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Upper Ordovician sequences of western Estonia

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Abstract

The Upper Ordovician (uppermost Caradoc-Ashgill) section of western Estonia consists of a series of seven open-shelf carbonate sequences. Depositional facies grade laterally through a series of shelf-to-basin facies belts: grain-supported facies (shallow shelf), mixed facies (middle shelf), mud-supported facies (deep shelf and slope) and black shale facies (basin). Locally, a stromatactis mud mound occurs in a middle-to-deep shelf position. Shallow-to-deep shelf facies occur widely across the Estonian Shelf and grade laterally through a transitional (slope) belt into the basinal deposits of the Livonian Basin.

Each sequence consists of a shallowing-upward, prograding facies succession. Sequences 1 (Upper Nabala Stage) and 2 (Vormsi Stage) record step-wise drowning of underlying shelf units (lower Nabala) that culminated in the deposition of the most basinal facies (Fjäcka Shale) in the Livonian Basin. Sequences 3–6 comprise the overlying Pirgu Stage and record the gradual expansion of shallow and middle-shelf facies across the Estonian Shelf. The Porkuni Stage (sequence 7) is bracketed by erosional surfaces and contains the shallowest-water facies of the preserved strata. The uppermost part of the section (*Normalograptus persculptus* biozone) is restricted to the Livonian Basin, and includes redeposited carbonate and siliciclastic grains; it is the lowstand systems tract of the lowest Silurian sequence 8. Sequence 7 and the overlying basinal redeposited material (i.e., the lowstand of sequence 8) correspond to the latest Ordovician (Hirnantian) glacial interval, and the bracketing unconformities are interpreted as the widely recognized early and late Hirnantian glacial maximums.

The sequences appear correlative to Upper Ordovician sequences in Laurentia. Graptolite biozones indicated that the Estonian sequences are equivalent to carbonate ramp sequences in the western United States (Great Basin) and mixed carbonate-siliciclastic sequences in the eastern United States (Appalachian Basin–Cincinnati Arch region). These correlations indicate a strong eustatic control over sequence development despite the contrasting tectonic settings of these basins.

Keywords: Ordovician; Stratigraphy; Sedimentology; Baltic; Estonia

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1. Introduction

Sequence stratigraphic analysis is widely used to supplement and refine traditional lithostratigraphic and biostratigraphic studies. Numerous early–middle Paleozoic studies have presented regional or basin-

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scale sequence stratigraphic interpretations. However, the ability to correlate sequences between different regions and plates is limited by the precision and accuracy of the biostratigraphic correlations. These correlations are particularly difficult during intervals characterized by high levels of endemics among the benthic faunas.

High levels of endemism characterize the late Ordovician. The stages within the terminal Ashgill Series are difficult to correlate globally, and the base of the series is difficult to recognize outside the type area because it does not correspond to a graptolite or conodont biozone boundary (Barnes, 1992). One result is that most Ordovician interregional sequence correlations have been generalized or focused on pre-Ashgill strata (Nicoll et al., 1992; Nielsen, 1992; Ross and Ross, 1992, 1995). Another result has been the development of numerous regional series and stage divisions for the later Ordovician. Recent studies on graptolite, conodont and chitinozoan biostratigraphy have helped to clarify some of the temporal relations between the regional chronostratigraphic schemes (for example, Finney et al., 1997; Nõlvak, 1999; Nõlvak and Grahn, 1993; Williams et al., 2001).

A secondary difficulty in correlating sequences is that different approaches have been used to delineate sequences. Most workers have relied upon facies patterns, although some have stressed correlation of reported unconformities (Ross and Ross, 1992) or exposure surfaces (Cooper and Keller, 2001). Benthic assemblages were also used as measures of sea-level changes (for Silurian examples, see Johnson et al., 1991a,b; Johnson, 1996) and, in some cases, integrated with sedimentological facies analysis (Harris and Sheehan, 1996, 1997).

The classic Baltic Ordovician section of Estonia have been studied for over a century, and the stratigraphy, paleontology and general facies relations are well established (Kaljo and Nestor, 1990; Raukas and Teedumäe, 1997). The paper presents a sequence stratigraphic model for the Upper Ordovician (uppermost Caradoc-Ashgill Series) strata of western Estonia that integrates sedimentologic and biostratigraphic data from a shelf-to-basin core transect. The sedimentological descriptions and sequence interpretations are comparable to previous studies of equivalent strata in the western (Harris and Sheehan, 1996, 1997) and eastern (Holland, 1993; Holland and Patzowsky, 1996; Pope and Read, 1997) United States. Based on these facies-based sequence models and the current biostratigraphic framework, we propose sequence correlations between Baltica and Laurentia.

2. Geological setting and methods

The study area is located on the northwestern (present day orientation) part of the East European (or Russian) Platform between the Baltic Shield to the north and the Livonian Basin, a broad embayment of the Scandinavian Basin, to the south (Fig. 1) (Jaanusson, 1973, 1976; Bassett et al., 1989; Kaljo, 1990; Raukas and Teedumäe, 1997). The East European Platform is bounded to the southwest by the Tornquiest-Teisseyre Line and the Caledonian Front that delineate the edge of the Precambrian basement (EUGENO-S Working Group, 1988). The East Baltic area, including Estonia, was tectonically stable throughout the study interval, which was prior to Caledonian foreland basin deposition in the late Silurian (Bassett et al., 1989; Raukas and Teedumäe, 1997).

