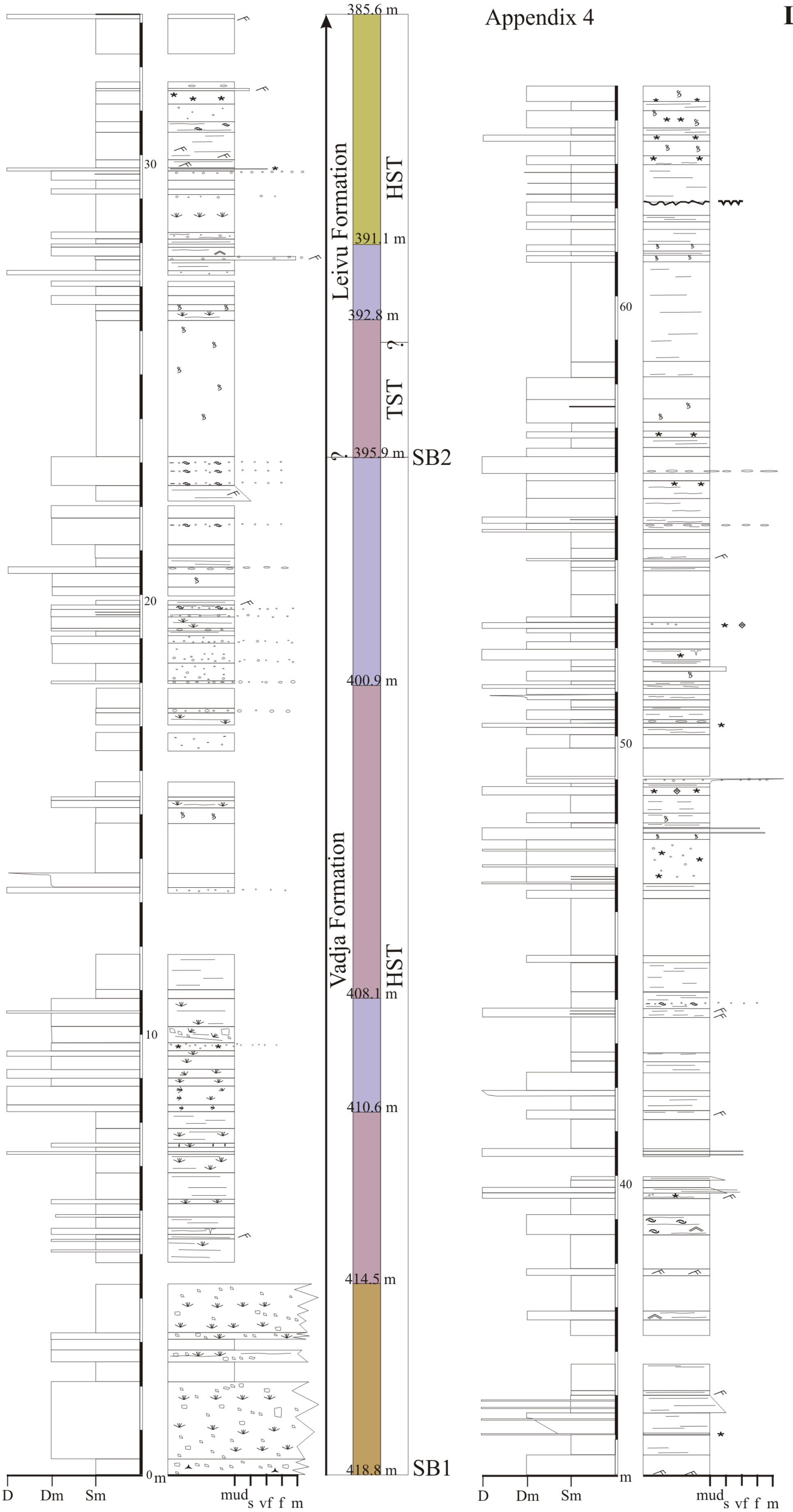


Valga-10/2

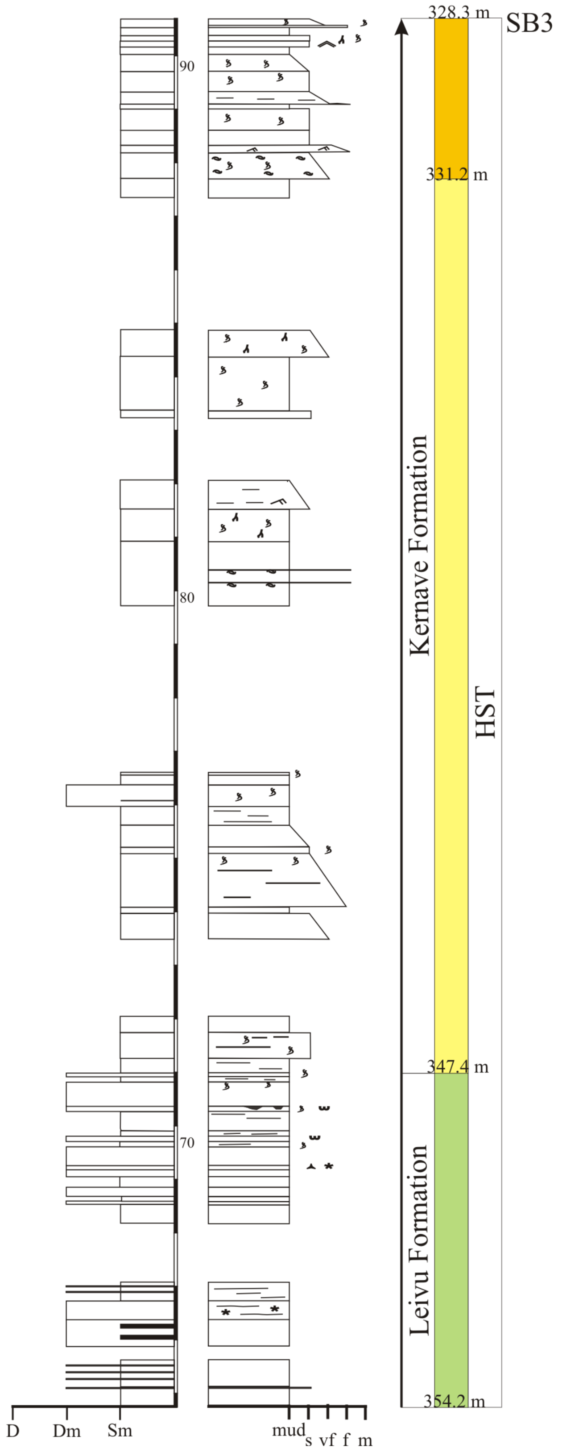

157.0 m
159.5 m
162.2 m
176.4 m
80
70
Leivu Formation
HST
D
Dm
Sm
mud
s
vf
f
m
139.6 m
SB3
157.0 m
100
90
Kernave Formation
HST
D
Dm
Sm
mud
s
vf
f
m

