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The Upper Ordovician of Estonia: facies, sequences, and basin development

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ABSTRACT

Sequence stratigraphic analysis of the Nabala–Porkuni regional stages (RSs; upper Katian–Hirnantian) of Estonia clarifies the Late Ordovician evolution of the Estonian Shelf–Livonian Basin. The integration of depositional facies, biostratigraphy, carbon isotope chemostratigraphy, karst surfaces, and hiatuses indicates seven sequences: (1) Nabala (Paekna and Saunja Formations (Fms)); (2) Vormsi (Kõrgessaare, Tudulinna, and Fjäcka Fms); (3) Lower Pirgu (Moe and Jonstorp Fms); (4) Middle Pirgu (most of the Adila and Halliku Fms, and Jelgava and Parovėja Fms); (5) Upper Pirgu (Kabala Member (Mb), part of the Halliku Fm); (6) Lower Porkuni Sequence (most of the Ärina Fm); and (7) part of the Upper Porkuni–Juuru Sequence (Kamariku Mb and Saldus Fm). A lowstand systems tract is only identified in the uppermost sequence. Transgressive units are marked by onlapping depositional packages. Highstands consist of one or more shallowing-upward shelf packages (notably in the Vormsi, Lower Pirgu, and Middle Pirgu sequences). The sequences record the progradation of shallow-to-middle ramp facies as sediment infilled the northern edge of the Livonian Basin, leading to an open shelf (Porkuni RS). Eustasy was the major factor in sequence boundary formation with larger amplitude sea level oscillations associated with Hirnantian (Porkuni) glaciations. A shift to more strongly differentiated ramp facies at the Nabala–Vormsi transition coincides with the initial collision of Baltica and Avalonia.

Introduction

This study describes the depositional facies and stratigraphic sequences of the upper Katian–Hirnantian (Upper Ordovician) strata of Estonia, and interprets the evolution of the Estonian Shelf of the East Baltic region. Sequence stratigraphy provides a method for interpreting facies patterns and stratigraphic relations within a chronostratigraphic framework. A sequence-by-sequence facies analysis can reveal the detailed history of relative sea level changes and basin-scale depositional patterns that can clarify tectonic history. This report builds on our prior study of western Estonia (Harris et al. 2004) in three ways. First, it uses additional core data to extend the stratigraphic analysis to include mainland Estonia. Second, the integration of core coverage with recent biostratigraphic and chemostratigraphic studies clarifies the position and temporal resolution of facies changes, stratigraphic hiatuses, and stratal relationships at a systems tract level. Third, the expanded geographical coverage reveals the evolution of the Estonian Shelf from a carbonate ramp to an open shelf at the end of the Ordovician, and subtle tectonic influences on depositional patterns.

Geological setting and stratigraphy

The study area lies along the north flank of an epicontinental basin on the paleocontinent of Baltica that formed during the late Precambrian and that was influenced by the collision with the Avalon microcontinent during the Late Ordovician (Torsvik and Rehnström 2003; Cocks and Torsvik 2005). It straddles the transition between the Estonian Shelf and the Livonian Basin, an embayment of the Scandinavian Basin

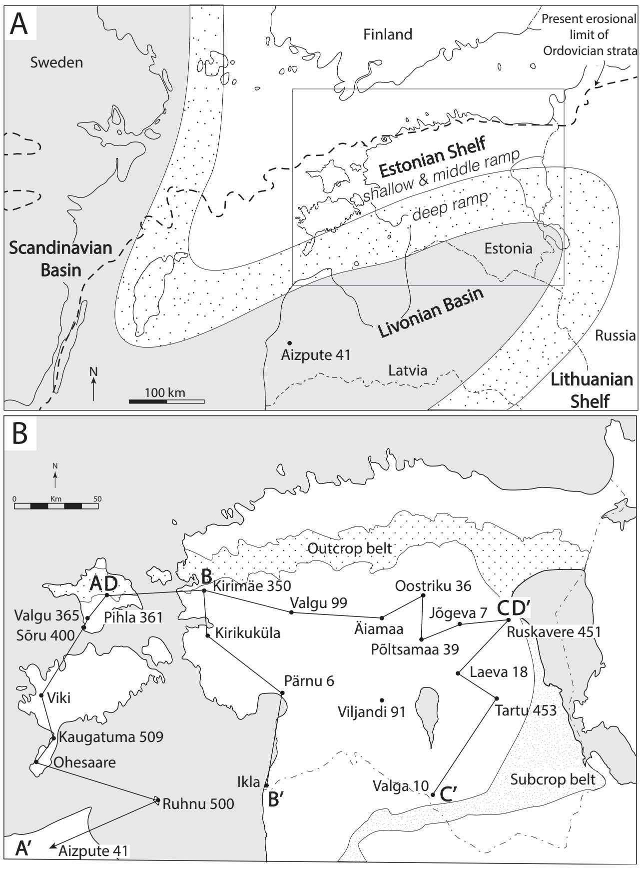

Fig. 1. Location map of the study area. **A** – major paleogeographic features of the Baltic region during the late Katian (Vormsi–Pirgu RSs). The location of the Aizpute core in northwestern Latvia is shown. The boxed area indicates the location of B. Modified from Ainsaar and Meidla (2001). **B** – locations of studied cores and the lines of cross sections A–A' to D–D' used in Figs 4–7.

(Jaanusson 1973, 1976; Bassett et al. 1989; Kaljo 1990; Raukas and Teedumäe 1997; Fig. 1A). The northern Estonian outcrop belt nearly parallels depositional strike and exposes a section of shallow-ramp and middle-ramp carbonates (Fig. 1B). The section deepens southward across the central Estonian deep-ramp zone into deep-water shales of the Livonian Basin in southern Estonia, western Latvia, and northwestern Lithuania. The Lithuanian Shelf forms the southeastern edge of the Livonian Basin in eastern Latvia, southeastern Lithuania, and northwestern Belarus.

The stratigraphic nomenclature of the study area is complex, reflecting the location along an environmental gradient and resulting in the use of different formation names for shallow and deep sections (Fig. 2). Within the East Baltic, regional stages provide a consistent framework (Bassett et al. 1989; Männil 1990; Männil and Meidla 1994; Raukas and Teedumäe 1997 and references therein) based on biostratigraphic work on conodonts (Männik and Viira 1990), chitinozoans (Nõlvak and Grahn 1993; Nõlvak 1999), ostracodes (Meidla and Sarv 1990; Meidla 1996), graptolites (Männil 1976; Männil and Meidla 1994), brachiopods (Hints 1990), bentonite correlations (Kiipli et al. 2004), and, most recently, carbon isotope chemostratigraphy (Ainsaar et al. 2010, 2015; Meidla et al. 2020; Hints et al. 2023). These stratigraphic studies are also the basis for correlations of the Baltic regional stages with global stages (Hints et al. 1994; Goldman et al. 2023; Meidla et al. 2024). This study addresses the upper Nabala, Vormsi, Pirgu, and Porkuni regional stages (RSs), and is equivalent to the upper Katian and most of the Hirnantian Global Stages. This study's lithostratigraphic nomenclature follows general usage with more recent updates (Raukas and Teedumäe 1997; Hints et al. 2005; Meidla et al. 2024; Fig. 2).

