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An updated correlation of the Silurian strata in Estonia

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ABSTRACT

The correlation of the Silurian succession of Estonia with the global standard has long been considered reliable. However, new information, particularly on the distribution of microfossils, has changed our understanding of the Silurian stratigraphy in the region. Recent palaeontological and geochemical data suggest that: the lower part of the Juuru Regional Stage (RS) is of Hirnantian age; the age of the base of the Raikküla RS in terms of global chronostratigraphy remains problematic; the Aeronian–Telychian boundary correlates with a level in the middle of the Rumba Formation (Fm); the base of the Adavere RS is of latest Aeronian age; the former Riksu Fm is considered to be the proximal, older part of the Sõrve Fm; the traditional lower boundary of the Jaagarahu RS is diachronous, and the closest biostratigraphic horizon that could be used is the first appearance datum of *Jeppssonia sagitta rhenana*; the Wenlock–Ludlow boundary correlates with a level in the upper Rootsiküla RS; the base of the Paadla RS corresponds to a level in the upper Gorstian, in the lower(?) *Phlebolepis ornata* Vertebrate Biozone; the Sauvere and Himmiste beds of the Paadla Fm are of late Gorstian age, and the Uduvere Beds are of early Ludfordian age, corresponding to part of the *Ancoradella ploeckensis* Conodont Biozone; identifying the Ludlow–Přídolí boundary in the Estonian succession is problematic, lacking reliable criteria at present. With these amendments, we present an updated regional correlation scheme drawn on a regular time scale for the first time. A problem that needs to be addressed in the future is providing better biostratigraphic definitions for the bases of regional stages.

Introduction

The study of Silurian rocks in Estonia commenced in the early 19th century (Engelhardt and Ulprecht 1830). The first stratigraphic classification of these strata was proposed by Schmidt (1858, 1881, 1892). Several of Schmidt's units (originally called *Schicht*) are close equivalents of today's regional stages, and his notation system (G, H, J, etc.) is still in use. Bekker (1922, 1925) and Luha (1930, 1933, 1946) established the formal nomenclature of the Silurian regional stages, adopting contemporary geographical names for the units.

Before the 1940s, geological studies in Estonia were based mainly on natural outcrops and small quarries. A new era of research began in the late 1940s, when extensive geological mapping, drilling, and research projects were started by the state geological survey and research institutions. The studies, based on rich core material, substantially improved knowledge of Silurian geology and stratigraphy in the region. A particularly active period of Silurian studies started in the late 1950s and 1960s. During the following decades, various aspects of the Silurian succession of Estonia were investigated, and the results were published in several monographs (e.g. Jürgenson 1966; Kaljo 1970, 1977a; Kaljo and Klaamann 1986). The most recent thorough review of Silurian geology, stratigraphy, and fossils was published in chapters of the book *Geology and Mineral Resources of Estonia* (e.g. Nestor 1997; Nestor and Einasto 1997).

During the long history of Silurian research, the regional stratigraphic scheme has been revised and updated several times. Most of the formations, members, and beds that are in use today were defined and described in the monograph *The Silurian of Estonia* (Kaljo 1970). Further amendments to the stratigraphic nomenclature and correlations with successions in adjacent areas were published in the unified regional stratigraphic schemes (Resolution… 1978; Decisions… 1987) and several other papers (e.g. Aaloe et al. 1976; Nestor and Nestor 1991, 2002; Perens 1992, 1995;

Jeppsson et al. 1994; Nestor 1995, 1997; Nestor et al. 2003; Viira and Einasto 2003; Kaljo et al. 2015).

The correlation between the Silurian regional stages and formations in Estonia and the global chronostratigraphic standard has been considered reliable and has changed little since the definition of most of these units. However, studies in recent decades have revealed several correlation problems, and the need to restudy and revise some parts of the scheme has become evident. An early version of the updated correlation scheme was published in field guidebooks (Männik 2014; Männik et al. 2024). The aim of this study is to present a revised regional correlation scheme together with comments and discussions on recent developments in the Silurian stratigraphy of Estonia. The updated scheme proposed in this paper is drawn, for the first time, on the time scale of Melchin et al. (2020). However, the calibration of the time scale is expected to change in the future, as there are only a few (eight) U–Pb dates for the Silurian, and the construction of the time scale is considered problematic by some authors (Štorch et al. 2024).

Geological background

During the Ordovician and Silurian, from the late Tremadocian to the end of the Přídolí, the territory of present-day Estonia was part of the northern flank of a shallow cratonic sea in the western part of the Baltica continent (Fig. 1). In the earlier stages of development, this sea extended from Norway to the Volga region and from Finland to the Belarussian–Mazurian Precambrian massif. During the final stages of development, the basin was restricted to the Baltic Syneclise in the East Baltic area and northern Poland (Nestor and Einasto 1997). In the Silurian, Baltica was located in equatorial latitudes and drifted gradually northwards (Melchin et al. 2004). From the Late Ordovician Katian Epoch until the end of the Silurian, the Baltic Palaeobasin was characterised by a wide range of tropical shelf environments with accumulation of carbonate deposits and the occurrence of diverse biota (Nestor and Einasto 1997; Dronov and Rozhnov 2007).

Silurian strata are exposed in western, central, and eastern Estonia; in southern Estonia, they are overlain unconformably by the uppermost Lower Devonian terrigenous rocks. As a result of the gradual infilling of the sedimentary basin from north to south and from east to west during the early Palaeozoic, the oldest Silurian rocks are found in the eastern and northern parts of the outcrop area (Fig. 1). Toward the south and southwest, progressively younger strata are exposed. The Silurian succession can be studied in several small historic quarries and several larger modern ones across central Estonia. The main natural outcrops are located along the northern and western coasts of Saaremaa Island.