Appendix 4

Ludza-15/1

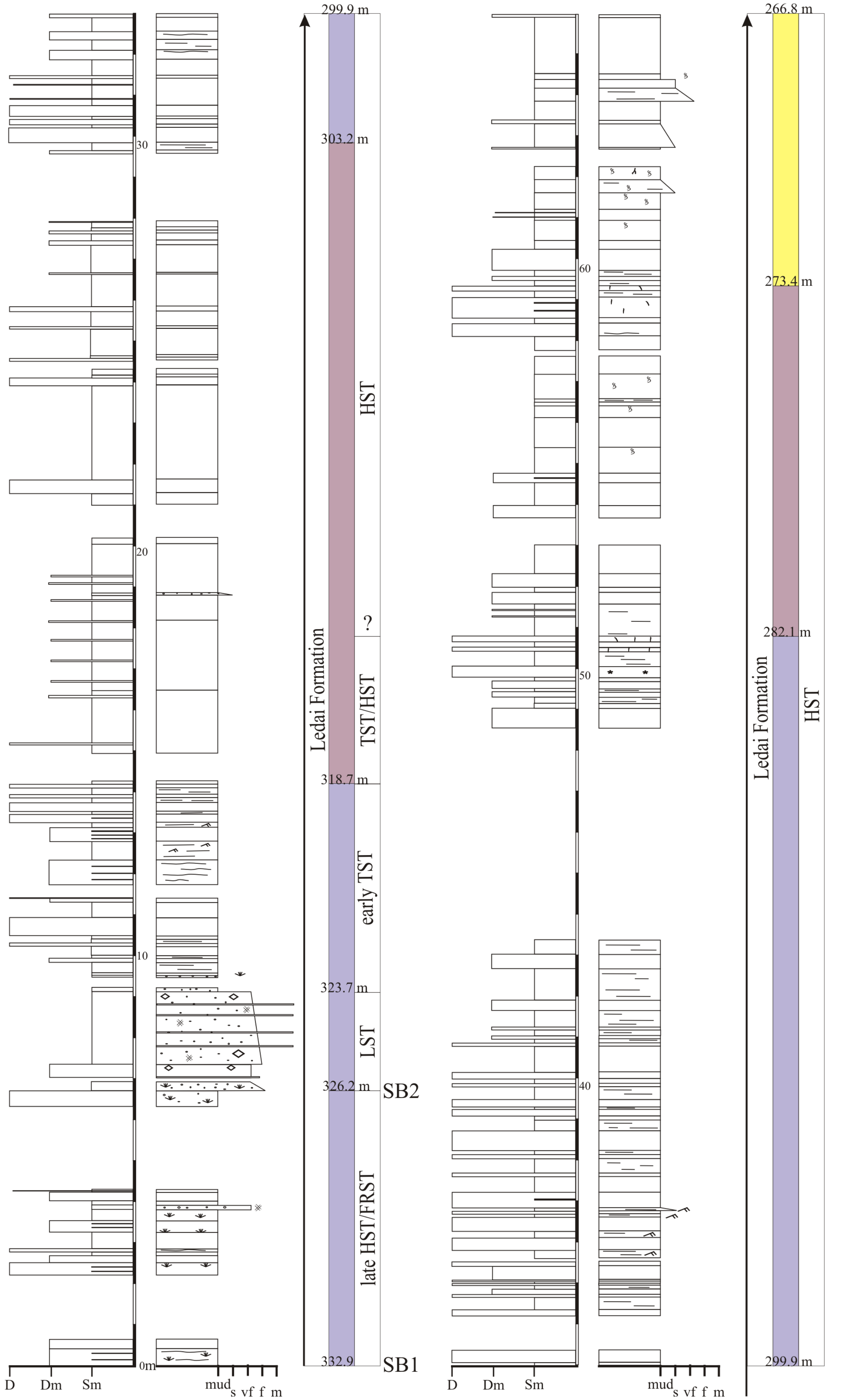


Ludza-15/2

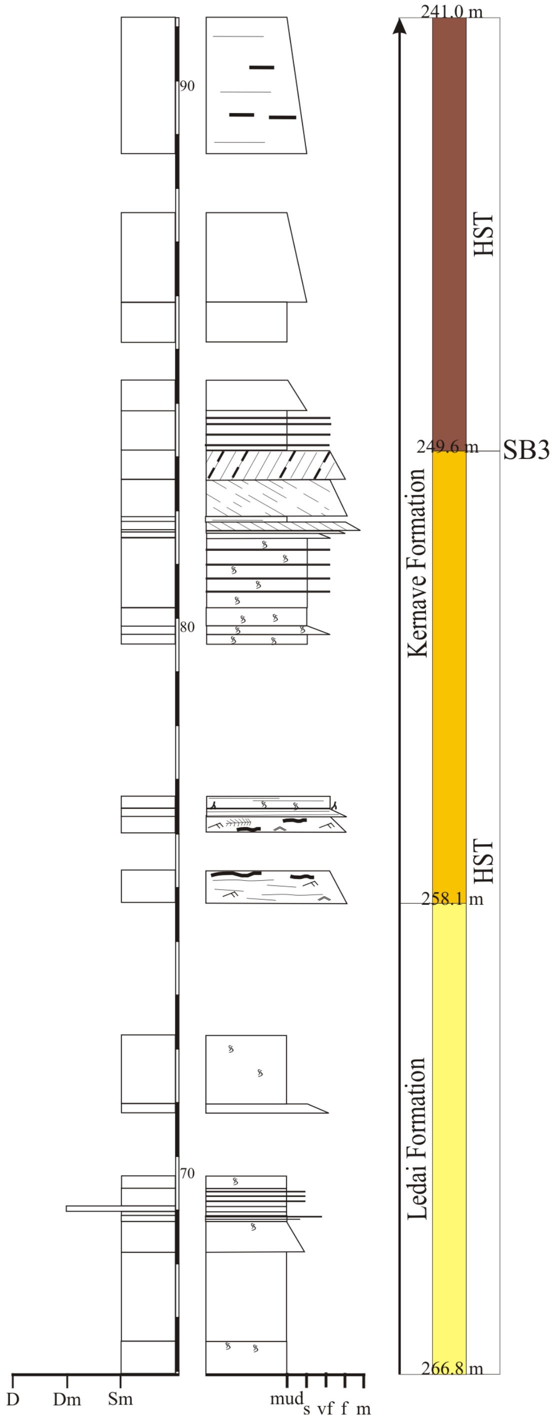