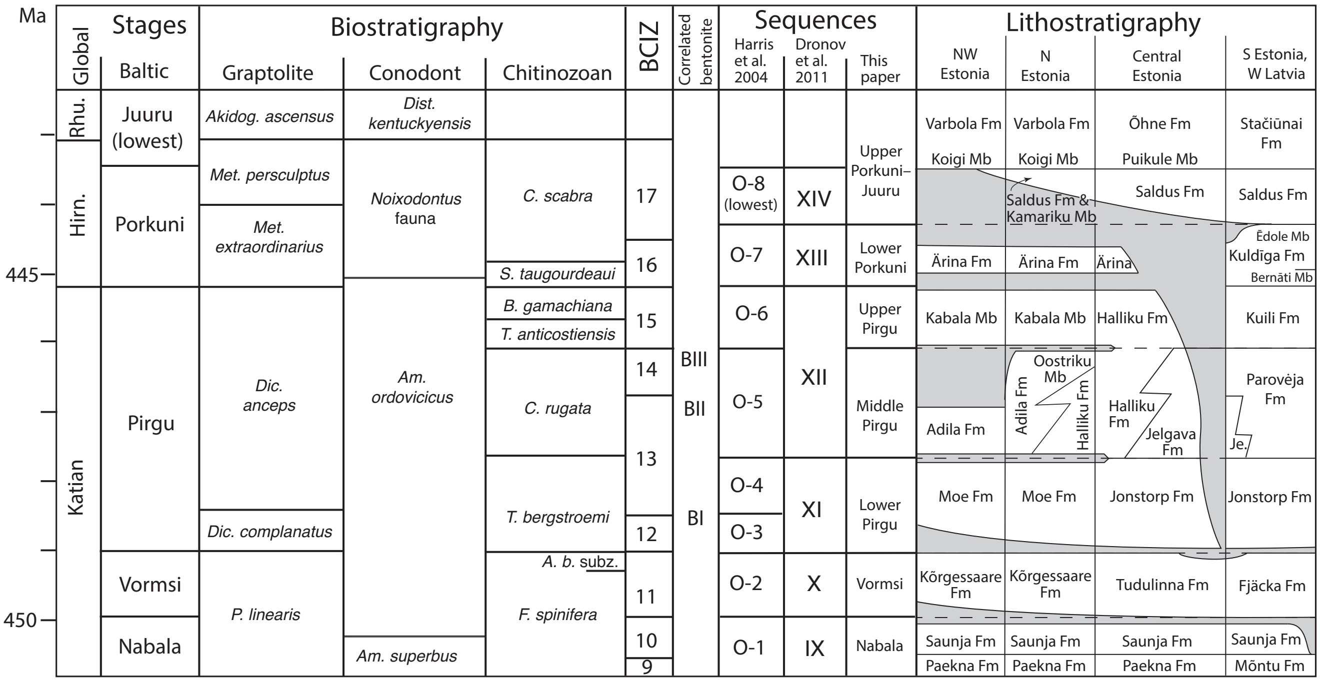

Fig. 2. Late Ordovician (Nabala to basal Juuru RSs) stratigraphy. Abbreviations: Hirn. – Hirnantian, Rhu. – Rhuddanian, BCIZ – Baltic carbon isotope zones (Ainsaar et al. 2010), *Akidog.* – *Akidograptus*, *Met.* – *Metabolograptus*, *Dic.* – *Dicellograptus*, *P.* – *Pleurograptus*, *Dist.* – *Distomodus*, *Am.* – *Amorphognathus*, *C.* – *Conochitina*, *S.* – *Spinachitina*, *B.* – *Belonechitina*, *T.* – *Tanuchitina*, *A. b.* subz. – *Acanthochitina barbata* subzone, *F.* – *Fungochitina*, Fm – formation, Mb – member, Je. – Jelgava. The Kamariku Mb is part of the Ärina Fm (see text for discussion). The time scale is from Goldman et al. (2020, 2023) and Meidla et al. (2024).

This paper uses the absolute time scale currently in use by the Estonian Geological Survey (Goldman et al. 2020, 2023; Meidla et al. 2024), pending consideration of ongoing research (Zhang et al. 2025).

Materials and methods

This study is based on a detailed, centimeter-scale description of 23 cores distributed from the Estonian Shelf to the Livonian Basin (Fig. 1B). The cores were described on sedimentological logs at a 1:50 scale that summarized depositional texture, sedimentary structures, grain size, ichnofabric index, clay content, color, and fossil content. The cores are held at the core storage facilities of the Geological Survey of Estonia and the Department of Geology of Tallinn University of Technology. Twenty-two of the cores were drilled in Estonia, and one in Latvia. Most cores penetrated the entire study section (upper Nabala through Porkuni RSs). The cores do not include the type sections of the stratigraphic units studied because most formations were defined in outcrop sections, and others are in cores that we did not examine. Our major criteria were to select cores that are relatively complete, provide coverage across the facies belts, and include useful biostratigraphic and chemostratigraphic data. We have also made use of stage-level thickness maps that incorporate data from numerous additional wells (Raukas and Teedumäe 1997).

A critical factor in the analysis of these sections is the identification of stratigraphic hiatuses using biostratigraphy, bentonite correlations, and carbon isotope chemostratigraphy. The study spans eight Baltic carbon isotope zones (BCIZ), seven chitinozoan zones, and five graptolite zones. Four conodont zones occur within the studied section, with the *Amorphognathus ordovicicus* Zone dominating the lower three-quarters. Three key bentonite beds correlated by phenocryst chemistry provide additional chronostratigraphic horizons in the Pirgu RS (Kiipli et al. 2004; Hints et al. 2005). Multiple studies of the BCIZ and chitinozoan zones in key cores have clarified the age relationships among these chronostratigraphically useful horizons (Bauert et al. 2014; Hints et al. 2014; Ainsaar et al. 2015; Meidla et al. 2020; Hints et al. 2023), resulting in an integrated chronostratigraphic framework (Fig. 2).

Depositional facies

The studied cores extend from the Estonian Shelf to the northern edge of the Livonian Basin, and are characterized by five interfingering facies. These facies shifted north and south across the profile, reflecting transgressions and regressions (Jaanusson 1973, 1976; Einasto 1986, 1995; Bassett et al. 1989; Nestor 1990a, 1990b; Nestor and Einasto 1997; Harris et al. 2004; Dronov et al. 2011).

Grain-supported facies

The grain-supported facies consists of packstones and grainstones with a diverse marine fauna and common sedimentary structures indicative of wave and current activity. Four subfacies occur: (1) Packstones containing physical structures (ripples, wavy and cross laminations) overprinted by burrowing and bioturbation indicate depositional conditions at or above fairweather wavebase. These are widespread in updip Vormsi, Pirgu, and Porkuni RSs. (2) Ooid grainstone with cross-beds and wavy, flat, and cross lamination styles is restricted to the Porkuni RS. (3) Algal grainstone beds adjacent to lower Pirgu algal mounds are dominated by the calcareous algae *Palaeoporella*. (4) Intraclastic floatstone beds (1–3 m thick) occur at the base of some channel fills in the Porkuni RS (Jõgeva and Oostriku cores).

The grain-supported facies is interpreted as a shallow-water deposit that accumulated above fairweather wavebase. In the Vormsi and Pirgu RSs, it typically occurs at the top of shallowing-upward facies successions in updip locations. In the Porkuni RS, the grain-supported facies occurs across the shelf and includes ooid grainstones. Quartz sand is widespread in Porkuni RS strata, reaching up to 40% in the basal parts of the Saldus Formation (Fm) in some cores. In the most basinward core (Aizpute, northwestern Latvia), a 3-m bed of rippled ooids and quartz sand occurs.

Mixed facies

The mixed facies primarily consists of two subfacies: (1) the interbedded packstone and wackestone subfacies that are marked by abundant burrows, a diverse marine biota, and a high level of bioturbation, and (2) the argillaceous wackestone subfacies with a higher clay content that occurs as thin beds within this subfacies. The absence of physical sedimentary structures and the interlayering of grain-rich and argillaceous deposits suggest deposition at intermediate depths between fairweather and storm wavebase.

The mixed facies occurs in middle ramp settings throughout the Vormsi and Pirgu RSs, and in the most updip facies preserved in the upper Nabala RS (Saunja Fm).

Mud-supported facies

The mud-supported facies includes several subfacies differentiated based on faunal and clay content; all are well burrowed. (1) The main part of the Saunja Fm consists of the mudstone subfacies with echinoids, bryozoans, gastropods, ostracodes, and other fossil fragments with marly interbeds. (2) The fossiliferous wackestone subfacies contains a diverse marine fauna (echinoderms, tabulate corals, rugose corals, brachiopods, calcareous algae, etc.) with argillaceous and/or mudstone interbeds. It predominates in deep-ramp zone areas of the Vormsi (Tudulinna Fm) and Pirgu RSs (Halliku and Jonstorp Fms) and also occurs in the lagoon in northern Estonia (Pirgu RS). (3) The argillaceous mudstone-marl subfacies contains up to 40–45% clay and fine fossil fragments. It occurs in the Tudulinna Fm (Vormsi RS) in the deep-ramp zone and in the Pirgu RS along the edge of the Livonian Basin.