Based on the distinctly expressed lateral facies changes shown by the Silurian rocks, two major facies belts have been distinguished: the Central Estonian and South Estonian facies belts (Kaljo 1977b). The Central Estonian Facies Belt is dominated by various limestones and late-diagenetic dolostones, which were originally rich in shelly faunas. These

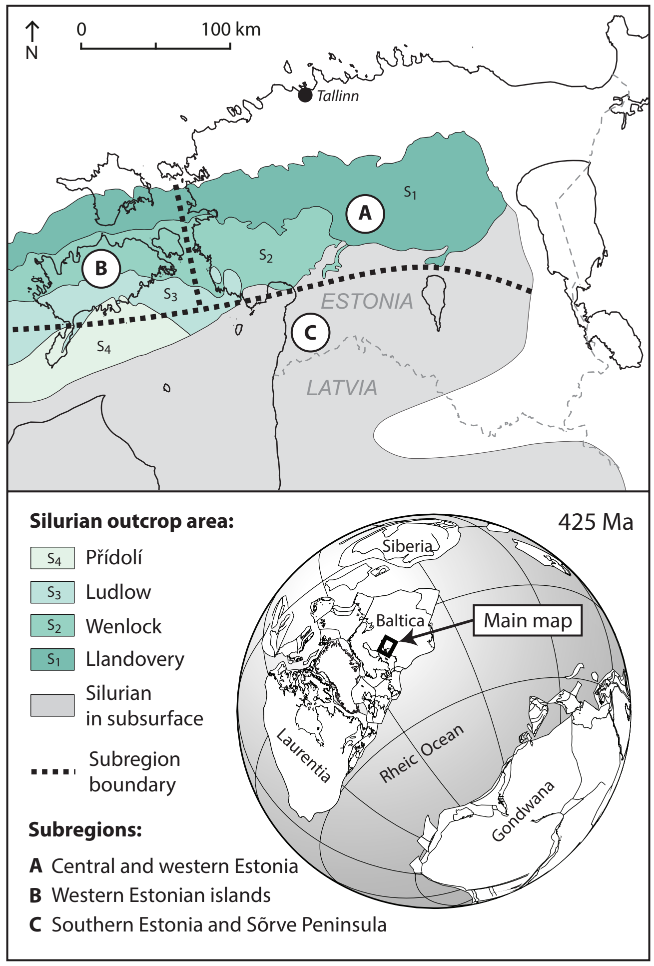


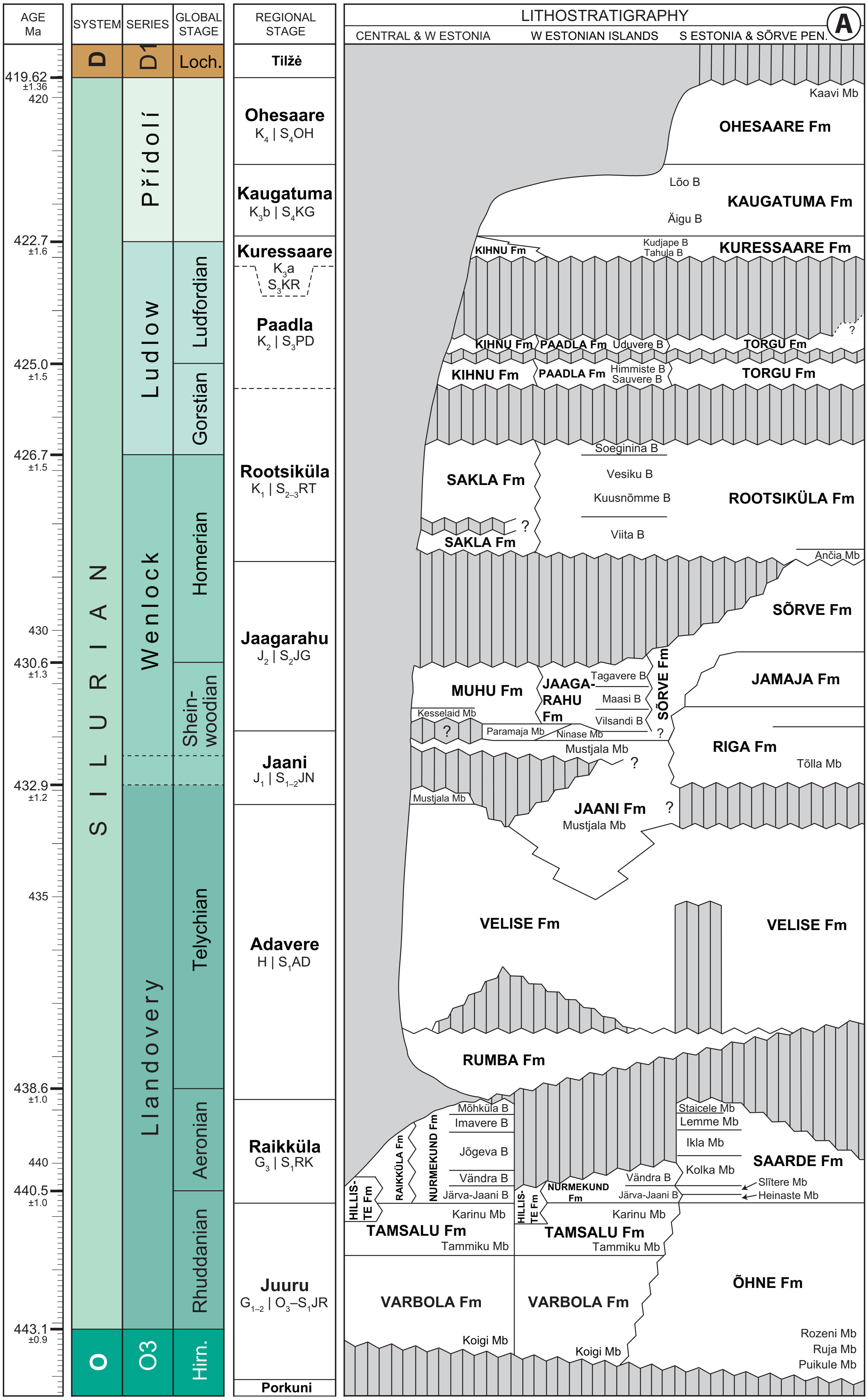
Fig. 1. Map of the distribution area of Silurian rocks in Estonia, and subregions of lithostratigraphic classification shown in Fig. 2A. Note that the boundaries between outcrop areas of series are approximate. The 425 Ma palaeogeographical reconstruction was created with BugPlates software using data from Torsvik and Cocks (2013).