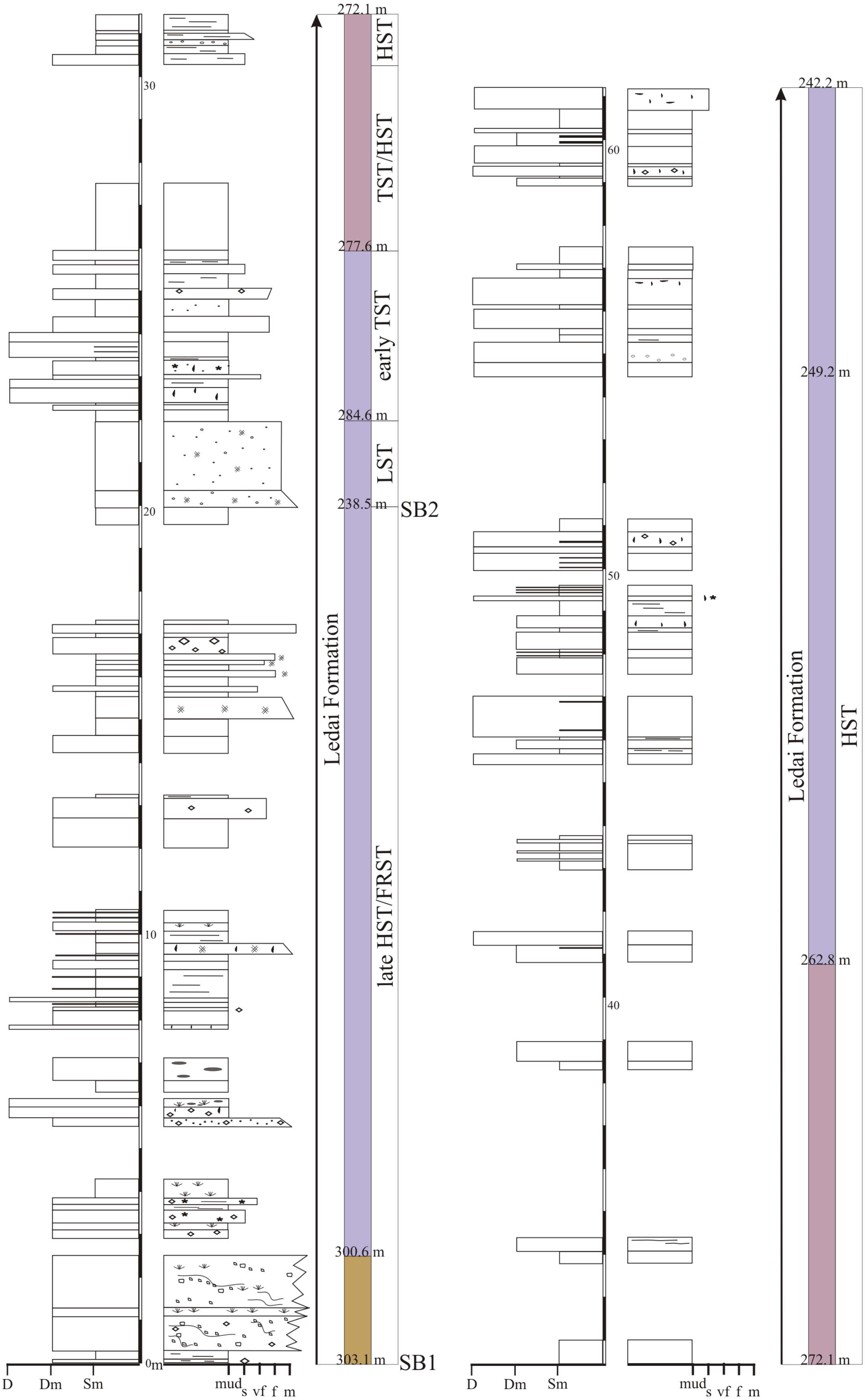
328.3 m
SB3
331.2 m
90
80
70
Kernave Formation
HST
347.4 m
Leivu Formation
354.2 m
D
Dm
Sm
mud
s
vf
f
m