These subfacies all record quiet-water deposition. The mudstone subfacies is limited to the Saunja Fm, whereas the wackestone subfacies accumulated widely during the Vormsi–Pirgu time. The argillaceous mudstone-marl subfacies records the increased clay influx that characterizes the Vormsi RS.

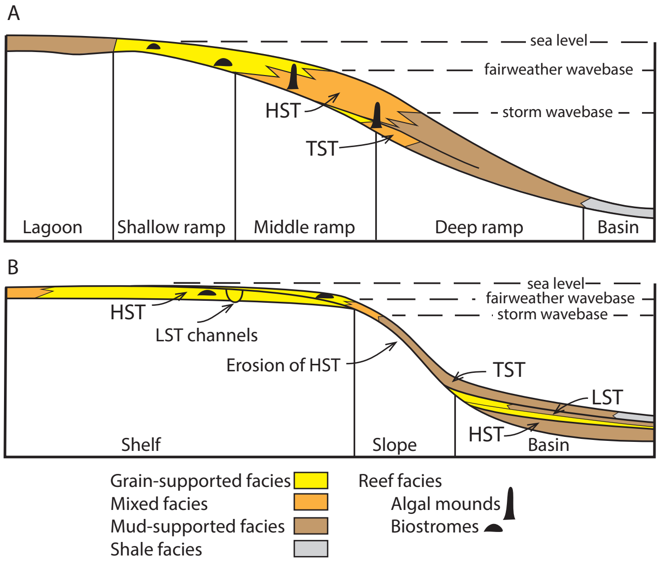

Fig. 3. Facies models with systems tracts. **A** – ramp facies model for the Nabala, Vormsi, and Pirgu RSs. **B** – open-shelf facies model for the Porkuni RS. Abbreviations: HST – highstand systems tract, TST – transgressive systems tract, LST – lowstand systems tract.

Shale facies

Basinal sections of the Vormsi RS consist of laminated to bioturbated black, dark gray, and green shales with horizontal burrows. The sparse fauna predominantly consists of graptolites. These shales are assigned to the Fjäcka Fm, a unit that occurs throughout the central Livonian and Scandinavian basins.

Mud mound facies

Two mud mounds occur in the studied cores in the lower Pirgu RS. (1) The Moe Fm in the Kaugatuma core contains a 5.7 m-thick unit of the stromatactis subfacies. The mound is red to pink in color and consists of four 1–2.6 m-thick stromatactis beds interbedded with 20-cm-thick beds of skeletal packstone. It is overlain by a 90-cm-thick bed of skeletal packstone. (2) The Jõgeva core penetrated a 25.3 m-thick algal mound dominated by *Palaeoporella* algae (Perens 1995). This subfacies contains abundant algae, crinoid clasts, and vugs; it is highly dolomitized. Both mounds initially formed in middle-ramp settings; the Jõgeva mound was more updip and persisted into shallow-ramp conditions.

Mud mounds consisting of stromatactis, *Palaeoporella*, or a combination of both subfacies are widespread in Pirgu sections of the East Baltic (Kröger et al. 2017). The thickest (52 m) mud mound occurs in the Võhma core, 24 km west of Põltsamaa, and includes both subfacies (Kröger et al. 2017).

Although not encountered in the described cores, patch reefs and biostromes are reported from the Pirgu and Porkuni RSs in shallow-ramp sections. These are up to 3 m thick and consist of a core with abundant stromatoporoids and tabulate corals flanked by pelmatozoan grainstone (Kröger et al. 2017).

Facies model

The Nabala to Pirgu strata were deposited on a broad homoclinal ramp; the depositional facies reflect an energy gradient related to fairweather and storm wavebase (Read 1983; Burchette and Wright 1992; Fig. 3A). The grain-supported, mixed, and mud-supported facies belts represent progressively deeper and lower-energy settings of shallow, middle, and deep ramp environments, respectively. The distribution of the shale facies is limited to the deep basin. Within the middle ramp settings, the *Palaeoporella* bioherms and stromatactis mud mounds form local shoals and patch reefs. Pirgu sequences include a zone of updip mud-supported facies that represents a lagoon landward of the shallow ramp shoal and patch reef environments. Thicker shallow- and middle-ramp facies accumulations resulted in shallowing and progradation of the facies succession.

Porkuni age facies are similar but are interpreted as representing an open shelf setting with shallow shelf and basin facies separated by an erosional/bypassing slope (James et al. 2010; Fig. 3B). Grain-supported facies delineate an extensive zone of shallow-water deposition; basinal marls and mudstones are interbedded with grain-supported beds with abundant quartz, small lithoclasts, and redeposited ooids. The intervening stratigraphic gap between these facies and the deposits in the Livonian Basin is interpreted as due to slumps, slides, and erosion associated with a major hiatus in a slope setting.

Stratigraphic hiatuses

Well-documented stratigraphic hiatuses occurring within the studied Estonian Shelf sections are marked by missing biostratigraphic and/or carbon isotope zones (Einasto 1995; Nestor and Einasto 1997; Ainsaar et al. 2010; Meidla et al. 2024). These occur at the top of the Nabala RS, at the top of the Vormsi RS, in the middle of the Pirgu RS (at the top of the Moe and Jonstorp Fms), in the upper Pirgu RS (at the base of the Kabala Member (Mb)), at the top of the Pirgu RS, and in the middle of the Porkuni RS (below the Kamariku Mb of the Ärina Fm and the Saldus Fm; Fig. 2). In updip cores, hiatuses are marked by missing biozones and the absence of transgressive beds (found in more basinward cores).

The most extensive hiatuses occur in two specific positions in the profile. At the outer edge of the Porkuni shelf, erosion along the shelf margin and slope locally removed all or most of the Pirgu RS, probably augmented by sliding and slumping as the ramp prograded and built an open-shelf platform with a steepened outer slope (Figs 4–6). Shallow open-shelf sections are marked by local erosional channels cut into deposits of the Pirgu and Porkuni RSs (Fig. 7).

Sequences

Placing the facies distribution into a sequence stratigraphic framework reveals the three-dimensional facies architecture and depositional history of the Estonian Shelf (Figs 4–8). The NNE–SSW orientation of the Livonian Basin results in facies trends slightly oblique to the outcrop belt, resulting in a transition into slightly deeper environments to the east (Figs 1 and 7).