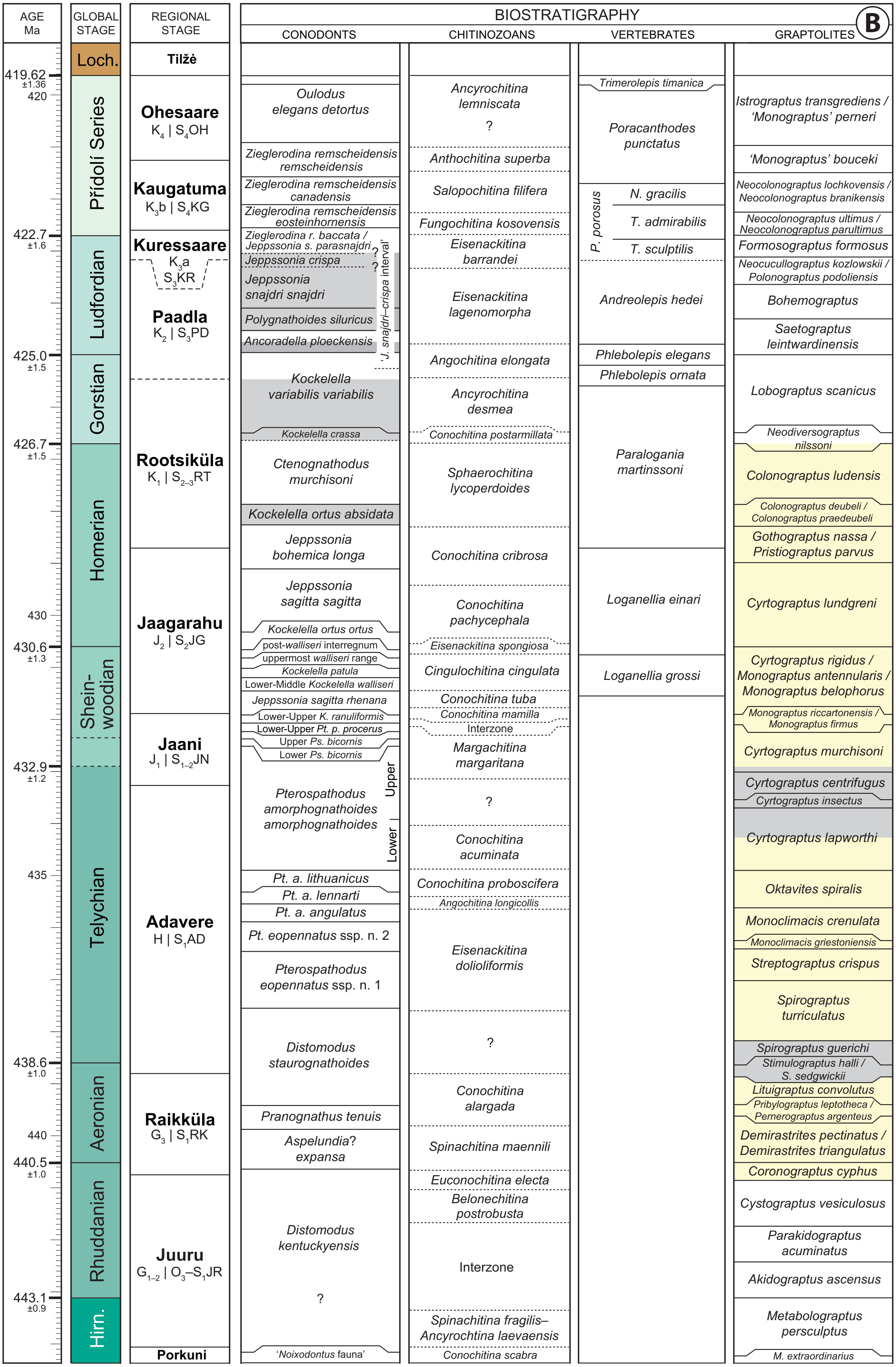
rocks are widespread across the islands of the West Estonian Archipelago, as well as in the western and central parts of mainland Estonia. In general, these strata are well exposed. However, on the mainland, the Silurian succession is less complete, and its upper part has undergone extensive dolomitisation. In contrast, the South Estonian Facies Belt is characterised primarily by argillaceous carbonate rocks (marls) and siliciclastic mudstones containing deeper-water shelly faunas and, at certain levels, occasional graptolites. These rocks are unconformably overlain by the uppermost Lower Devonian siliciclastics and can be studied in drill-core sections only.

Silurian stratigraphic scheme of Estonia

Introductory remarks

The Silurian succession in Estonia is subdivided into ten regional stages (RS) (Kaljo 1970; Nestor 1997; Fig. 2). However, due to the sporadic distribution of macrofauna and limited information on microfossils, these stages were defined by a combination of palaeontological and sedimentological data, and their boundaries were based mainly on lithological criteria (see Kaljo 1970 and references therein). No boundary


AGE Ma
SYSTEM
SERIES
GLOBAL STAGE
REGIONAL STAGE
LITHOSTRATIGRAPHY
A
CENTRAL & W ESTONIA
W ESTONIAN ISLANDS
S ESTONIA & SÕRVE PEN.
419.62 ±1.36
420
422.7 ±1.6
425.0 ±1.5
426.7 ±1.5
430
430.6 ±1.3
432.9 ±1.2
435
438.6 ±1.0
440
440.5 ±1.0
443.1 ±0.9
D
D1
Loch.
S I L U R I A N
Přídolí
Ludlow
Wenlock
Llandovery
Ludfordian
Gorstian
Homerian
Shein-woodian
Telychian
Aeronian
Rhuddanian
O
O3
Hirn.
Tilžė
Ohesaare
K4 | S4OH
Kaugatuma
K3b | S4KG
Kuressaare
K3a
S3KR
Paadla
K2 | S3PD
Rootsiküla
K1 | S2–3RT
Jaagarahu
J2 | S2JG
Jaani
J1 | S1–2JN
Adavere
H | S1AD
Raikküla
G3 | S1RK
Juuru
G1–2 | O3–S1JR
Porkuni
Kaavi Mb
OHESAARE Fm
Lõo B
KAUGATUMA Fm
Äigu B
KIHNU Fm
Kudjape B
Tahula B
KURESSAARE Fm
?
KIHNU Fm
PAADLA Fm
Uduvere B
TORGU Fm
KIHNU Fm
PAADLA Fm
Himmiste B
Sauvere B
TORGU Fm
Soeginina B
Vesiku B
Kuusnõmme B
Viita B
SAKLA Fm
ROOTSIKÜLA Fm
SAKLA Fm
Ančia Mb
SÕRVE Fm
MUHU Fm
JAAGA-RAHU Fm
Tagavere B
Maasi B
Vilsandi B
SÕRVE Fm
JAMAJA Fm
Kesselaid Mb
Paramaja Mb
Ninase Mb
RIGA Fm
Mustjala Mb
Tõlla Mb
Mustjala Mb
JAANI Fm
Mustjala Mb
VELISE Fm
VELISE Fm
RUMBA Fm
Mõhküla B
Imavere B
Jõgeva B
Vändra B
Järva-Jaani B
RAIKKÜLA Fm
NURMEKUND Fm
HILLIS-TE Fm
Staicele Mb
Lemme Mb
Ikla Mb
Kolka Mb
SAARDE Fm
Vändra B
Järva-Jaani B
NURMEKUND Fm
Slītere Mb
Heinaste Mb
Karinu Mb
TAMSALU Fm
Tammiku Mb
Karinu Mb
TAMSALU Fm
Tammiku Mb
ÕHNE Fm
VARBOLA Fm
VARBOLA Fm
Koigi Mb
Koigi Mb
Rozeni Mb
Ruja Mb
Puikule Mb