The northern Estonian outcrop belt nearly parallels depositional strike and exposes a section of shallow and middle-shelf facies (Estonian Shelf) (Fig. 2) (Jaanusson, 1973, 1976; Bassett et al., 1989; Kaljo, 1990; Nestor, 1990b; Nestor and Einasto, 1997; Männil and Meidla, 1994). Sections to the south are in the subsurface but may be examined in numerous cores. The shelf sections grade from the Estonian Shelf through a central Estonian transitional belt into basinal facies in southern Estonian, western Latvia and northwestern Lithuania (the axis of the Livonian Basin). The southeastern edge of the basin is delineated by a similar transition into shelf facies in eastern Latvia, southeastern Lithuania and northwestern Belarus.

This paper presents the results of an investigation of a north–south transect from the Estonian Shelf to the Livonian Basin based upon cores from Saaremaa, Hiiumaa and Ruhnu Islands of western Estonia and one core from western Latvia (Fig. 2). The cores were described on sedimentologic logs at a 1:50 scale that summarized depositional textures, grain size, ichnofabric index, clay content, color and fossil content.

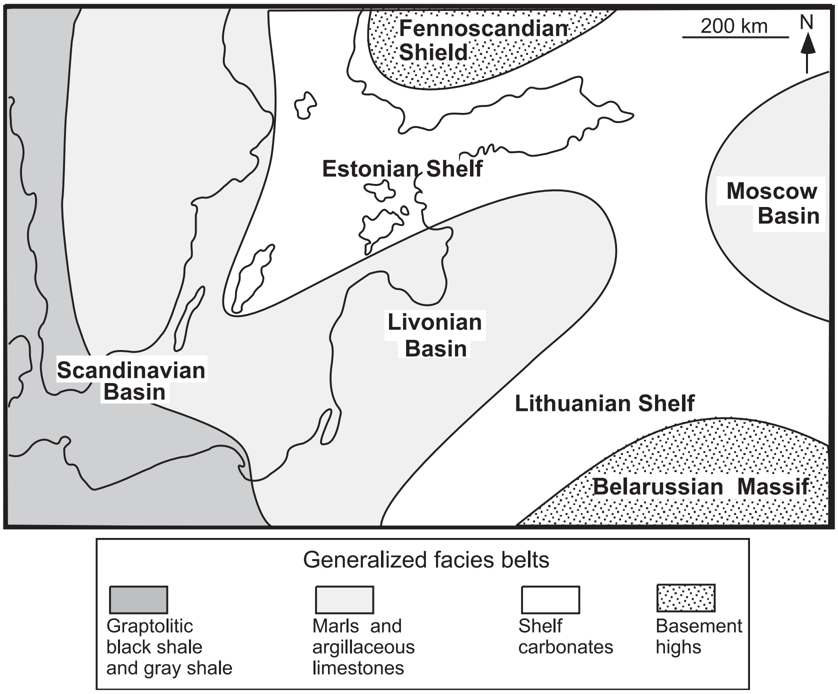

Fig. 1. Major tectonic and paleogeographic features of the Baltic region (modified from Jaanusson, 1976). The shale facies belt corresponds to Jaanussons' (1976) Scanian Confacies, the marl belt to his Central Baltoscandian Confacies (including the Livonian Tongue), and the shelf carbonate belt to his North Estonian Confacies and Lithuanian Confacies.

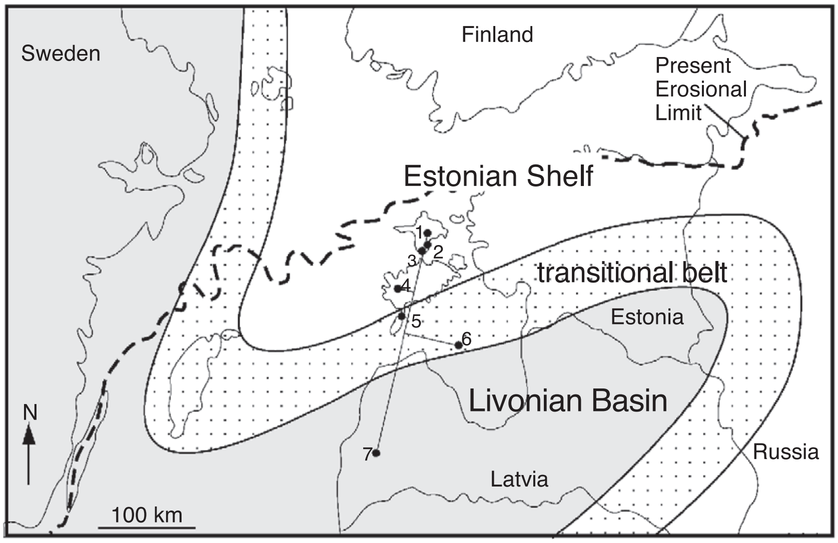

Fig. 2. Late Ordovician facies belts (modified from Ainsaar and Meidla, 2001). The positions of the described cores (dots) and the cross section presented in Fig. 5 (line) are indicated. The wells are: 1 = Pihla (F-361), 2 = Valgu (F-363), 3 = Sõru (#400), 4 = Viki, 5 = Kaugatuma, 6 = Ruhnu and 7 = Aizpute-41.