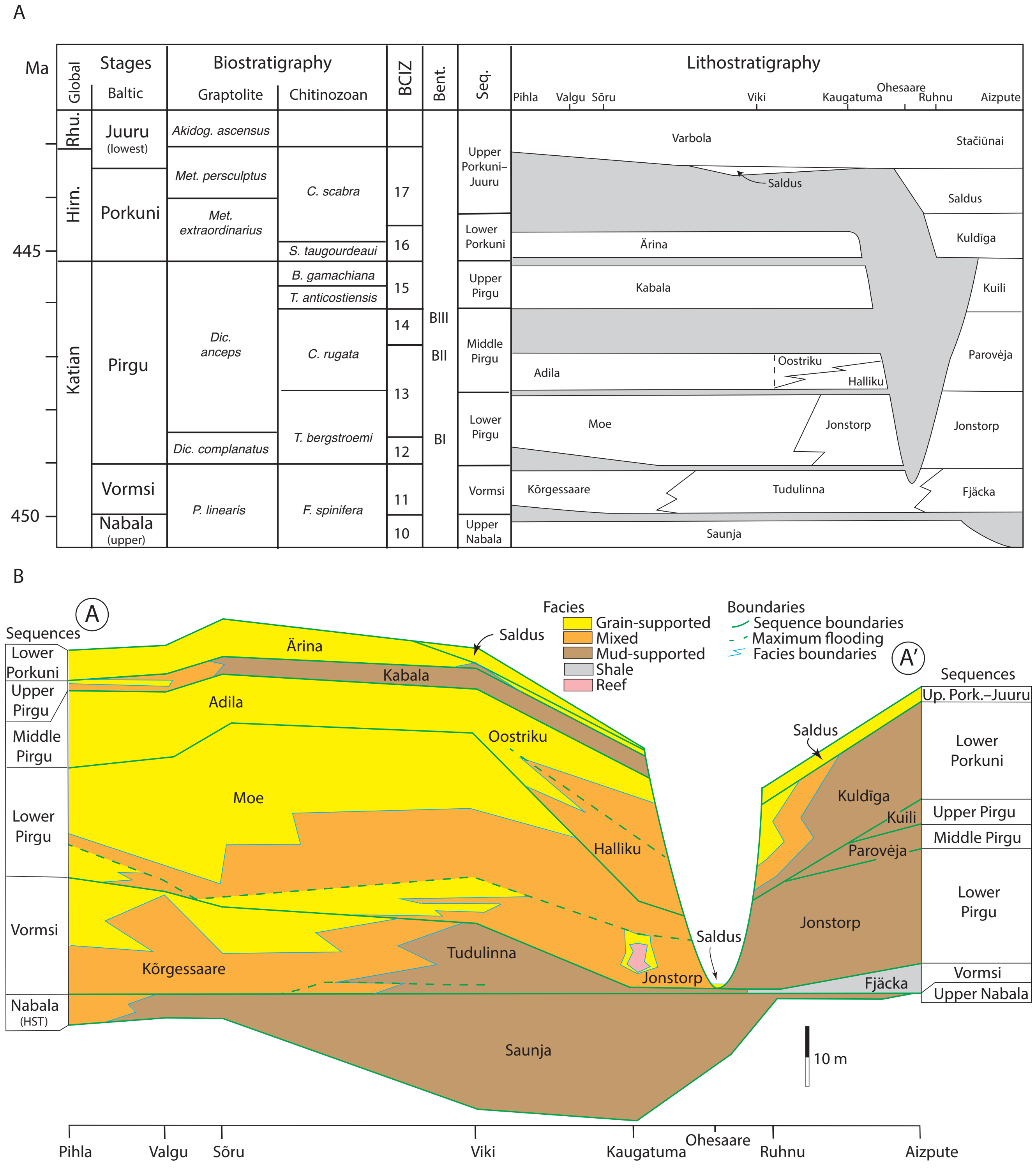

Fig. 4. Section A–A′ (Fig. 1B). The Aizpute core is located in northwestern Latvia (Fig. 1A). **A** – chronostratigraphy; **B** – facies relations and sequence interpretations. Note that the Saldus Fm is recognized in the Viki and Kaugatuma cores (unlike in Harris et al. 2004), following Hints et al. (2014). Abbreviations: Bent. – bentonite, Seq. – sequences, Up. Pork. – Upper Porkuni; for other abbreviations, see Fig. 2.

The facies patterns, erosional features, and stratigraphic gaps provide the basis for dividing the studied section into five complete sequences and two partial sequences. Ideally, sequences consist of onlapping transgressive systems tracts (TST) overlain by a maximum flooding surface, which is the base of a shallowing-upward highstand systems tract (HST) capped by an exposure surface (Fig. 3). In practice, some transgressive units cannot be resolved (in downdip sections) or are missing (in updip sections), and some highstands are eroded. A lowstand systems tract (LST) is only clearly resolvable in the Upper Porkuni–Juuru Sequence.

Nabala Sequence

The Nabala Sequence consists of the laterally equivalent Paekna and Mõntu Fms, and the overlying Saunja Fm. They are within the *Fungochitina spinifera* chitinozoan biozone; the lower

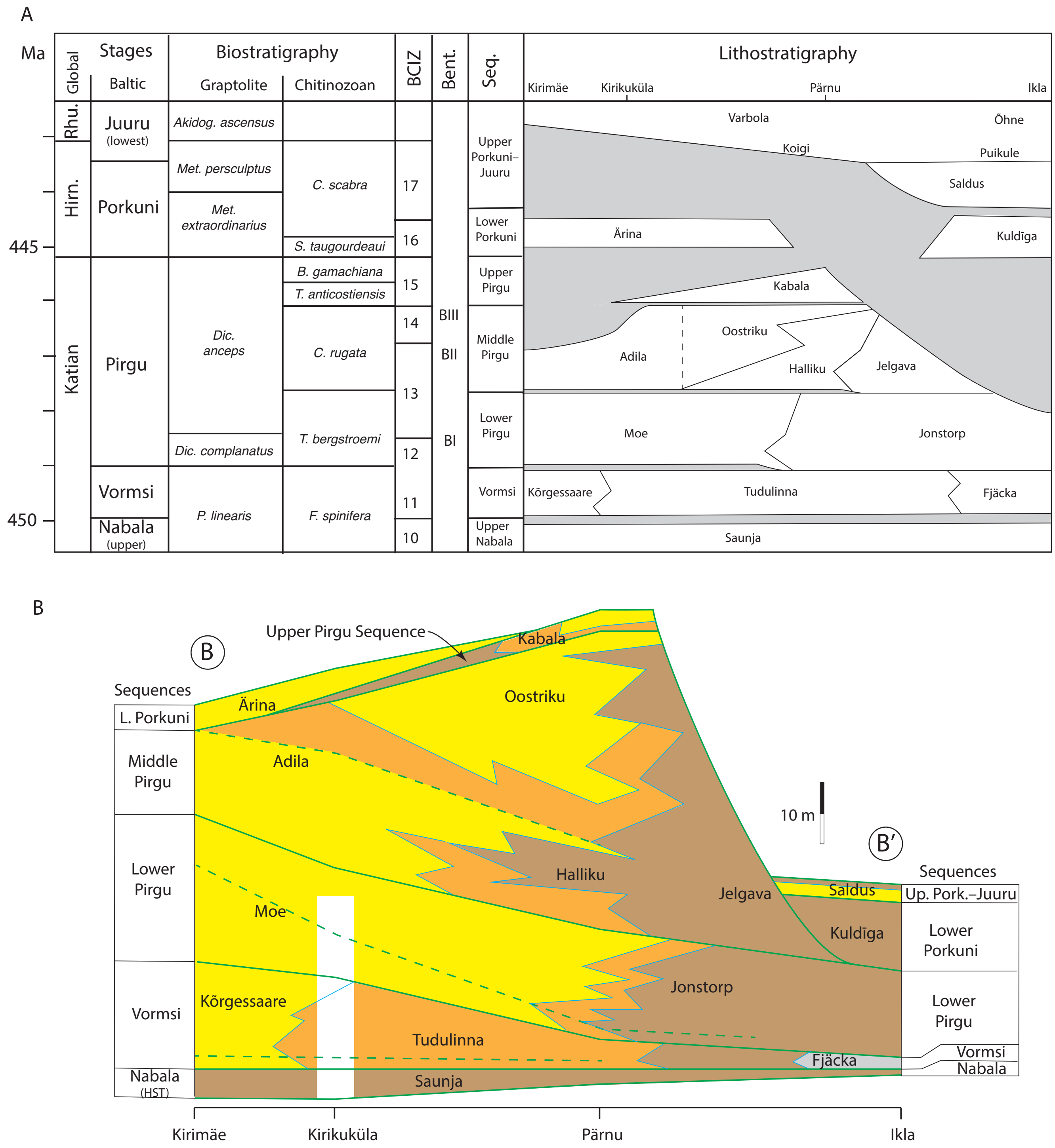

Fig. 5. Section B–B′ (Fig. 1B). **A** – chronostratigraphy; **B** – facies relations and sequence interpretations. See Fig. 4 for the key. The uncolored section of the Kirikuküla core represents missing core. Abbreviation: L – Lower; for other abbreviations, see Figs 2 and 4.

units are in BCIZ 9, whereas the Saunja Fm forms the Saunja Carbon Isotope Excursion (BCIZ 10) (Ainsaar et al. 2010).