AGE Ma
GLOBAL STAGE
REGIONAL STAGE
BIOSTRATIGRAPHY
CONODONTS
CHITINOZOANS
VERTEBRATES
GRAPTOLITES
B
419.62 ±1.36
420
422.7 ±1.6
425.0 ±1.5
426.7 ±1.5
430
430.6 ±1.3
432.9 ±1.2
435
438.6 ±1.0
440
440.5 ±1.0
443.1 ±0.9
Loch.
Přídolí Series
Ludfordian
Gorstian
Homerian
Shein-woodian
Telychian
Aeronian
Rhuddanian
Hirn.
Tilžė
Ohesaare
K_4 | S_4OH
Kaugatuma
K_3b | S_4KG
Kuressaare
K_3a
S_3KR
Paadla
K_2 | S_3PD
Rootsiküla
K_1 | S_{2-3}RT
Jaagarahu
J_2 | S_2JG
Jaani
J_1 | S_{1-2}JN
Adavere
H | S_1AD
Raikküla
G_3 | S_1RK
Juuru
G_{1-2} | O_3–S_1JR
Porkuni
Oulodus elegans detortus
Zieglerodina remscheidensis remscheidensis
Zieglerodina remscheidensis canadensis
Zieglerodina remscheidensis eosteinhornensis
Zieglerodina r. baccata / Jeppssonia s. parasnajdri
Jeppssonia crispa
Jeppssonia snajdri snajdri
Polygnathoides siluricus
Ancoradella ploeckensis
'J. snajdri–crispa interval'
?
?
Kockelella variabilis variabilis
Kockelella crassa
Ctenognathodus murchisoni
Kockelella ortus absidata
Jeppssonia bohemica longa
Jeppssonia sagitta sagitta
Kockelella ortus ortus
post-walliseri interregnum
uppermost walliseri range
Kockelella patula
Lower-Middle Kockelella walliseri
Jeppssonia sagitta rhenana
Lower-Upper K. ranuliformis
Lower-Upper Pt. p. procerus
Upper Ps. bicornis
Lower Ps. bicornis
Pterospathodus amorphognathoides amorphognathoides
Upper
Lower
Pt. a. lithuanicus
Pt. a. lennarti
Pt. a. angulatus
Pt. eopennatus ssp. n. 2
Pterospathodus eopennatus ssp. n. 1
Distomodus staurognathoides
Pranognathus tenuis
Aspelundia? expansa
Distomodus kentuckyensis
?
'Noixodontus fauna'
Ancyrochitina lemniscata
?
Anthochitina superba
Salopochitina filifera
Fungochitina kosovensis
Eisenackitina barrandei
Eisenackitina lagenomorpha
Angochitina elongata
Ancyrochitina desmea
Conochitina postarmillata
Sphaerochitina lycoperdoides
Conochitina cribrosa
Conochitina pachycephala
Eisenackitina spongiosa
Cingulochitina cingulata
Conochitina tuba
Conochitina mamilla
Interzone
Margachitina margaritana
?
Conochitina acuminata
Conochitina proboscifera
Angochitina longicollis
Eisenackitina dolioliformis
?
Conochitina alargada
Spinachitina maennili
Euconochitina electa
Belonechitina postrobusta
Interzone
Spinachitina fragilis–Ancyrochitina laevaensis
Conochitina scabra
Trimerolepis timanica
Poracanthodes punctatus
P. porosus
N. gracilis
T. admirabilis
T. sculptilis
Andreolepis hedei
Phlebolepis elegans
Phlebolepis ornata
Paralogania martinssoni
Loganellia einari
Loganellia grossi
Istrograptus transgrediens / 'Monograptus' perneri
'Monograptus' bouceki
Neocolonograptus lochkovensis / Neocolonograptus branikensis
Neocolonograptus ultimus / Neocolonograptus parultimus
Formosograptus formosus
Neocucullograptus kozlowskii / Polonograptus podoliensis
Bohemograptus
Saetograptus leintwardinensis
Lobograptus scanicus
Neodiversograptus nilssoni
Colonograptus ludensis
Colonograptus deubeli / Colonograptus praedeubeli
Gothograptus nassa / Pristiograptus parvus
Cyrtograptus lundgreni
Cyrtograptus rigidus / Monograptus antennularis / Monograptus belophorus
Monograptus riccartonensis / Monograptus firmus
Cyrtograptus murchisoni
Cyrtograptus centrifugus
Cyrtograptus insectus
Cyrtograptus lapworthi
Oktavites spiralis
Monoclimacis crenulata
Monoclimacis griestoniensis
Streptograptus crispus
Spirograptus turriculatus
Spirograptus guerichi
Stimulograptus halli / S. sedgwickii
Lituigraptus convolutus
Pribylograptus leptotheca / Pernerograptus argenteus
Demirastrites pectinatus / Demirastrites triangulatus
Coronograptus cyphus
Cystograptus vesiculosus
Parakidograptus acuminatus
Akidograptus ascensus
Metabolograptus persculptus
M. extraordinarius