The seven Upper Ordovician cores discussed in this contribution are held by the Geological Survey of Estonia and the Institute of Geology (Tallinn). The studied cores total approximately 461 m.

3. Stratigraphy and facies

Ordovician and Silurian stratigraphy utilizes regional stage names but correlations within the East Baltic area are well established due to a long history of investigations (Bassett et al., 1989; Männil, 1990; Männil and Meidla, 1994; Kaljo, 1990; Raukas and Teedumäe, 1997 and references therein). Regional series and stages are used in the Baltic region but the correlations with the standard series are fairly well established (Hints et al., 1994). The regional Harju Series consists of the Nabala, Vormsi, Pirgu and Porkuni Stages, and is equivalent to the uppermost Caradoc and Ashgill Series (Fig. 3). The major uncertainty is the precise position of base of the Vormsi Stage in relation to the Caradoc-Ashgill boundary within the *Pleurograptus linearis* biozone.

The stratigraphic nomenclature is complex and not all authors agree on the appropriate stratigraphic name for some core intervals, although stage-level assignments appear very consistent across the study area. We have adopted a nomenclature that conforms to the general usage (Raukas and Teedumäe, 1997; Fig. 3). Many faunal groups have been used for biostratigraphy, including 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) and brachiopods (Hints, 1990).

Ordovician and Silurian facies (Nestor, 1990a,b; Nestor and Einasto, 1997; Einasto, 1986, 1995; Bassett et al., 1989) indicate that a carbonate shelf formed the margins of the Livonian Basin. Facies belts were well differentiated in the late Ordovician (late Caradoc-Ashgill) and earliest Silurian (early-to-middle Llandovery) due to increased subsidence in the Livonian Basin (Nestor, 1990b). Five facies belts are recognized along a shelf-to-basin transect (Einasto, 1986, 1995; Bassett et al., 1989; Nestor, 1990a,b; Nestor and Einasto, 1997): (1) argillaceous, laminated and bioturbated dolomicrites interpreted as tidal flat and lagoon deposits; (2) skeletal, oolitic, oncolitic and peloidal calcarenites and boundstones representing high-energy shoal and reef conditions; (3) micritic limestones with storm beds were deposited in middle shelf settings; (4) calcareous mudstones and marls deposited in deep-shelf settings; and (5) graptolitic shales representing basinal conditions.

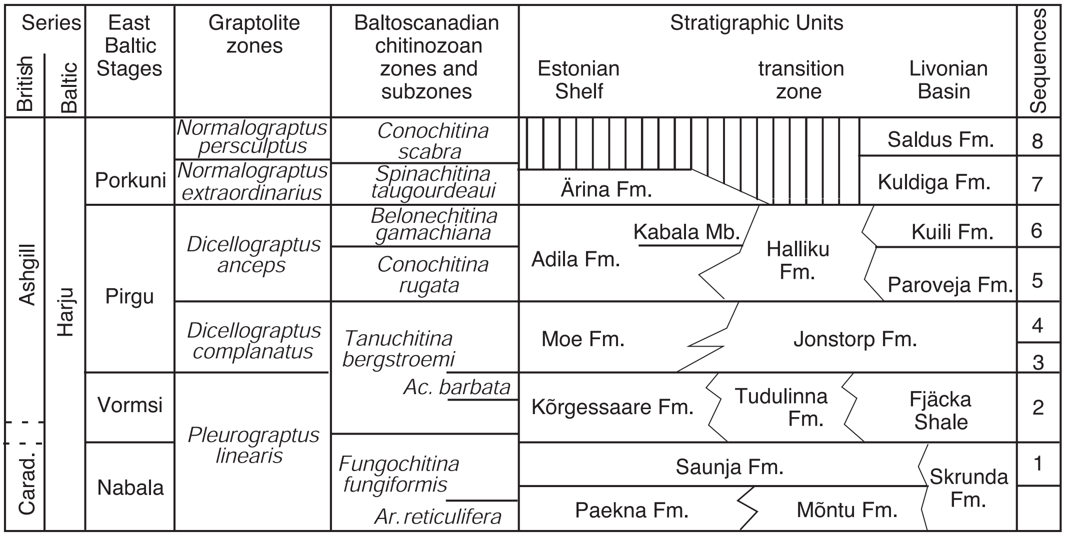

Fig. 3. Stratigraphy of the study interval (modified from Raukas and Teedumäe, 1997). Sequences are discussed in the text. Abbreviated chitinozoans are: *Ac. barbata* = *Acanthochitina barbata* and *Ar. reticulifera* = *Armoricochitina reticulifera*.

Einasto (1995) and Nestor and Einasto (1997) have shown that the Estonian Ordovician–Silurian shelf sections include numerous hiatuses and evidence for cyclicity on different time scales. Correlations to worldwide cycles have focused on Silurian strata (Johnson et al., 1991a,b), although Dronov and Holmer (1999) proposed a sequence interpretation for the Ordovician of the Baltic region.

4. Depositional facies and sequences

The studied core sections are aligned along a north–south cross section across the Estonian Shelf and into the Livonian Basin. The core transect spans the three intermediate facies belts of prior workers. The most restricted facies belt (tidal flat and lagoon) is missing due to erosional truncation, and the basinal shales are restricted to Vormsi strata in the southernmost well of the study area (Fig. 2). The facies are briefly described here because of some ambiguity in past descriptions (e.g., micritic limestones can refer to a wide range of Dunham textures).