Butkunai-241/1

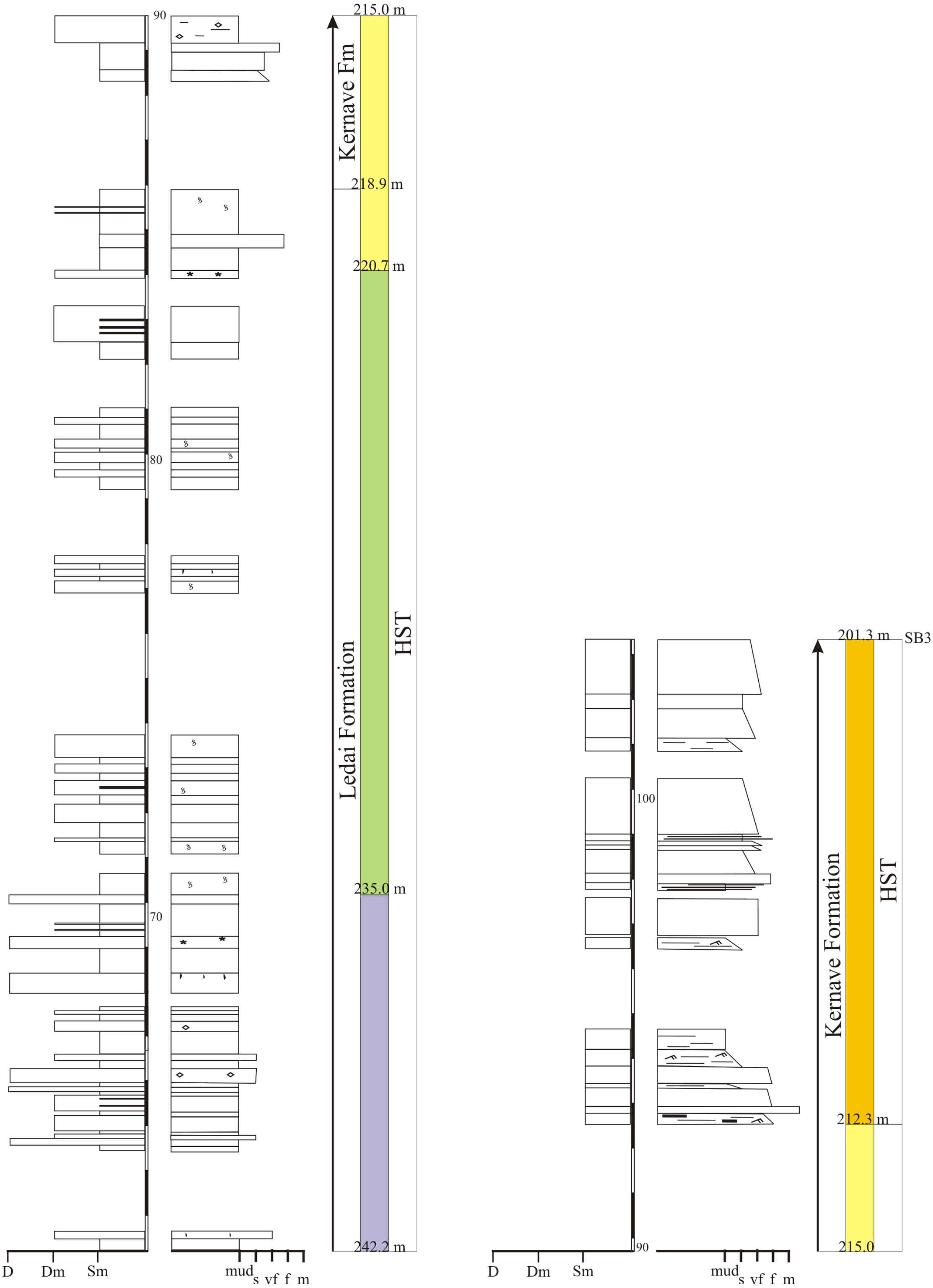


Butkunai-241/2



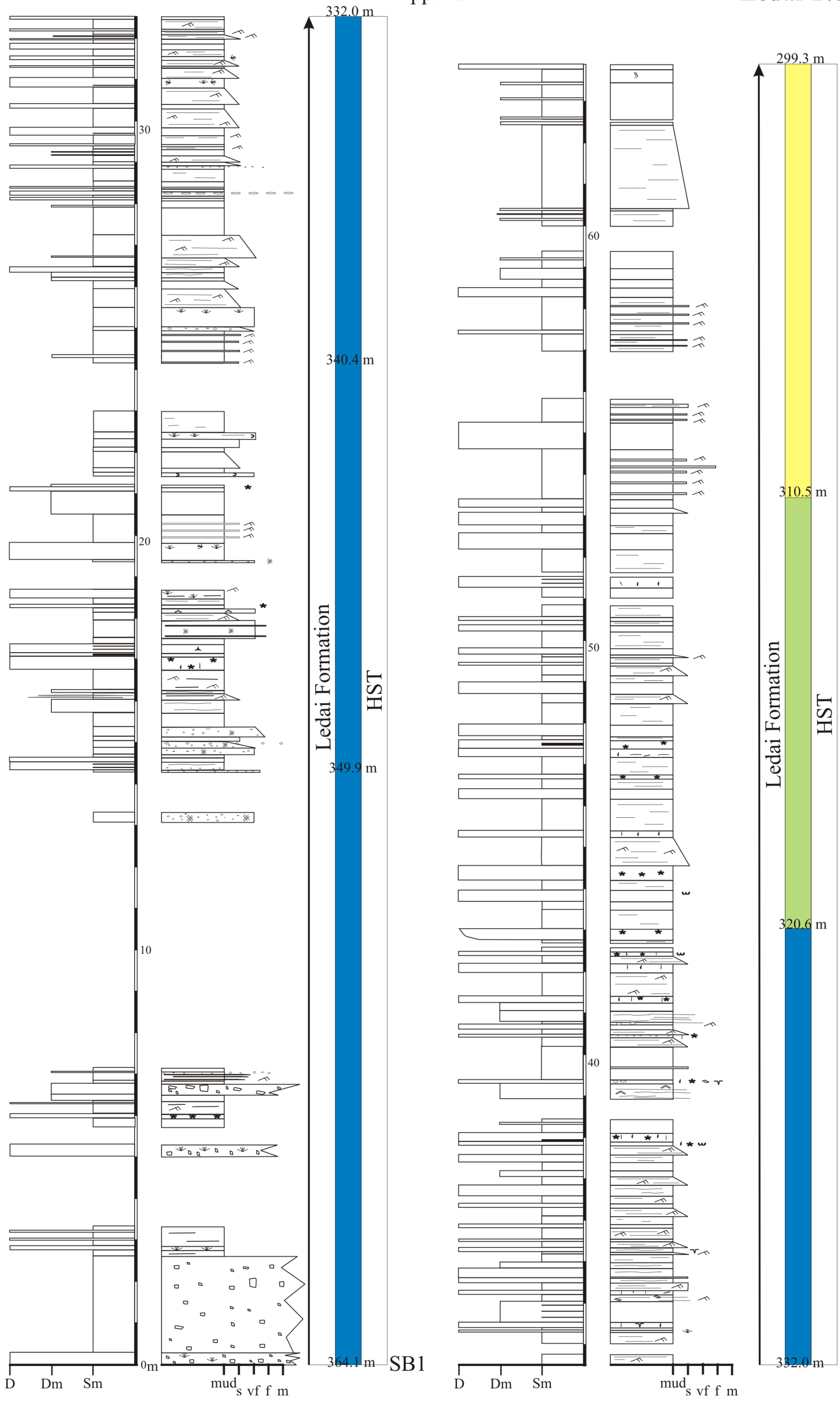


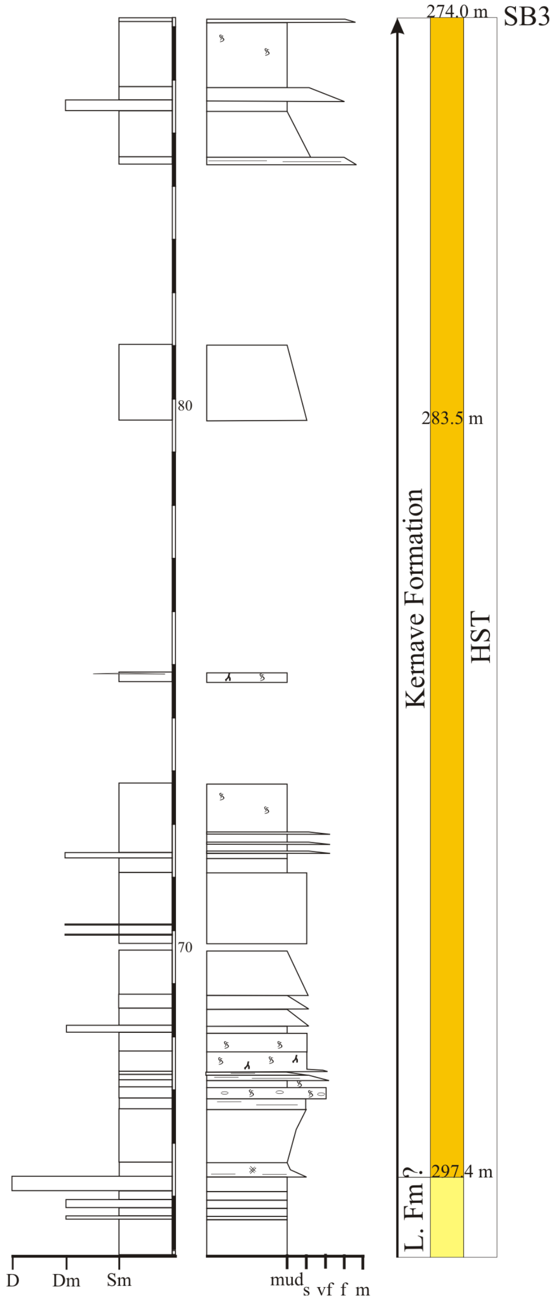
272.1 m
HST
TST/HST
277.6 m
early TST
284.6 m
LST
238.5 m
SB2
Ledai Formation
late HST/FRST
300.6 m
303.1 m
SB1
30
20
10
0m
D
Dm
Sm
mud
s
vf
f
m
242.2 m
60
50
40
249.2 m
262.8 m
272.1 m
Ledai Formation
HST


90
80
70
215.0 m
218.9 m
220.7 m
235.0 m
242.2 m
Kernave Fm
Ledai Formation
HST
D
Dm
Sm
mud
s
vf
f
m
201.3 m
SB3
212.3 m
215.0
100
90
Kernave Formation
HST
D
Dm
Sm
mud
s
vf
f
m