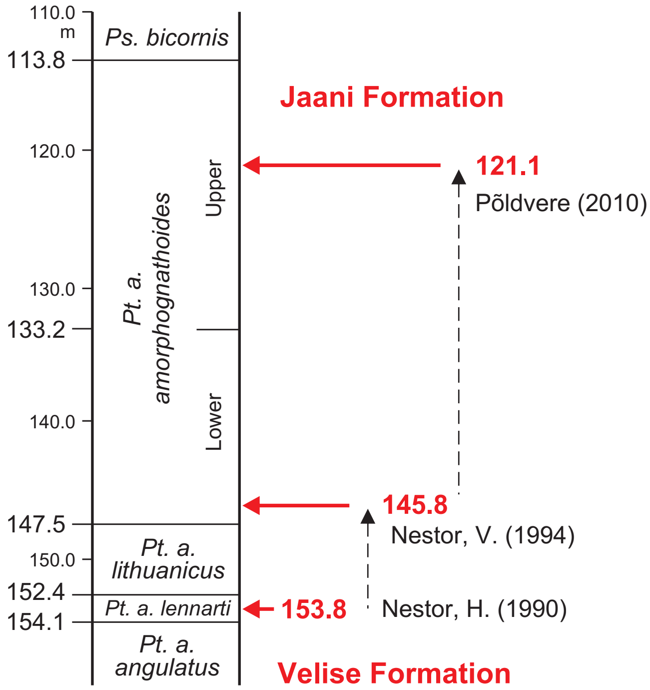


Fig. 3. Changes in interpretations of the base of the Jaani Formation in the Viki core section, after H. Nestor (1990), V. Nestor (1994), and Põldvere (2010). Abbreviations: *Ps.* – *Pseudooneotodus, Pt. a.* – *Pterospathodus amorphognathoides*.

stratotypes were established at the time, and although some were proposed later (e.g. Nestor 1993 and references therein), they have not gained broad acceptance or adoption. As a result, the boundaries of the RSs remain poorly constrained from a biostratigraphic perspective.

Based on lithology, the stages were subdivided into formations (Fm) within different facies belts. Before the 1990s, the rules of the Stratigraphic Code of the former Soviet Union (Stratigraphic… 1977) were followed in the region. According to that code, a formation was considered a topostratigraphic unit, defined mainly by its specific lithological composition, while its boundaries were adjusted based on biostratigraphic data and considered to be isochronous – a feature that is evident in the earlier stratigraphic schemes from the 'box-like' appearance of the formations. Formations were also considered as subdivisions of regional stages and thus mandatorily limited to a single regional stage. The stratigraphic scheme of Nestor (1997) followed this same principle.

These rules have caused some confusion and resulted in repeated revisions of several formational boundaries from publication to publication, based on newly obtained biostratigraphic data. A good example of this is the changing position of the lower boundary of the Jaani Fm in the Viki drill core (Fig. 3). This boundary marks the base of the Jaani RS and was believed to correlate with the Llandovery–Wenlock boundary. During the initial studies, the boundary was tentatively drawn at 153.8 m based on lithological criteria (Nestor, H. 1990). Later, it was shifted upwards, considering the level of appearance of *Margachitina margaritana* (Nestor, V. 1994), and further up to the depth of 121.1 m by Põldvere (2010), where it is marked by a K-bentonite which, based on bio- and chemostratigraphic information (Männik 2007b), correlates with the bentonite at 345.8 m in the Ohesaare core section, the proposed type section of the base of the Jaani Fm and Jaani RS (Nestor, H. 1993). In comparison with the conodont succession, the proposed base of the Jaani Fm in the Viki core section has been moved from the middle *Pt. a. lennarti* Conodont Biozone (CZ; boundary in Nestor, H. 1990) into the upper part of the *Pt. a. amorphognathoides* CZ (Põldvere 2010).

Based on specific lithological characteristics, several (but not all) formations have been further subdivided into members (Mb). Additionally, as many intervals of the Silurian succession reveal apparent cyclicity, particularly within the shallow-water Central Estonian Facies Belt, cyclostratigraphic units consisting of alternating types of rocks (reflecting sea-level changes and often bounded by gaps) were distinguished. These cyclicity-based units were called 'beds' (*kihid* in Estonian, *слои* in Russian) and treated as subdivisions of formations, but sometimes also as substages.

The general lithological and palaeontological characteristics of the units presented in the Silurian stratigraphic scheme of Estonia are summarised in Nestor (1997) and references therein.

The present-day high-resolution biostratigraphy in the region, being the main tool for regional and interregional correlations, is based mainly on conodonts (Viira 1999; Männik 2007a, 2007b, 2007c) and chitinozoans (Nestor 2012 and references therein). However, the use of chitinozoan

Fig. 2. Updated Silurian stratigraphic scheme of Estonia. **A** – chronostratigraphy and lithostratigraphy; **B** – biostratigraphy. The global Silurian time scale is from Melchin et al. (2020). For the Llandovery–Wenlock boundary, two levels marking the limits of an uncertainty interval are indicated: the lower line (432.9 Ma) roughly corresponds to the base of the *Cyrtograptus murchisoni* graptolite biozone, and the upper line marks the approximate level of the base of Wenlock as defined in its stratotype at Hughley Brook, England (further comments are provided in the text). Graptolite biozonation is modified from Cramer et al. (2011). The Llandovery–Wenlock part of the conodont biozonation is based on Jeppsson (1997), Jeppsson and Calner (2003), and Männik (2007a, 2007b). The biozonation in the Ludlow interval (excluding the upper Ludfordian) is modified from Cramer et al. (2011), and the uppermost Ludfordian–Přídolí biozonation is from Viira (1999). The '*J. snajdri–crispa* interval' marks the total range interval of the closely related and difficult-to-distinguish *J. s. snajdri*, *J. crispa*, and *J. s. parasnajdri*. Due to common identification problems, all representatives of these taxa are identified as *J. snajdri* s.l. in Märss and Männik (2013). The chitinozoan biozonation is modified from Nestor (2012), and that of vertebrates and its correlation with the conodont biozonation is from Märss and Männik (2013). In the columns of regional stages, below the names of regional stages are their traditional Schmidt's notations (G, H, J, etc.), and those used in geological maps by the Geological Survey of Estonia are also indicated. Abbreviations: D – Devonian, D1 – Lower Devonian, O – Ordovician, O3 – Upper Ordovician, Hirn. – Hirnantian, Loch. – Lochkovian, Pen. – peninsula, Mb – Member, Fm – Formation, B – Beds; conodonts: *K.* – *Kockelella*, *Zieglerodina r.* – *Zieglerodina remscheidensis*, *Jeppssonia s.* – *Jeppssonia snajdri*, *Pt. a.* – *Pterospathodus amorphognathoides*, *Pt. p.* – *Pterospathodus pennatus*, *Ps.* – *Pseudooneotodus*; vertebrates: *N.* – *Nostolepis*, *P.* – *Poracanthodes*, *T.* – *Thelodus*; graptolites: *M.* – *Metabolograptus*, *S.* – *Stimulograptus*. Colours: yellow background denotes reliably correlated graptolite biozones; grey denotes missing biozones in Estonia, interpreted as gaps.

biozonation in shallow-water carbonates (limestones and dolostones) is often limited due to the sporadic occurrence of these organic-walled microfossils and some inconsistencies in their ranges. In the upper part of the succession, starting in the Wenlock, vertebrates also provide useful stratigraphic information (Märss 1986; Märss and Männik 2013).