4.1. Facies

Five facies summarize the upper Nabala-Porkuni Stages sections in the western Estonian transect (Fig. 4, Table 1).

4.1.1. Grain-supported facies

The grain-supported facies consists of grainstone and packstone subfacies with a diverse marine biota. Sedimentary structures are most varied and abundant in the grainstone subfacies, which also contains ooids in some localities. This subfacies occurs only in the Porkuni stage. The packstone subfacies occurs throughout the Estonian Shelf sections.

4.1.2. Mixed facies

Interbedded and burrowed-mixed packstone and wackestone constitute the bulk of the mixed facies. Important characteristics are a diverse marine fauna, a variety of benthic algae, pervasive burrowing and a slightly higher clay content than the grain-supported facies. Thin wackestone interbeds contain a less diverse biota and more clay than the packstone beds. The mixed facies occurs between the grain-supported and mud-supported facies.

4.1.3. Mud-supported facies

Wackestone is the most common subfacies within the mud-supported facies in shelf sections. The wackestone subfacies contains a diverse marine biota, but corals are absent. The mudstone subfacies contains ostracodes and fossil fragments, and is limited to the upper Nabala Stage. The marl subfacies contains only fossil fragments, and occurs throughout the basinal (Aizpute) core. The subfacies also extends up-dip into the transitional belt in the Vormsi Stage. The redeposited subfacies is restricted to a 3 m section at the top of the Porkuni Stage in the basinal (Aizpute) well. The redeposited subfacies contains ooids, intraclasts and quartz sand, interpreted to have been derived from ooid-rich Porkuni shelf and upper slope deposits. The mud-supported facies is most abundant at the southern (basinward) end of the transect.

4.1.4. Black shale facies

Laminated to bioturbated black, dark gray and dark green shales of the Fjäcka Shale occur in the most basinward part of the transect in the Vormsi Stage.

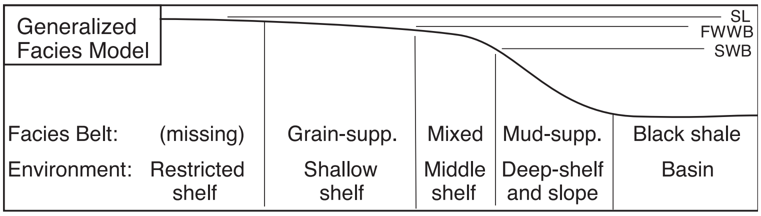

Fig. 4. Facies model for the Upper Ordovician of western Estonia. Key to abbreviations: SL = sea level, FWWB = fair-weather wave-base and SWB = storm wave-base.

Table 1
Facies summary

Facies	Lithologies	% Clay	Identifiable grain types	Sedimentary structures	Ichn. Index
Grain-supported facies	Grainstone subfacies (includes some mud-lean packstone)	< 3%	Ooids, brachiopods, echinoderms, rugose, tabulates, stromatoporoids.	Cross-beds, cross, wavy and ripple laminations, burrows.	2–5
	Packstone subfacies	5–20%	Peloids, algae, brachiopods, bryozoans, trilobites, ostracodes, echinoderms, rugose, tabulates, stromatoporoids, gastropods, nautiloids.	Wavy and flat laminations, burrows.	3–5
Mixed facies	Wackestone/packstone subfacies	5–30%	Algae, brachiopods, bryozoans, trilobites, ostracodes, echinoderms, rugose, stromatoporoids, gastropods, nautiloids.	Burrows.	5
	Wackestone subfacies	20–40%	Brachiopods, trilobites.	Burrows.	5
Mud-supported facies	Wackestone subfacies	5–40%	Peloids, algae, brachiopods, echinoderms, bryozoans, stromatoporoids, gastropods.	Burrows.	5
	Mudstone subfacies	5%	Ostracodes.	Burrows.	5
	Marl subfacies	35–50%	Echinoderms.	Burrows, flat laminations.	4
	Redeposited subfacies	< 10%	Ooids, quartz, brachiopods, ostracodes.	Ripples, wavy laminations, strorm beds, argillaceous seams.	2–3
Black shale facies	Black shale subfacies	>70%	Graptolites, brachiopods, trilobites.	Horizontal burrows.	
Mud mound facies	Stromatactis subfacies	15%	Algae, echinoderms, “stromatactis”.		
	Wackestone/packstone subfacies	15–20%	Echinoderms, brachiopods.	Occurs as interbeds within boundstone.	

Fauna is sparse and consists predominantly of graptolites with minor brachiopods and trilobites.

4.1.5. Mud mound facies

Reefs occur throughout the Upper Ordovician of the Baltic in middle-upper Caradoc and Ashgill strata (Nestor, 1995). A 5.6-m-thick stromatactis mud mound interval occurs in lower Pirgu strata in the Kaugatuma (transitional belt) core. The mud mound facies is red-to-pink in color and consists of thin stromatactis interbedded with packstone lenses.

4.2. Facies model

The facies pattern indicates that a carbonate ramp or open-shelf model is applicable to the section (Figs. 4 and 5; Burchette and Wright, 1992; Wright and Burchette, 1996). Nestor (1990b) proposed an open-shelf model, and this appears appropriate for the post-Nabala section based on the thickness patterns and the abrupt facies change and possible submarine truncation surfaces south of the Kaugatuma well. The broad distribution of the mud-supported facies may indicate that a traditional ramp facies model may be more appropriate for the Saunja Formation (upper Nabala Stage).