The Paekna and Mõntu Fms were not studied in detail in this study. They consist of packstones in the northwestern part of the study area and grade into mixed wackestones and mudstones toward the south. The overlying Saunja Fm varies in thickness between less than 5 and 20 m (Fig. 8A) across the study area, but thins to less than 1 m in northwestern Latvia (Calner et al. 2010) and is locally absent in the Aizpute core. The unit consists of the mud-supported facies (mudstone subfacies), except in the Pihla core, the most northwesterly location, where the mixed facies occurs; evidence of progradation is absent. The lower boundary is a marine flooding surface marked by a sharp contact with the underlying units. The upper boundary is a regional karst surface documented by Calner et al. (2010), who attributed some of the thickness variations to karst-related erosion. Seismic studies in the Baltic Sea west of the studied wells indicate that this horizon is also marked by erosional channels (Tuuling and Flodén 2000). The absence of the Saunja Fm in the Aizpute core is attributed to erosion along the sequence boundary.

The Paekna and Mõntu Fms are interpreted as shallow- and middle-ramp facies of the TST, overlain by a marine flooding surface. The deep-ramp facies of the Saunja Fm

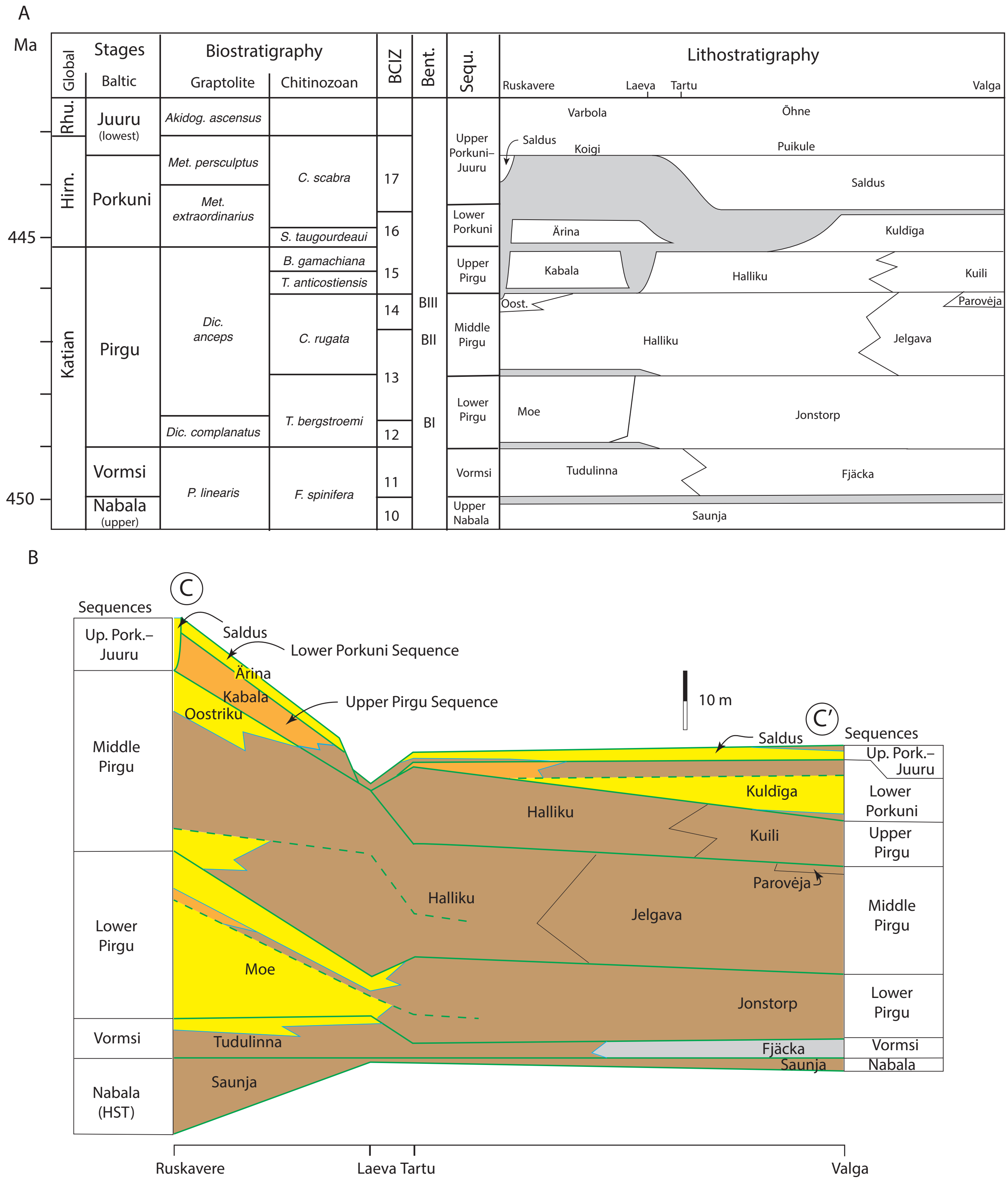

Fig. 6. Section C–C′ (Fig. 1B). **A** – chronostratigraphy; **B** – facies relations and sequence interpretations. See Fig. 4 for the key. Abbreviation: Oost. – Oostriku; for other abbreviations, see Figs 2, 4 and 5.

form the HST capped by the regional exposure surface. There is no evidence for highstand progradation within the study area.

Vormsi Sequence

The Vormsi Sequence consists of the time-equivalent Kõrgessaare, Tudulinna, and Fjäcka Fms. The sequence is in BCIZ 11 and the *F. spinifera* chitinozoan zone (including the *Acanthochitina barbata* chitinozoan subzone in its upper part). Grain-supported facies and mixed facies comprise the updip Kõrgessaare Fm; mixed facies and mud-supported facies comprise the Tudulinna Fm; and the Fjäcka Fm consists of shale facies. The thickness of the sequence varies from less than 5 m in the basin to over 20 m in shallow-ramp areas (Fig. 8B). The facies and thickness patterns define a typical ramp-to-basin profile.

The basal boundary of the sequence is the regional karst surface above the Saunja Fm. In shallow-to-middle ramp set-