Due to the rare occurrence of graptolites in the Silurian strata in Estonia, the correlation of several RSs with the standard graptolite succession has been – and still is – challenging. However, in the last decades, integrated biostratigraphic studies on graptolites, conodonts, and chitinozoans from core sections of southwestern Estonia and western Latvia have improved the situation considerably (Loydell et al. 1998, 2003, 2010; Loydell and Nestor 2005). The reported co-occurrences of graptolites and conodonts from Gotland, Sweden (Jeppsson and Calner 2003) have further helped to improve the correlations. As a result, most of the mid–upper Llandovery and Wenlock graptolite biozones can be reliably correlated into shallow-water settings in Estonia that do not yield graptolites. Dating of other intervals (particularly in the Rhuddanian and Přídolí; Fig. 2) has remained less precise, but combined biostratigraphic and chemostratigraphic ($\delta^{13}C$, K-bentonites) data have allowed reasonable, albeit indirect, dating of some intervals (Kiipli et al. 2012; Märss and Männik 2013; Männik 2014; Kaljo et al. 2015; Fig. 2). Few attempts have been made to apply quantitative stratigraphic methods to make use of large datasets and increase the resolution of the regional temporal framework (e.g. Sadler 2012; Hints et al. 2018 and references therein).

Changes in some conodont biozone names compared to previous ones (Fig. 2 versus e.g. Männik et al. 2024) result from the revision of the genus *Ozarkodina* and the transfer of several former taxa of this genus to the new genera *Zieglerodina* and *Jeppssonia*, introduced by Murphy et al. (2004) and Barrick et al. (2024), respectively.

Comments on selected stratigraphic units and levels

Ordovician–Silurian boundary and base of Juuru Regional Stage

The lower boundary of the Silurian System was ratified by the Silurian Subcommission of the International Union of Geological Sciences (IUGS) in 1984 (Holland 1985). It is defined by the first appearance datum (FAD) of *Akidograptus ascensus* Davies in the boundary stratotype, the Dob's Linn section in Scotland (Rong et al. 2008). Although graptolites are missing from the Ordovician–Silurian boundary interval in Estonia, the Porkuni RS has long been considered to correspond to the Hirnantian *Metabolograptus extraordinarius* and *M. persculptus* graptolite biozones (GZ). Similarly, the lower part of the Juuru RS has been correlated with the lower Rhuddanian *A. ascensus–Parakidograptus acuminatus* GZ (Kaljo et al. 2001, 2008; Brenchley et al. 2003).

The boundary between the Porkuni and Juuru RSs is marked by a sharp change in lithology resulting from a gap in Estonian sections (Meidla et al. 2014a and references therein). Correlation of the boundary interval in Estonia with the formally defined Ordovician–Silurian boundary has been based on the occurrence of Hirnantian trilobites, brachiopods, and ostracods in the Kuldiga and Saldus Fms that are considered equivalent to the Porkuni RS, as well as finds of *Stricklandia lens prima* Williams in the Varbola Fm, which was traditionally attributed to the Juuru RS (Kaljo et al. 1988; Nestor 1997). In practice, the strata immediately below and above the Porkuni–Juuru boundary often do not yield any fossils for reliable dating, and both the regional stage boundary and the system boundary are drawn at the level of a supposed major sedimentary gap in the succession (Ainsaar et al. 2015; Meidla et al. 2020 and references therein). Recent $\delta^{13}C$ studies indicate that the basal part of the Varbola Fm, the Koigi Mb, and sometimes also the lower part of the Varbola Fm above the Koigi Mb fall into an interval of declining $\delta^{13}C$ values, which most likely represents the latest part of the Hirnantian Isotope Carbon Excursion (e.g. Ainsaar et al. 2015; Gul et al. 2021). This suggests that the Varbola Fm is partly of late Hirnantian age (Meidla et al. 2020, 2023a, 2023b) and that the Ordovician–Silurian boundary in the Estonian succession correlates with a level within the Varbola Fm (Ainsaar et al. 2011, 2015; Meidla et al. 2020; Gul et al. 2021). Further to the south, the gradual decline in $\delta^{13}C$ values is observed extending over a remarkably longer interval in the Õhne Fm (e.g. in the Tartu core section; Bauert et al. 2014) and in the Stačiunai Fm in Latvia and Lithuania (Ainsaar et al. 2011; Meidla et al. 2020; Hints et al. 2023). There, the boundary level suggested by carbon isotope stratigraphy may be more than 10 m higher than the traditional position based on the distinct lithological change.

Due to the low-diversity faunas in the Varbola, Õhne, and Stačiunai Fms, finding a reliable biostratigraphic marker for the lower boundary of the Silurian in the region is complicated. One possible guidance level may be the FAD of the chitinozoan *Belonechitina postrobusta* (Nestor), although in the Estonian succession it appears in the middle part of the Varbola and Õhne Fms (Meidla et al. 2020, 2023b), probably within the *Cystograptus vesiculosus* GZ (Nestor 2012). However, this assumption should be taken with caution, as the oldest graptolite occurrences in Estonia are younger, belonging to the *Coronograptus cyphus* GZ. Elsewhere in the world, *B. postrobusta* in many cases makes its first appearance in the *ascensus–acuminatus* GZ (Butcher 2013).