Although the nearshore facies is missing, the remaining facies belts indicate decreasing energy from north to south, paralleling the regional transition from the Estonian Shelf to the transitional (slope) belt and into the Livonian Basin. The grain-supported facies represents a shallow shelf, the mixed facies a middle shelf, and the mud-supported facies a deep shelf and low-angle slope. The black shale facies forms the most basinal facies. This distribution and the absence of nearshore facies (tidal flats, shorelines) indicate erosional removal of up-dip restricted-shelf and shallow-shelf deposits that existed north of the present outcrop.

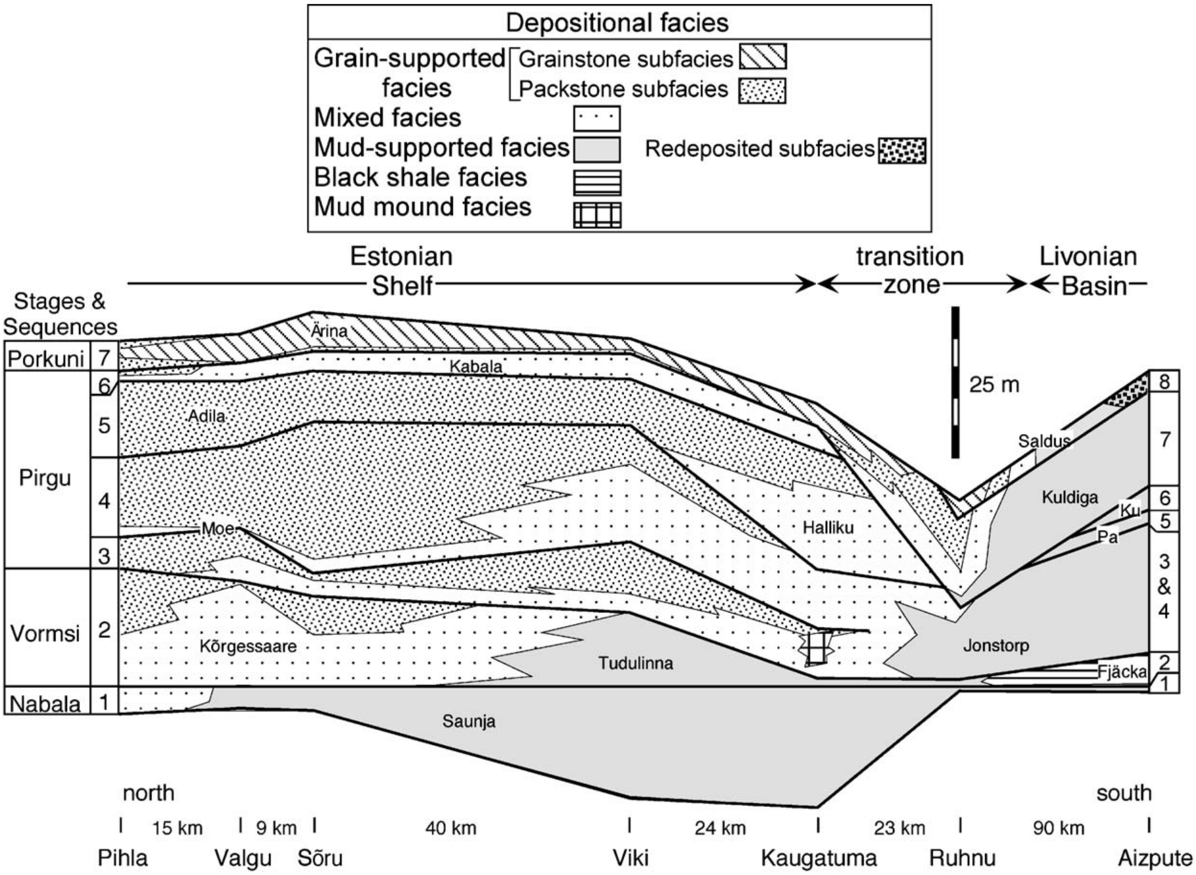

Fig. 5. Facies cross-section (see Fig. 2 for location). Distances between the cores are scaled except for the Ruhnu–Aizpute distance. Alternate interpretations of the Saldus Formation are discussed in the text. Abbreviated formation names are: Ku = Kuili, Pa = Paroveja.

The mud mound facies occurs in association with the transition from the mixed to mud-supported facies, in a middle-to-deep shelf setting. Various types of Ordovician reefs in the Baltic occur in a range of facies ranging from deep ramp muds (Boda reefs, Sweden) to inner shelf grainstones (Vasalemma reefs, Estonia) (Nestor, 1995). The Pirgu stromatactis mud mound described here developed near storm wave-base. Similar Pirgu mud mounds are reported from central Sweden (Jaanusson, 1979), Gotland and central Estonia (Nestor, 1995). This reef type contrasts with the coral and stromatoporoid-dominated reef facies that occur widely in Porkuni and Silurian of the Baltic region (Nestor, 1995) that are organic reefs (in the sense of Riding, 2002).

The facies geometry delineates seven prograding shelf complexes that grade laterally from grain-supported shelf facies through the mixed facies, and into mud-supported facies in outer shelf or basinal areas (Fig. 5). Each complex shallows upward recording the migration of the facies belts in an offshore direction.