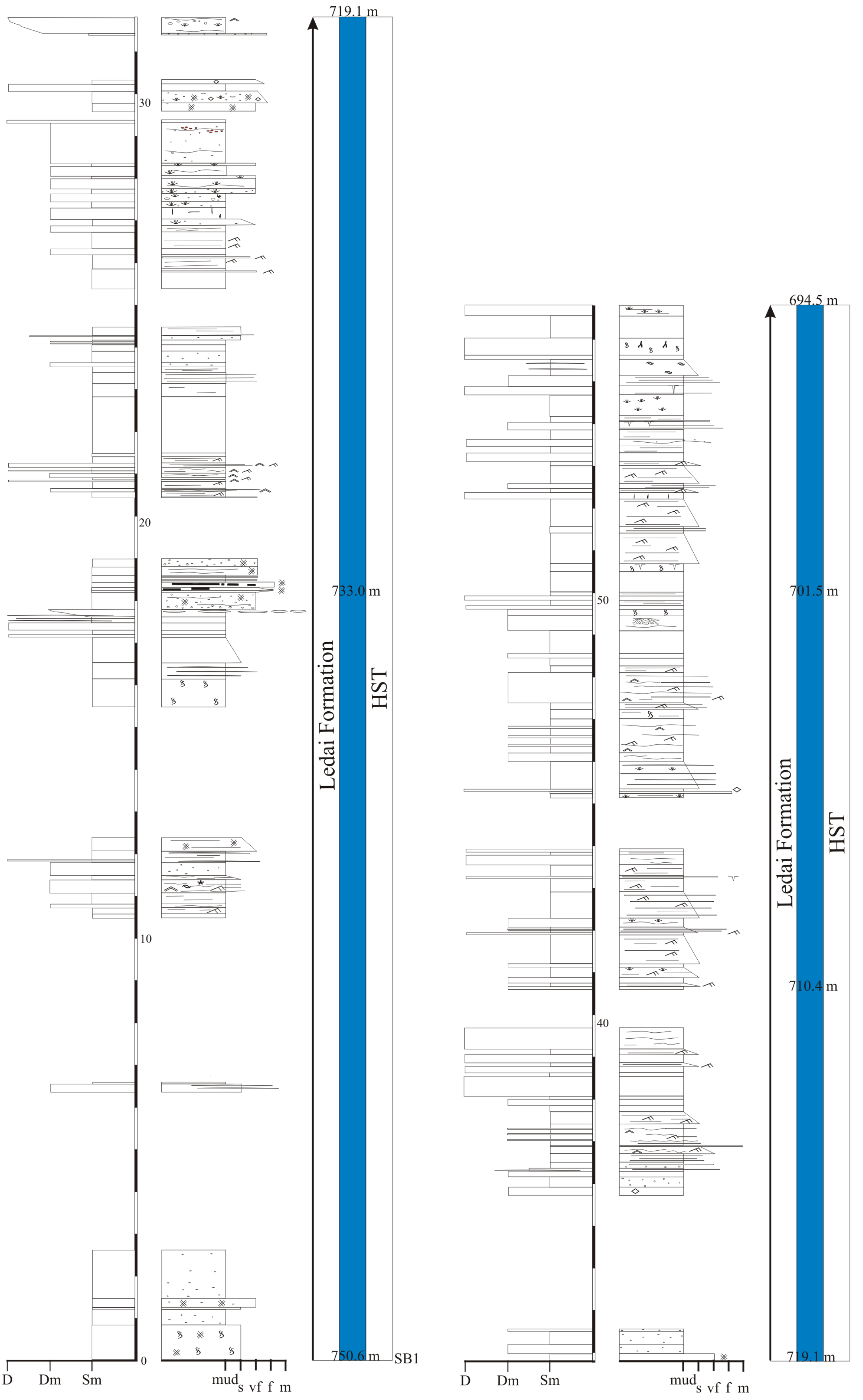
Appendix 7

Ledai-179/1



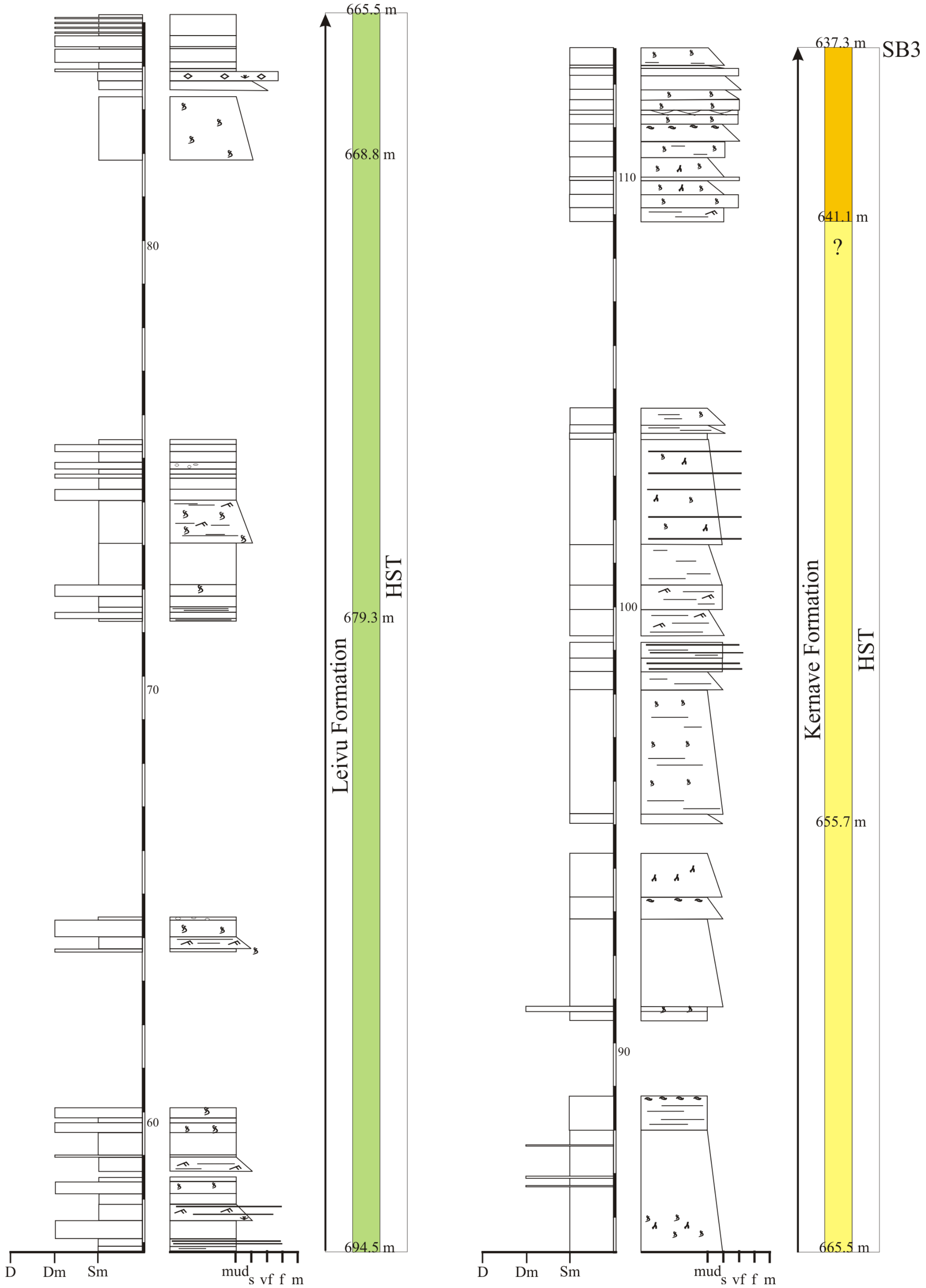

274.0 m
SB3
283.5 m
297.4 m
Kernave Formation
L. Fm?
HST
80
70
D
Dm
Sm
mud