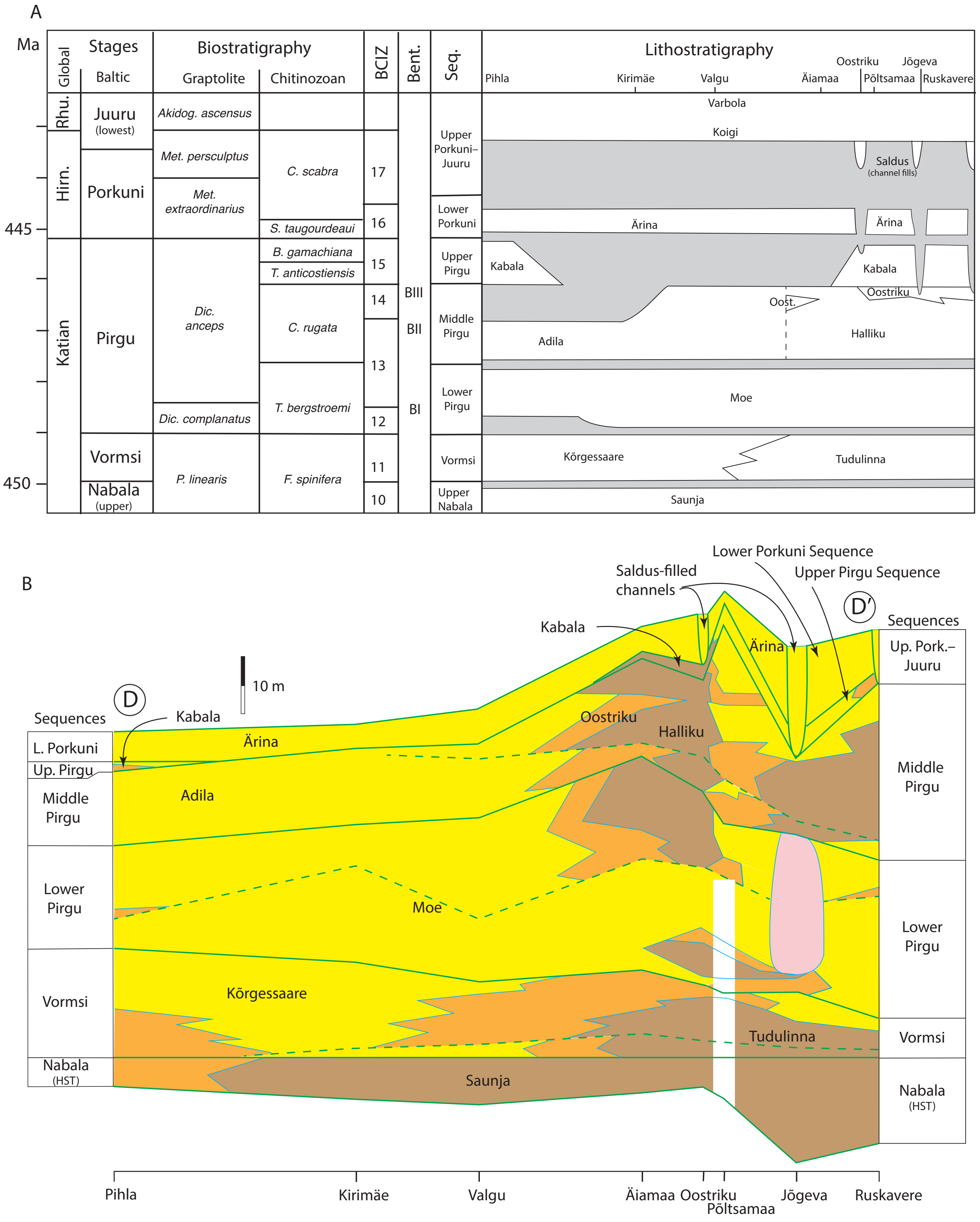

Fig. 7. Section D–D′ (Fig. 1B). **A** – chronostratigraphy; **B** – facies relations and sequence interpretations. See Fig. 4 for the key. The uncolored section of the Põltsamaa core represents missing core. Abbreviation: L. – lower; for other abbreviations, see Figs 2, 4 and 5.

tings, this surface is overlain by a thin (~2 m) shallowing-upward parasequence, which forms the TST, although it is absent in the northwest, indicating a subtle hiatus. A thick (10–13 m) shallowing-upward, prograding HST capped by grain-supported facies (shallow ramp) extends across the northern part of the study area. The upper boundary coincides with the stage boundary. Hints et al. (2007) attributed thickness variations in northern and central Estonia to erosion. The Vormsi RS is unusually thin in some outer-ramp cores (0.3 m in Ohesaare, 1.2 m in Kaugatuma), and the *Acanthochitina*

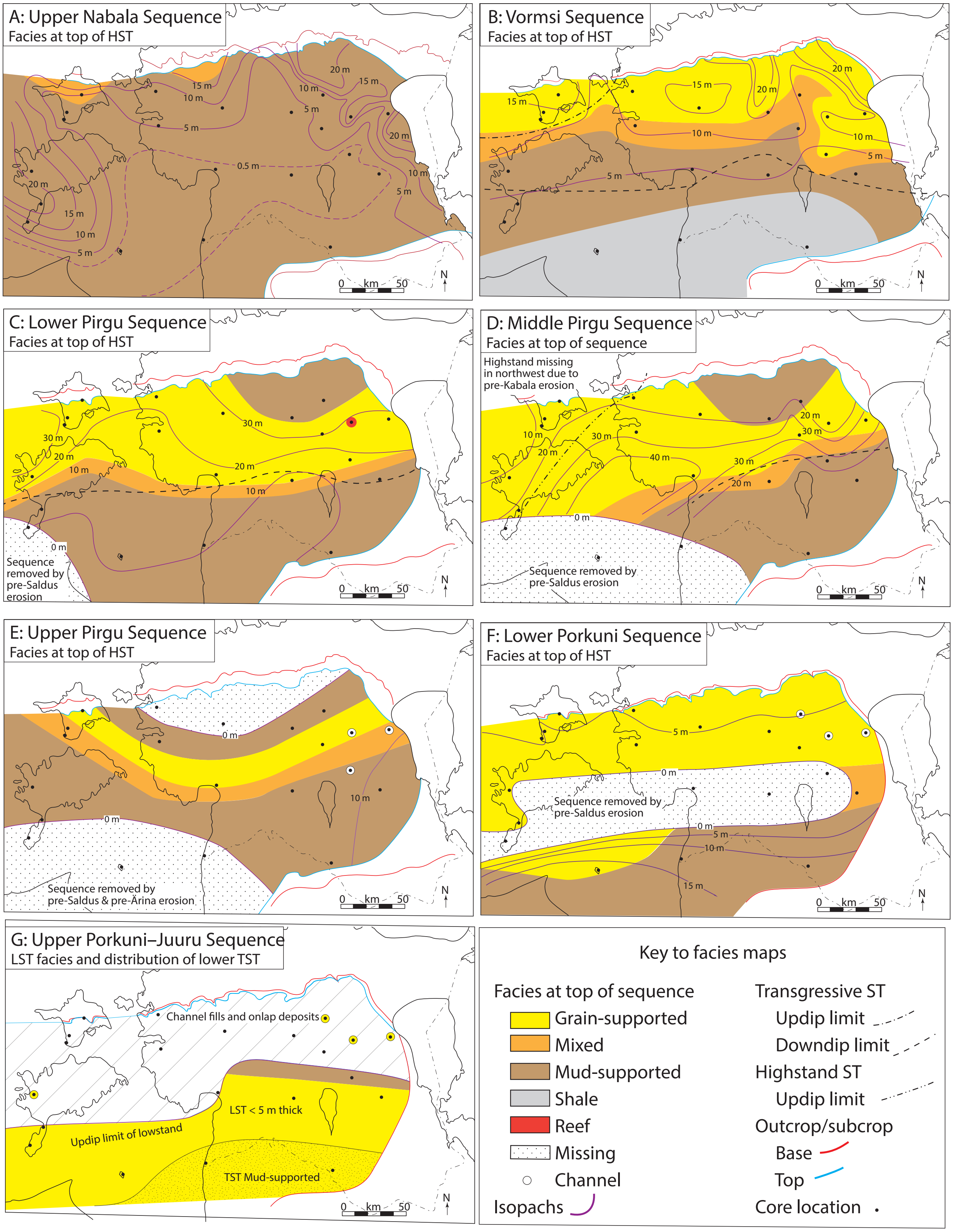

Fig. 8. Sequence isopach and facies maps. Facies at the top of the highstand systems tract (HST) except for the northwestern part of D. For abbreviations, see Fig. 3.

barbata chitinozoan subzone is missing in some southern cores (Kaugatuma, Ikla, and Viljandi; Nõlvak, unpublished data), indicating erosion along the upper boundary.

The Vormsi Sequence is bounded by erosional unconformities, and consists of a thin onlapping TST and a thick prograding HST. In contrast to the underlying Nabala Sequence, the full suite of ramp facies is present.

Lower Pirgu Sequence

The Lower Pirgu Sequence consists of the Moe and Jonstorp Fms, and is in the *Tanuchitina bergstroemi* chitinozoan biozone and BCIZ 12 and the lower part of BCIZ 13.

The Moe Fm consists of a shallowing-upward succession that consists of mixed facies (middle ramp) overlain by grain-supported facies (shallow ramp). The algal bioherm in the Jõgeva core formed in the middle ramp and extends upward into the shallow shelf, where it is capped by a karst surface (Perens 1995; Fig. 7). To the northeast, an area of mud-supported facies occurs, representing a lagoon north of shallow-ramp deposits (Fig. 8C). The Jonstorp Fm primarily consists of mud-supported (deep ramp) facies with some mixed (middle ramp) facies along its northern extent. In the Kaugatuma core, the lower part of the formation includes a stromatactis bioherm within the mixed facies (Fig. 4).