4.3. Sequences

The facies pattern (Fig. 5) indicates that the uppermost Caradoc and Ashgill (upper Nabala-Porkuni) strata record seven depositional sequences, each represented by one of the shallowing-upward shelf complexes. The lowstand of an eighth sequence occurs in the Livonian Basin.

The facies patterns are asymmetric with relatively thin transgressive intervals alternating with thicker regressive/progradational packages. Subaerial exposure surfaces or peritidal indicators are absent below the base of the Porkuni Stage, and lowstand deposits cannot be differentiated except for the uppermost strata (sequence 8) in the Livonian Basin. Submarine erosional surfaces coincide with some sequence boundaries in transitional and basinal areas based on seismic studies (Tuuling and Flodén, 2000) and stratigraphic gaps (as discussed below). These observations indicate that Ashgill sea-level fluctuations did not fall sufficiently to expose the studied localities until the end of the Pirgu Stage. Sequence boundaries are placed at the top of the shallowest facies within the shallowing-upward packages, although this may place some lowstand deposits within the preceding sequence in deeper-water settings. We hope to test these interpretations with additional detailed biostratigraphic data.

Sequence 1 consists of the Saunja Formation (upper Nabala Stage), a typical middle-to-deep ramp unit based on the broadly distributed facies belts. The basal sequence boundary is marked by a sharp facies transition from grain-supported facies of the underlying Paekna or Mõntu formations (lower Nabala Stage) to the deep-ramp, mud-supported facies of the Saunja. In most cores, this sequence consists of the mudstone subfacies with a relatively low faunal abundance and low clay content. Shallower middle-ramp mixed facies occurs in the most up-dip (Pihla) section indicating the restricted distribution of middle-ramp environments during deposition of sequence 1. This sequence thins to 1–2 m of marl and calcareous shale (tentatively assigned to the Skrunda Formation) in the most basinal well (Aizpute).

The overlying Vormsi Stage units (Kõrgessaare, Tudulinna and Fjäcka Formations) comprise sequence 2. Seismic studies in the Baltic Sea west of the study area (within the Estonian Shelf) indicate that the base of sequence 2 is an erosional surface marked by channels (Tuuling and Flodén, 2000). Within the studied well transect, the facies belts are narrower than in sequence 1 and the clay content increases in all wells. The up-dip sequence 2 facies record the transition to shallow shelf settings (grain-supported facies) (Fig. 5). Shallow and middle shelf deposits extended across most of the shelf by the end of sequence 2. In basinal sections, the black shale facies of the Fjäcka Shale represent the maximum deepening within the studied interval. The facies changes between sequences 1 and 2 reflect a greater environmental differentiation along the depositional transect, and may be linked to early Caledonian tectonic events in Scandinavia (A.T. Nielsen, pers. comm.).

The overlying Pirgu Stage is subdivided into four sequences that exhibit shallowing-upward facies patterns on the Estonian Shelf and grade laterally through the transitional zone into mud-supported facies in the Livonian Basin. Sequences 3 and 4 comprise the Moe and Jonstorp formations, and the two overlying sequences (5 and 6) make up the Adila, Kabala and their equivalents.

Sequences 3 and 4 have similar facies patterns. The transgression at the base of each sequence is marked by a tongue of mixed facies that extends into up-dip wells, and that shallows upward into the grain-supported facies. Mud-supported facies are limited to the transitional zone (slope) and basinal wells. The two sequences cannot be differentiated in the red marls of the Jonstorp Formation of the Aizpute well. Within sequence 3, a stromatactis mud mound occurs in the Kaugatuma core at the transition from outer to middle ramp environments.

The base of sequence 5 is marked by another tongue of the mixed facies (Halliku Formation) in the southern part of the shelf. The boundary occurs within grain-supported facies in up-dip locations although it is commonly associated with an increase in clay content or a subtle shift toward a muddier packstone. Highstand grain-supported facies extends across the entire shelf, and this sequence marks the establishment of a broad shallow-water shelf that was near normal wave-base. The overlying sequence 6 (Kabala Member) records a deepening event as the mixed faces transgressed over the outer shelf during facies backstepping.

The upper boundary of the Pirgu is erosional in some shelf and slope wells. In some up-dip wells in central Estonia (not shown here), sequence 6 is missing due to pre-Porkuni (i.e., pre-sequence 7) erosion (Ainsaar, 1995; Perens, 1995). Local variations in the depth of truncation and diagenetic alteration of the upper Pirgu limestones suggest that subaerial channels were cut into the Pirgu surface (Perens, 1995). In the transitional zone (Ruhnu and other nearby wells), some or all the Pirgu sequences are truncated below the Porkuni strata. These truncation surfaces lack any evidence of subaerial exposure and occur in slope and basin edge locations along the flank of the Livonian Basin. The erosion appears to be due to submarine erosion or slumping based the setting and associated muddy facies.

The stratigraphic relations within sequence 7 (Porkuni Stage) are complex but recent biostratigraphic and carbon isotope studies have clarified the temporal relations (Nõlvak, 1999; Nõlvak and Grahn, 1993; Kaljo et al., 2001, Brenchley et al., 2003) (Fig. 3). The shelf section (Ärina Formation) lies entirely within the *Spinachitina taugourdeaui* biozone. The basinal equivalent (Kuldiga Formation) includes some younger beds (lower part of the *Conochitina scabra* biozone). The overlying Saldus Formation contains the remainder of the *C. scabra* biozone, and lies within the uppermost Ordovician *Normalographtus persculptus* biozones.