s
vf
f
m

Taurage-11/1



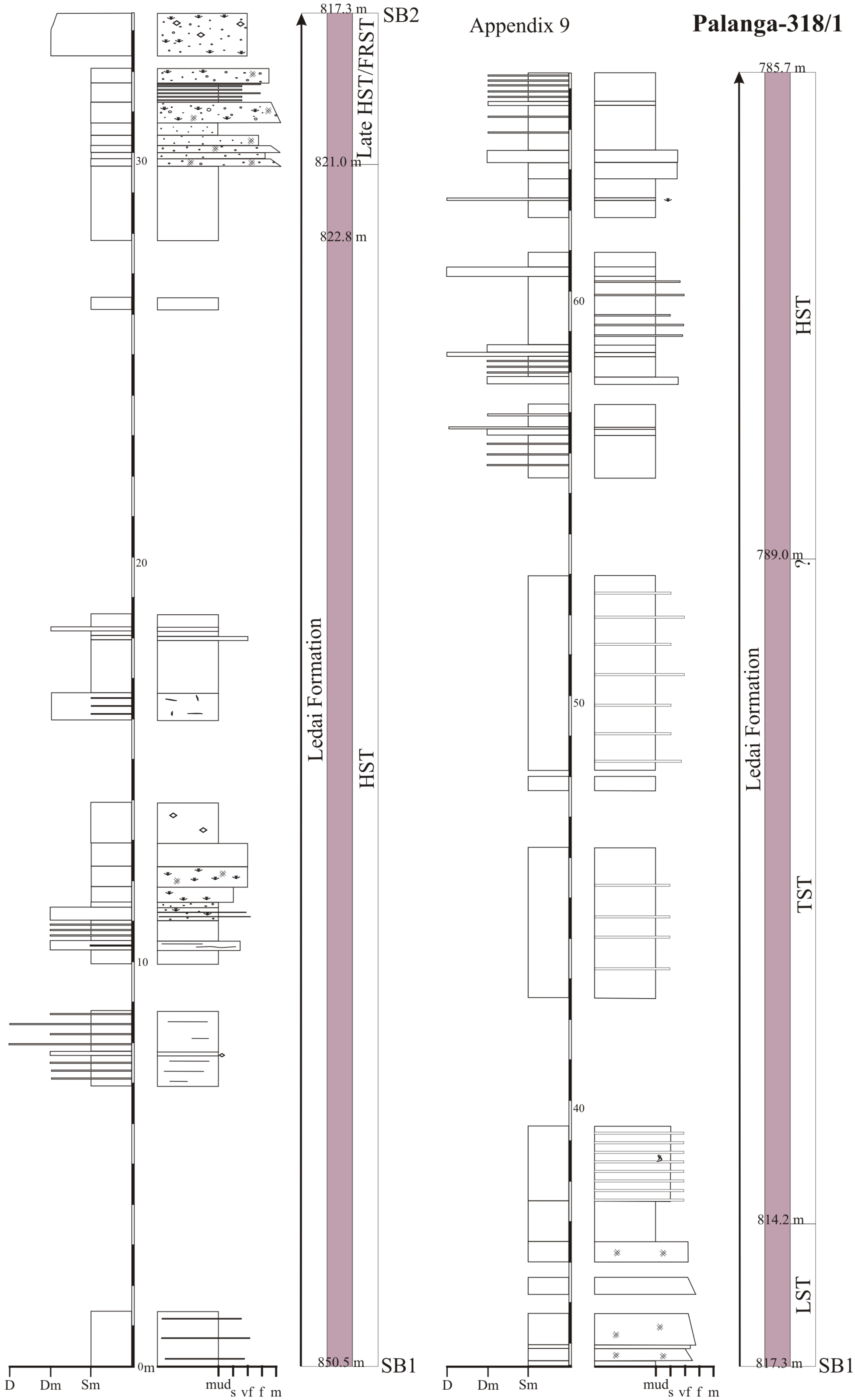
719.1 m
733.0 m
750.6 m
SB1
Ledai Formation
HST
30
20
10
0
D
Dm
Sm
mud
s
vf
f
m
694.5 m
701.5 m
710.4 m
719.1 m
50
40