The base of the sequence is locally marked by erosion at the top of the Vormsi RS. The sequence is generally 20–30 m thick in shallow-to-middle ramp sections, and thins to less than 10 m in deep ramp settings (Fig. 8C). In the extreme southwest (Ohesaare), the sequence is missing due to pre-Saldus erosion. A TST consisting of a shallowing-upward parasequence is recognizable in the northern two-thirds of the area but cannot be differentiated in southern cores. The base of the HST is marked by a maximum flooding surface along which the Kaugatuma bioherm terminated. The overlying HST records the progradation of high-energy shallow ramp deposits and the development of a lagoon to the northeast.

Middle Pirgu Sequence

The Middle Pirgu Sequence consists of the Adila (excluding the Kabala Mb), Oostriku, Jelgava, and Parovėja Fms, and most of the Halliku Fm. The sequence is in the *Conochitina rugata* chitinozoan biozone and BCIZ 13 and 14.

Across northern Estonia, the base of the sequence consists of grain-supported (shallow ramp) facies (lower Adila Fm) capped by a flooding surface, which is overlain by mixed and mud-supported (middle and deep ramp) facies of the Halliku Fm. At the top of the sequence, grain-supported facies (Adila and Oostriku Fms) delineate up to four shallowing-upward packages (Pärnu core; Fig. 5); to the northeast, mud-supported facies delineate a lagoon. The upper part of the sequence (including all of BCIZ 14) is missing in northwestern cores (Figs 2 and 8D). South of the grain-supported belt, mixed and mud-supported facies (Halliku Fm) and argillaceous mud-supported facies (Jelgava Fm) record middle and deep ramp environments. The most basinal deposits are the argillaceous mudstones and marls of the Jelgava and Parovėja Fms (Valga and Aizpute cores).

The thickness of the Middle Pirgu Sequence ranges from 10 to over 40 m (Fig. 8D). The thickest accumulations are across the middle of the study area, along the southern edge of the shallow ramp deposits of the underlying Lower Pirgu Sequence. In the southwest, the area of missing section due to pre-Ärina and pre-Saldus erosion expanded to include the Ruhnu and Ikla core locations.

The sequence overlies a sharp surface marked by karst (Jõgeva core). In the north, the TST is dominated by high-energy shallow ramp facies that grades into deeper ramp facies to the south and southeast. The HST sits above a major flooding surface, but it is missing, presumably eroded, in western and northwestern cores, an area with a relatively thin section. In contrast, the Pärnu core has a thick section of multiple prograding ramp packages. This pattern of sediment accumulation resulted in a thick section in the west-central part of the study area (with a maximum exceeding 40 m).

Upper Pirgu Sequence

The Upper Pirgu Sequence consists of the Kabala Mb of the Adila Fm, part of the Halliku Fm, and the Kuili Fm. It falls in BCIZ 15 and includes the *Tanuchitina anticostiensis* and *Belonechitina gamachiana* chitinozoan biozones.

This sequence is a relatively thin (<10 m except to the southeast) package of argillaceous, mixed, and mud-supported facies that extends into shallow ramp settings (Figs 4, 5 and 8E). This is overlain by a grain-supported (shallow ramp) facies that separates an expanded lagoon (mud-supported facies) from the deep ramp settings toward the south (Halliku and Kuili Fms). The lower boundary is a flooding surface that overlies the eroded Lower Pirgu Sequence. The upper boundary is a sharp surface that marks the stage boundary above. The Upper Pirgu Sequence is missing in several northern mainland cores due to updip erosion or non-deposition (Kirimäe, Valgu), or erosion below pre-Saldus channels (Jõgeva, Ruskavere, Laeva; Perens 1995). The sequence is also missing in the southwest (Ikla, Ruhnu, Ohesaare) due to pre-Ärina erosion.

Systems tracts are difficult to identify in this thin package; it appears to be primarily an HST initiated by rapid flooding. The thickest section (Tartu core) indicates more accumulation in deep ramp settings to the southeast.

Lower Porkuni Sequence

The Lower Porkuni Sequence consists of the Ärina (except the Kamariku Mb) and Kuldiga Fms. The sequence sits in the *Spinachitina taugourdeaui* and lowest *Conochitina scabra* chitinozoan zones, and in BCIZ 16 and (probably) the lowest BCIZ 17.

A notable gap divides the sequence into a northern zone and a southern zone (Fig. 8F). In northern sections, the Ärina Fm is composed of 2–6 m of grain-supported facies and is divided into four interbedded members (below the Kamariku Mb) that include patch reefs and oolitic shoals (Hints et al. 2000). Southern sections consist of thicker (10–16 m) mud-supported facies (Kuldiga Fm); the lower part of one core (Valga) consists of grain-supported facies. A limited area of mixed facies to the east (Tartu core) overlies the thickest section of the underlying sequence. Across both zones, quartz sand is a significant constituent (<15%) in some sections.

The sequence is bounded by erosional surfaces that are recorded by a widespread stratigraphic gap between the northern and southern zones, erosive fluvial channels, and influxes of quartz sand. The most extensive erosional surface occurs between the northern and southern zones based on lithostratigraphic and biostratigraphic data; in places, the entire Pirgu RS is absent (the Saldus Fm overlies a very thin Vormsi RS bed at Ohesaare). It appears to be a composite unconformity surface with truncation occurring below both the Lower and Upper Porkuni sequences (Figs 4–6). The stratigraphic gap is interpreted as the result of slumping and erosion along a margin steepened by the progradation of earlier ramps; the preserved mixed facies may be due to a lower slope to the east due to the thicker Upper Pirgu Sequence accumulation. In northern sections, the pre-Ärina surface truncates the Kabala Fm, which is thin or absent in some cores (Figs 7 and 8F). The upper sequence boundary is marked by numerous channels that cut into the Lower Porkuni, Upper Pirgu, and Middle Pirgu sequences (Perens 1995).

The two Porkuni sequences record the development of an open-shelf profile, which is attributed to the accumulation of a wedge of Vormsi and Pirgu ramp deposits (Figs 4 and 5).

Upper Porkuni–Juuru Sequence (LST and lower TST)

The Ordovician section contains the lower part of the Upper Porkuni–Juuru Sequence, including the Saldus Fm and the Kamariku Mb of the Ärina Fm. The Ordovician part of this sequence (LST and lower TST) is in the *Conochitina scabra* chitinozoan zone and in BCIZ 17.

The Porkuni part of this sequence consists of two components. The lower Saldus Fm in the basin and shelf channel fills consists of conglomerates and quartz-rich (up to 40–50%) rippled packstones. The upper Saldus Fm and Kamariku Mb are grain-supported facies with wavy ripples and normal marine fauna, whereas equivalent mud-supported facies (wackestones) occur in basinal areas (Fig. 8G).

The lower Saldus strata are interpreted as LST deposits that bypassed the exposed shelf (except for local channel fills) and accumulated in basinal areas. The TST is recorded in the shift to more normal marine deposits in the basin (Saldus Fm), shelf channel fills (Saldus Fm), and open-shelf (Kamariku Mb) settings. The full extent of the shelf deposits outside the channels is unclear because the Kamariku Mb is lithologically similar to the underlying Lower Porkuni Sequence beds; in the absence of typical basal Saldus Fm features (conglomerates and abundant quartz sand), paleontological and carbon isotope data are needed to identify the TST of this sequence (Ainsaar et al. 2015; Hints et al. 2023; Männik and Nõlvak 2023). The TST continues into the uppermost Ordovician beds of the lower Juuru RS in updip (Koigi Mb of the Varbola Fm) and downdip (Puikule Mb of the Õhne Fm) positions (Bauert et al. 2014; Ainsaar et al. 2015).