The shelf section (Ärina Formation) contains the high-energy shallow-shelf lithologies (i.e., grainstones with well-preserved physical structures). The upper contact is marked by subaerial erosion and channeling (Ainsaar, 1995; Perens, 1995), and carbon isotopic patterns indicate a hiatus corresponding to the upper *S. taugourdeaui* and *C. scabra* biozones in up-dip locations (Kaljo et al., 2001). Equivalent Kuldiga strata in the transitional zone (Ruhnu core) overlie a submarine erosion surface that removed the upper Pirgu Stage (sequences 5 and 6, and probably part of sequence 4). Sequence 7 consists of a relatively thick (16 m) shallowing-upward succession that coarsens upward from a thin mud-supported facies (1.8 m) through an interval of mixed facies into grain-supported facies (packstone subfacies). The hiatus observed in shelf sections is not apparent based on both biostratigraphic and carbon isotopic data (Nõlvak, 1999; Nõlvak and Grahn, 1993; Kaljo et al., 2001, Brenchley et al., 2003). In the basinal Aizpute well, sequence 7 consists of a 16-m-thick mud-supported unit.

The Saldus Formation is restricted to the Livonian Basin where it overlies the Kuldiga Formation. In the Aizpute well, it consists of a 3-m-thick unit of the redeposited subfacies (containing intraclasts, ooids, siliciclastics) that was derived from erosion of early Porkuni shelf deposits (i.e., the Ärina Formation). The equivalent section in the transitional zone (Ruhnu well) is a 2-m-thick cross-bedded grainstone with ooids and quartz sand that is interpreted as a high-energy shallow-shelf deposit. The quartz sand indicates erosion and redeposition from up-dip shelf areas, and a similar origin for the ooids cannot be ruled out. Stratigraphic evidence of erosion at this time is provided by other transition zone wells (not shown here) in which Silurian strata overlie Vormsi (sequence 2) strata due to erosion after deposition of the Ärina and Kuldiga formations. The limited distribution of Saldus strata and the abundance of redeposited material indicate that this unit is probably the lowstand deposit at the base of an eighth sequence that predominantly consists of lowest Silurian strata.

These age and facies relationships indicate that both the upper and lower boundaries of sequence 7 are erosional surfaces up-dip. The maximum shallowing occurs within the *scabra* biozone based on absence of *scabra*-age strata in shelf sections and the redeposited material in down-dip wells. The Porkuni interval is equivalent to the latest Ordovician (Hirnantian) glaciations. The unconformities that bracket Porkuni strata on the shelf correspond to the widely recognized early and late Hirnantian sea-level falls associated with this glaciation (Brenchley et al., 1994).

5. Discussion

5.1. Comparisons to prior work on the Baltic region

The sequence interpretation developed above is based upon a facies analysis of a core transect. Sequence boundaries are based upon relatively sharp deepening events that separate major prograding ramp systems. The facies descriptions differ from those used by previous workers (Nestor, 1990a,b), and the result is a relatively simple facies model that provides a basis for our sequence interpretation.

The studied interval is part of the upper Caradoc-Ashgill “macrocycle” (Nestor, 1990b; Raukas and Teedumäe, 1997). Einasto (1995) divided the upper Caradoc–middle Llandovery section into nine cycles of clay-rich limestones/marls overlain by pure limestone. The Ashgill section includes the upper (pure limestone) part of his cycle 2, all of cycles 3–5 and the lower (marl) part of cycle 6. Einasto (1995) also used discontinuity surfaces to correlate his core sections.

The sequence model presented here utilizes a different approach that emphasizes shifts in depositional facies. Variations in clay content (marl/limestone) are not directly utilized in defining sequences, although the variations are related due to the variable clay content of different facies (Table 1). Our approach does not attempt to correlate discontinuity surfaces (Einasto, 1995) because their utility in regional correlation is uncertain. Most discontinuity surfaces are sharp subfacies changes that may or may not correspond to regional surfaces. The surfaces are most abundant in shallow shelf facies and the number of surfaces varies between time-equivalent sections. Some surfaces are mineralized and the impregnating material varies by paleogeographical position (Saadre, 1992, 1993). Although most sequence boundaries are discontinuity surfaces, we lack criteria to select and correlate sequence boundaries from among the numerous discontinuity surfaces present within each core.

Despite these differences, sequence interpretation proposed here shares numerous features with Einasto (1995). Both models include regressions at the base of the *P. linearis* biozone (base of sequence 1), base (base of sequence 5) and middle (base of sequence 6) of the *Dicellograptus anceps* biozone, and at the base and top of the Porkuni (bracketing sequence 7). We propose a more detailed subdivision of the lower Pirgu Stage based on the facies evidence for multiple prograding ramp complexes.

Dronov and Holmer (1999) delineated regional sequences for the entire Ordovician section of the Baltic region based on general facies patterns and unconformities. They proposed that the strata studied here occur in four sequences: the Wesenberg sequence (Saunja and underlying units), the Fjäcka sequence (Kõrgessaare and Moe), the Jonstorp sequence (Adila) and Tommarp sequence (Ärina). The sequence interpretation presented here is similar to that of Dronov and Holmer (1999) with finer subdivisions of several of their sequences based on facies patterns recognized in our study. This results in the addition of sequence boundaries within their Wesenberg (base of sequence 1), Kõrgessaare (bases of sequences 3 and 4) and Jonstorp (base of sequence 6) sequences.