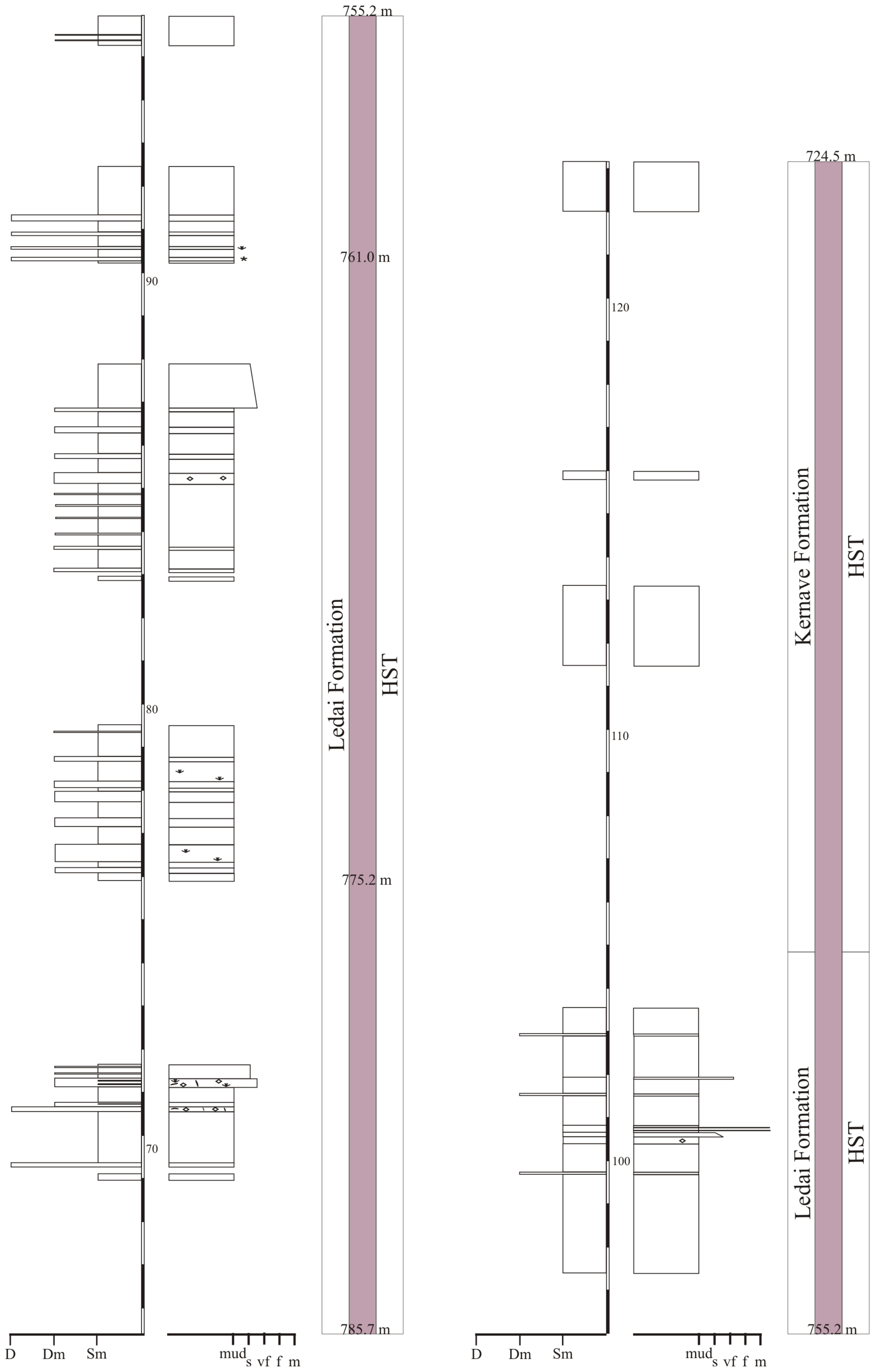
Taurage-11/2


665.5 m
668.8 m
679.3 m
694.5 m
Leivu Formation
HST
80
70
60
D
Dm
Sm
mud
s
vf
f
m
637.3 m
SB3
641.1 m
?
655.7 m
665.5 m
Kernave Formation
HST
110
100
90
D
Dm
Sm
mud
s
vf
f
m

Appendix 9

Palanga-318/1





755.2 m
761.0 m
775.2 m
785.7 m
90
80
70
Ledai Formation
HST
D
Dm
Sm
mud
s
vf
f
m
724.5 m
755.2 m
120
110
100
Kernave Formation
HST
Ledai Formation
HST
D
Dm
Sm
mud
s
vf
f
m

Symbols

Facies associations

- prodelta deposits
- delta front/mouth bar deposits
- barrier-island deposits
- siliciclastic peritidal deposits
- fresh water influenced peritidal
- mixed peritidal deposits
- carbonate peritidal deposits
- lagoonal deposits
- shallow subtidal deposits
- deep subtidal deposits
- breccia
- SB
- msf
- the boundary of the succession

Sedimentary strutures

- current ripple
- wave ripple
- caverns
- mudcrack
- cypsum
- bioturbation
- crystal
- crack, viens
- anhydrite diapirs
- carstification
- shell fragments
- a.clast of clay
- b.clast of dolomite
- quarts grains
- halite pseudomorfs