Discussion

Comparison to prior sequence interpretations

Our sequence interpretation is similar to prior East Baltic studies, although it differs from Nielsen (2004, 2011) in some details (see discussion in Simmons et al. 2020). The first detailed sequence interpretation of the East Baltic Ordovician by Dronov and Holmer (1999, 2002) included three sequences across the Vormsi, Pirgu, and Porkuni RSs. Subsequent work (Harris et al. 2004; Dronov et al. 2011) included finer subdivisions; the scheme presented here is similar (Fig. 2). The primary differences involve the interpretation of the Pirgu RS. (1) Harris et al. (2004) interpreted the Moe–Jonstorp section as consisting of two sequences; here the lower unit is interpreted as the transgressive systems tract, making the Lower Pirgu Sequence equivalent to Sequence XI of Dronov et al. (2011). (2) This paper follows Harris et al. (2004) in dividing the Adila–Halliku section into two sequences based on the facies, stratigraphic gaps (erosion below the Kabala Mb in the western wells), and the karst feature at the top of the reef mound in the Jõgeva core, splitting Sequence XII of Dronov et al. (2011) into the Middle and Upper Pirgu sequences.

Facies and sequences

Nabala, Vormsi, and Pirgu facies delineate a series of depositional sequences of shallow-to-middle ramp sections that thin basinward across deep ramp and basin settings. Porkuni facies record two thin open-shelf sequences. While each sequence has its unique features, some general patterns emerge. (1) While onlapping TSTs occur in most ramp sequences (Nabala to Middle Pirgu), thinner sequences lack clear TST accumulations. (2) HSTs have a more consistent facies pattern marked by one or more shallowing-upward packages in outer shelf sections with limited erosion (most notably, the Middle Pirgu Sequence in the Pärnu core). (3) Sequence boundaries are characterized by hiatuses detected by biostratigraphic and/or chronostratigraphic gaps, and by sedimentological features such as karst and incised channels. In some cases, ramp sequence boundaries are represented by facies offsets. (4) Pre-Porkuni-age algal reef mounds occur in middle ramp positions and may reach considerable thickness (25–50 m). In contrast, the high-diversity Porkuni-age reef fauna forms low-relief biostromes within shallow ramp grain-supported facies.

The shift in sequence boundary style from the Nabala–Pirgu ramp sequences to the Porkuni sequences occurs in response to higher-amplitude sea-level changes associated with Hirnantian glaciations on an open-shelf profile. Despite these differences, the sequences align with global eustatic records (Haq and Schutter 2006; Cooper and Sadler 2012).

Sequences and basin development

Variations in sequence architecture document the development of the north flank of the Livonian Basin. (1) The Nabala Sequence lacks significant lateral facies differentiation across the study area and is capped by a regional karst surface (Calner et al. 2010). (2) The Vormsi Sequence is marked by a well-developed facies zonation from shallow ramp to deep basin. The onlapping TST and prograding HST indicate significant variations in lateral facies and depth, which resulted in thicker accumulations along the updip northern part of the study area. (3) The prograding ramps of the Lower and Middle Pirgu sequences built an updip sediment wedge with maximum accumulation in the Middle Pirgu Sequence across central Estonia. This led to the formation of a low-energy lagoon north of the high-energy deposits of the shallow ramp and a broadening of the shallow ramp. (4) The thin Upper Pirgu Sequence flooded over the shallow ramp but was truncated by a sharp exposure surface. (5) The Porkuni sequences record the development of an open shelf characterized by sequence boundaries marked by updip channels, stratigraphic hiatuses, and an LST at the base of the Upper Porkuni–Juuru Sequence.

Superimposed on the gradual accumulation of the sedimentary wedge, two subtle tectonic influences can be identified. The first relates to changes in ramp deposition between the Nabala and Vormsi sequences across the study area. The facies belts narrowed, deep basin shales appeared, and prograding HSTs developed. This change coincides with the widespread karst surface across Baltoscandia documented by Calner et al. (2010). This shift occurred at a time of changing tectonic geometries; Southwest Baltica (current orientation) was subducting under Avalonia during the oblique closure of the Tornquist Ocean (Winchester et al. 2002; Torsvik and Rehnström 2003; Cocks and Torsvik 2005). Mazur et al. (2017) indicated that the initial collision occurred at 450 Ma, the estimated date of the Nabala–Vormsi boundary. This suggests that the Nabala–Vormsi facies change was due to regional subsidence changes related to tectonics. A second tectonic signal emerges from the pattern of updip stratigraphic hiatuses. During most of the study interval, the accommodation minimum was toward the Fennoscandian Shield to the north. However, the Middle Pirgu HST is missing from the updip cores in the western and northwestern areas of Estonia, indicating that regional subsidence patterns were not uniform across the study area.

Conclusions

The main results of this study involve sequence architecture, stratigraphic gaps, and basin development.

1. The Nabala–Porkuni RSs can be divided into seven sequences (or partial sequences) based on the integration of facies patterns, stratigraphic gaps, and varied chronological data. Within these sequences, systems tract analyses provide insights into the internal architecture of the sequences and patterns of deposition.
2. The identification of stratigraphic gaps is critical to any sequence stratigraphic interpretation. While many gaps are widespread across the study area, others are more local. Thus, the duration and position of gaps had to be established in each core.
3. Nabala–Pirgu facies are a composite of carbonate ramp sequences with thin TSTs overlain by thicker prograding HSTs. These built a broad platform characterized by a landward lagoon. By Porkuni time, the ramp developed into an open shelf with sufficient relief, allowing local erosion and/or slumping along its basinward margin.
4. The sequence framework highlights the pattern of basin development that responded primarily to eustatic sea-level changes. Against this background, two subtle tectonic influences are detectable. The termination of the Nabala-age ramp by a regional karst surface and the narrowing of the profile may have been related to a plate-tectonic reconfiguration. In addition, updip hiatuses indicate that regional subsidence patterns varied through time.

Data availability statement

All data used in this study are contained within the article.

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Eesti Ülem-Ordoviitsiumi faatsiesed, järjendstratigraafia ja basseini areng

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Eesti aluspõhja Ülem-Ordoviitsiumi Nabala kuni Porkuni lademete (Ülem-Katy–Hirnanti) järjendstratigraafiline analüüs aitab selgitada paleobasseini karbonaatsete settekomplekside levikut ja settimise arengut, muutusi fauna ja süsiniku stabiilsete isotoopide koostises ning kivimkehi piiritlevaid settelünki. Eri tüüpi tunnuste integreerimine võimaldab eristada settebasseini arengus seitset etappi ehk sekventsi: (1) Nabala (Paekna ja Saunja kihistu), (2) Vormsi (Kõrgessaare, Tudulinna ja Fjäcka kihistu), (3) Alam-Pirgu (Moe ja Jonstorpi kihistu), (4) Kesk-Pirgu (suurem osa Adila ja Halliku kihistust, Jelgava ja Parovėja kihistu), (5) Ülem-Pirgu (Adila kihistu Kabala kihistik, osa Halliku kihistust), (6) Alam-Porkuni (suurem osa Ärina kihistust) ja (7) Ülem-Porkuni–Juuru sekvents (Ärina kihistu Kamariku kihistik ja Salduse kihistu, Koigi ja Puikule kihistik). Meretaseme sügavaim madalseis kajastub ainult kõige ülemises sekventsis. Sekventside transgressiivseid etappe iseloomustab vanuseliselt nooremate setendite levik ranniku suunas. Sekventside kõrgseisu kulg koosneb ühest või mitmest ülespoole madalduvast settetsüklist. Settejärjestused kajastavad nii madal- kui ka süvaveeliste faatsieste nihkumist basseini keskosa suunas, mis jätkus kuni Liivi basseini põhjaosa settimisruumi täitumiseni setetega Porkuni eal. Maailmamere taseme eustaatilised langused, mis olid peamised sekventsipiire markeerivate settelünkade tekitajad, olid suurima amplituudiga Hirnanti mandrijäätumise episoodi ajal Porkuni eal. Faatsieste sügavusliku diferentseerumise süvenemine Nabala ja Vormsi ea vahetusel langeb ajaliselt kokku Baltika ja Avaloonia mandrilaamade kollisiooni algusega.