5.2. Comparisons to Laurentian sections

Upper Ordovician sequence interpretations have been developed for at least two well-studied areas of Laurentia: the central and southern Appalachians and Cincinnati Arch in the eastern United States, and the Great Basin of the western United States. The Ashgill sequence interpretations for these regions are similar to that proposed here for western Estonia (Fig. 6).

The Ashgill Great Basin sections consist of a series of prograding carbonate ramp sequences that accumulated along the western passive margin of Laurentia (Harris and Sheehan, 1996, 1997). Recent biostratigraphic work (Finney et al., 1997, 1999; Williams et al., 2001) has clarified the correlations between the Great Basin and Estonian sections (Fig. 6). The *P. linearis* biozone (late Nabala-Vormsi) and the Porkuni-age *C. extraordinarius*, and *G. perscupltus* biozones occur in both regions. The intervening Pirgu-age units contain two biozones in each area that appear to be approximately correlative.

Baltic sequences 1 and 2 are absent in the Great Basin (or contained within the underlying Eureka Quartzite). Sequences 3–7 correlate, within the present biostratigraphic resolution, between the two areas. The sections in the two areas differ in several ways. Most obviously, the Estonian sections are thinner (approximately 35–40% of the Great Basin thickness), more argillaceous and the pre-Hirnantian sequences lack exposure caps. However, in both areas, the Hirnantian sea-level falls (at the base and top of sequence 7) are the most extensive. Sequence 7 contains the shallowest facies in the Estonian section and is offset off the shelf in the Great Basin. The base of underlying sequence 6 is marked by a sharp facies shift linked to an abrupt deepening of the shelf.

Upper Ordovician facies and sequences have been correlated from the foreland basin of the central and southern Appalachians to the Cincinnati Arch (Fig. 6) (Holland, 1993; Holland and Patzowsky, 1996; Pope and Read, 1997). The number and age of Ashgill sequences recognized by Holland (1993) and Holland and Patzowsky (1996) agree closely with the Estonian and Great Basin sections. The sections studied by Pope and Read (1997) appear to lack strata equivalent to the Porkuni (Hirnantian) strata. Their sequence 4 includes three small-scale cycles (indicated as sequen-

British Series	Series	Baltic Stages	Sequ.	Graptolite biozones		North American Sequences			Series
				Baltica	Laurentia	Great B.	Appalachians		
Ashgill	Harju	Porkuni	8	*Normalograptus persculptus*		S1 (pt)	?	?	Cincinatian
			7	*Normalograptus extraordinarius*		O5	C6	absent	
		Pirgu	6	*Dicellograptus anceps*	*Paraorthograptus pacificus*	O4	C5	4.3	
			5			O3	C4	4.2	
			4	*Dicellograptus complanatus*	*Dicellograptus ornatus*	O2	C3	4.1	
			3			O1	C2	3	
		Vormsi	2	*Pleurograptus linearis*			C1	2 (part)	
Car.		Nabala (upper)	1				M6		Moh.
				Williams et al. 2001	Finney et al. 1999	Harris & Sheehan 1996, 1997	Holland & Patzkowsky 1996	Pope & Read 1997	

Fig. 6. Sequence correlations of Estonian and Great Basin sections (correlations within North America are modified from Pope and Read, 1997). Stage abbreviations are: Car. = Caradoc and Moh. = Mohawkian. Pope and Read's (1997) sequence 4 is subdivided into three sequences (4.1–4.3) based on their sea-level curve.

ces 4.1–4.3 in Fig. 6) that correlate to Baltic sequences 4–6. Brett et al. (2002) have analyzed and correlated finer-scale cycles in the vicinity of the Nashville Dome, but we have not been able to identify similar correlatable cycles in the Estonian sections.

Despite different tectonic settings (continental interior basin, foreland basin, and passive margin), the Upper Ordovician sequences appear correlative from Estonia to the eastern and western United States. This strongly suggests that eustatic sea-level changes were the dominant control on sequence formation during the late Ordovician in these areas.

6. Conclusions

The Ordovician carbonate facies of western Estonia consists of a series of prograding carbonate ramp sequences based upon detailed facies analysis. One uppermost Caradoc (upper Nabala) and six Ashgill (Vormsi-Porkuni) sequences are bounded by significant transgressive facies shifts. The lowstand of an eighth sequence may be present in the uppermost Ordovician beds (*N. persculptus* biozone) of the Livonian Basin.

Recognition of these Upper Ordovician sequences should improve sedimentological interpretations of the Baltic sections. For example, the relatively subtle facies relations (and stratigraphic complexity) in the Pirgu interval can be more clearly resolved within this stratigraphic framework. The stratigraphic and facies position of sedimentological features such as redeposited material, submarine erosional surfaces and reefs can be placed within the context of this sequence model. Additional work (in progress) will test the applicability of this sequence model across the Estonian Shelf.

Finally, these Baltica sequences appear correlative to those occurring in two areas of Laurentia, the eastern (Appalachians) and western (Great Basin) United States. The facies and tectonic settings differ among the three areas, but the timing and facies shifts are similar, suggesting a strong eustatic control on Ashgill sequences.

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