Base of Raikküla Regional Stage

The Raikküla RS was originally established as lying between two distinctive units with pentamerid brachiopods: strata with *Borealis borealis* (Eichwald) below and beds rich in *Pentamerus oblongus* Sowerby above. The name 'Raikküla' was introduced for this unit by Schmidt (1881). In the second half of the 20th century, the concept of the unit evolved into a regional stage, with the lower boundary drawn at the top of the Tamsalu and Õhne Fms and considered equivalent to the base of the *Coronograptus cyphus* GZ (Nestor and Einasto 1997). The same concept of the regional stage was maintained by H. Nestor (1990, 1997), although the boundary of this zone was drawn at a lower horizon by Kaljo and Vingisaar (1969), based on the tentative record of *Pribylograptus sandersoni*

(Lapworth) and *P. incommodus* (Törnquist), co-occurring with *Rhaphidograptus toernquisti* (Elles and Wood) and *Dimorphograptus confertus* (Nicholson) in the upper 6 m of the Õhne Fm. In comparison with the updated graptolite record from the United Kingdom (Zalasiewicz et al. 2009), this assemblage cannot be taken as diagnostic of the *cyphus* GZ (equivalent to the *acinaces* and *revolutus* zones in modern British graptolite biostratigraphy; Zalasiewicz et al. 2009, fig. 2), leaving the age of the base of the Raikküla RS in terms of global chronostratigraphy open. In Fig. 2, the base of the Raikküla RS is tentatively indicated as corresponding to a level within the *C. cyphus* GZ, as indicated in Kaljo and Vingisaar (1969).

Age of Rumba Formation and Adavere Regional Stage

Dating of the Rumba Fm and the lower boundary of the Adavere RS has been problematic for a long time. Originally, based on a single find of the graptolite *Pseudoclimacograptus* (now *Metaclimacograptus*) *hughesi* (Nicholson) in the middle part of the formation in the Ikla core section (at the depth 316.6 m within cycle 5 sensu Einasto et al. 1972; see Kaljo and Vingisaar 1969), the Rumba Fm was considered to correspond to the *Stimulograptus sedgwickii* GZ (Nestor 1972). *M. hughesi*, common in the Rhuddanian and Aeronian, is known to reach the very top of the latter stage but has not been found in the Telychian (Loydell et al. 2015). This correlation of the formation has been followed in most subsequent publications and stratigraphic schemes (e.g. Nestor 1997 and references therein), but other correlations have been proposed (e.g. Nestor 2012; Männik 2014).

Based on the graptolites characteristic of the upper *Spirograptus turriculatus* GZ recorded in the sample at 964.6 m in the Aizpute-41 core section in western Latvia (Loydell et al. 2003; Walasek et al. 2018), below the Osmundsberg K-bentonite recognised at 964.4 m (Kiipli et al. 2010), the upper part of the formation is clearly of Telychian age. The Osmundsberg K-bentonite occurs in the upper half of the Rumba Fm in Estonia and serves as the boundary between cycles 8 and 9 of Einasto et al. (1972). The above data suggest that the Aeronian–Telychian boundary in Estonia should be looked for not higher than the middle of Rumba Fm and that the base of the Adavere RS correlates with a level in the uppermost Aeronian.

This correlation is further supported by chemostratigraphic data. In the $\delta^{13}C$ succession, the Rumba Fm is characterised by a distinct negative excursion, the 'Rumba low' (Kaljo and Martma 2000). In the Ikla core, the lowest $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ values (Gouldey et al. 2010) occur together with *M. hughesi* (Kaljo and Vingisaar 1969). However, in the El Pintado section in Spain (Loydell et al. 2015) and on Cornwallis Island in Arctic Canada (Melchin and Holmden 2006), the lowest $\delta^{13}C_{org}$ values, likely corresponding to the 'Rumba low', are recorded in the lower *Sp. guerichi* GZ, indicating the earliest Telychian age of the excursion. Recently, the 'Rumba low' was recognised in the Aeronian–Telychian transition in the Sommerodde-1 core from Bornholm, Denmark, with its lowest values at a level corresponding to the lower *Sp. guerichi* GZ, just above an unfossiliferous interval (Loydell et al. 2017; Hammarlund et al. 2019). This indicates that the 'Rumba low' correlates with the Aeronian–Telychian boundary interval, being a useful chemostratigraphic marker in sections where graptolites are missing (Hammarlund et al. 2019; Loydell et al. 2025). The data above suggest that the stage boundary in the Estonian succession lies, most probably, in the middle of the Rumba Fm, within cycle 5 sensu Einasto et al. (1972).

The Rumba Fm is separated from the underlying Nurmekund Fm in central and western Estonia, and the Saarde Fm in southern Estonia and southwestern Saaremaa, by a hiatus of variable duration (Fig. 2). Its size increases to the west and southwest (Einasto et al. 1972). The most significant gap in the graptolite record is observed in the Ohesaare core, where the interval from the *Demirastrites triangulatus* GZ to the upper *Sp. turriculatus* GZ and *Pterospathodus eopennatus* ssp. n. 1 CZ is missing (Loydell et al. 1998).

Boundary between Rumba and Velise formations

At the lower boundary of the Velise Fm, just above the contact with the underlying Rumba Fm, a rich and diverse conodont fauna, including the *Pterospathodus* lineage, appears. This supports a high-resolution biostratigraphic subdivision of the main part of the Adavere RS (Männik 2003, 2007a, 2010). The distribution of the lowermost conodont biozone in this interval, the *Pt. eopennatus* ssp. n. 1 CZ, suggests diachroneity of the lower boundary of the Velise Fm. This biozone is present in the sections in the distal part of the basin (e.g. Ruhnu-500 and Viki cores; Männik 2003, 2010), but gradually becomes thinner towards the proximal part of the basin and is missing in westernmost continental Estonia, where the lower boundary of the Velise Fm lies within the *Pt. eopennatus* ssp. n. 2 CZ (e.g. Paatsalu core; Hints et al. 2006). This indicates that the gap between the Rumba and Velise Fms increases from west to east. However, further east in this region, in the vicinity of Valgu village (Männik 2008), the *Pt. eopennatus* ssp. n. 1 CZ reappears in the lowermost Velise Fm. So far, the biostratigraphically proven maximum extent of the gap occurs in southwesternmost continental Estonia, where the lower half of the Velise Fm, corresponding to the *Pt. eopennatus* ssp. n. 1 CZ up to the *Pt. amorphognathoides lithuanicus* CZ, is missing in some sections (e.g. Ristiküla-174 core; Männik, unpublished data).

Contacts between Velise and Jaani formations, Adavere and Jaani stages, and Llandovery–Wenlock boundary

Traditionally, the boundary between the Velise and Jaani Fms has been drawn to coincide with the boundary between the Adavere and Jaani stages, and the same level has been correlated with the Llandovery–Wenlock boundary (Nestor 1997 and references therein). It is now known that the Llandovery–Wenlock boundary, as defined in its type section at Hughley Brook, England, lies close to or coincides with Datum 2 of the Ireviken Event (Aldridge et al. 1993; Jeppsson 1997). This is close to the boundary between the Lower and Upper *Pseudooneotodus bicornis* CZs, within the *Cyrtograptus murchisoni* GZ (Männik 2007b; Fig. 2). The boundary between the Adavere and Jaani stages is within the Upper *Pt. a. amorphognathoides* Conodont Subzone (Männik 2007a; Hints et al. 2022). However, based on data from the type section of the Mustjala Mb (Mustjala core section, at 85.8 m; Nestor 1993), the boundary between the Velise and Jaani Fms lies within the lowermost *Pt. a. lithuanicus* CZ, which corresponds to the interval from 85.85 to 82.60 m in this section (Männik, unpublished data). In the correlation chart (Fig. 2), the lower boundary of the Mustjala Mb is drawn based on published data from different sections in Estonia.

In western continental Estonia and on the islands in the Muhu Strait, the Llandovery–Wenlock boundary falls within an unconformity. In some sections, the strata corresponding to the Ireviken Event are missing entirely (Männik et al. 2014). In the distal graptolite-bearing environments, a gap corresponding to the upper *Cyrt. lapworthi*, *Cyrt. insectus* and probably *Cyrt. centrifugus* GZs was recognised (Loydell et al. 2003, 2010). If the latter hiatus is also present in proximal environments, its duration is below biostratigraphic resolution.

Jaani Regional Stage

Relationships between lithostratigraphic units traditionally included in the Jaani RS (Fig. 2) are drawn in accordance with the model of Perens (1995). This model is based on detailed lithological, geophysical, and biostratigraphic information from many core sections (mainly from Saaremaa) drilled and studied for geological mapping during the second half of the 20th century. According to that model, the lower half of the Jaani Fm is represented by marlstones of the Mustjala Mb that are replaced by the Tõlla Mb of the lower Riga Fm in the southwestern sections on the Sõrve Peninsula. Due to a regression, the shallow-water bioclastic deposits of the Ninase Mb started to accumulate on the northwestern and central parts of Saaremaa and smaller islands west of it. This formed a barrier bordering the northeastern area of Saaremaa and western continental Estonia, creating semi-restricted conditions where argillaceous sediments of the Paramaja Mb were deposited. On the Sõrve Peninsula, towards the central part of the basin, the Ninase Mb is laterally replaced by argillaceous limestones of the lower Sõrve Fm and further by marlstones of the upper Riga Fm.

The Riksu Fm was originally defined by H. Nestor (1995) as a lithologically transitional unit between the shallow shelf (upper Jaani and Jaagarahu Fms) and distal shelf to slope (upper Riga and Jamaja Fms) facies. Later, Nestor et al. (2001) reinterpreted the lower part of the Riksu Fm in the Riksu core as the Ninase and Paramaja Mbs of the Jaani Fm and correlated the lower boundary of the Riksu Fm with the traditional base of the Jaagarahu RS sensu Aaloe (1970), i.e. with the lower boundaries of the Jaagarahu and Muhu Fms. Lithologically, as stated by Nestor (1995, p. 92), the Riksu Fm is similar to the Sõrve Fm; both consist of cyclically alternating marlstones, argillaceous limestones, and nodular micritic limestones accumulated in an open shelf environment. These two units differ mainly by their age, the Riksu Fm being older than the Sõrve Fm, but otherwise they represent parts of the same lithological body, transitional between the shallow and distal shelf settings (Nestor 1997, fig. 69), with a diachronous lower boundary.

The scheme of this interval in Fig. 2 follows that of Nestor (1997), except that the Riksu Fm is abandoned and considered to be the proximal older part of the Sõrve Fm. The Paramaja Mb, indicated by Nestor (1997) as forming the uppermost part of the Jaani RS in the distalmost region, is replaced by the Riga Fm. The interval originally considered to be the lowermost part of the Riksu Fm (Nestor 1994) and later reinterpreted as representing the Ninase and Paramaja Mbs (Nestor et al. 2001) is poorly constrained and marked with a '?' in Fig. 2; further data are needed to clarify its position.

Boundary between Jaani and Jaagarahu regional stages

The boundary between the Jaani and Jaagarahu RSs has been historically based on sedimentology and drawn at a level of abrupt increase in carbonate content at the contact of the Jaani and Jaagarahu Fms in western Saaremaa, and at the contact of the Jaani and Muhu Fms in eastern Saaremaa and western continental Estonia (Nestor 1997 and references therein). The appearance of reefs has been considered to be the most characteristic feature of the lowermost Jaagarahu RS, although several authors have suggested likely diachroneity of the earliest reef units in this stratigraphic interval (Einasto and Männik 1991; Nestor 1994). The boundary has, unfortunately, been poorly constrained biostratigraphically.

In the Jaagarahu drill core (supplemental section to the old Jaagarahu quarry, the historical stratotype of both the Jaagarahu Fm and the Jaagarahu RS; Nestor 1993, 1997), *Jeppssonia sagitta rhenana* (Walliser) appears at a depth of 20.4 m, which is 1.0 m above the proposed base of the formation and regional stage at 21.4 m. It is followed by the appearance of *Ozarkodina martinssoni* Jeppsson about 15 m higher in the section (Männik, unpublished data). The same succession of appearances of these taxa is recorded in the Viki core (Männik 2010). However, there, *J. s. rhenana* appears in the Ninase Mb, which is usually attributed to the Jaani Fm (Jaani RS), whereas *Oz. martinssoni* appears in the lowermost part of the Vilsandi Beds of the Jaagarahu Fm (Jaagarahu RS).

In the chitinozoan succession, these conodonts appear in the *Conochitina mamilla* and *Con. tuba* chitinozoan biozones (ChZ), respectively (Nestor 2010). The appearance of *J. s. rhenana* has also been recorded in the Ninase Mb at Panga Cliff (in the *Con. mamilla* ChZ; Männik and Nestor 2014) and Suuriku Cliff (Meidla et al. 2014b). This indicates that the lower Jaagarahu Fm is older in northwestern Saaremaa than in the Panga section, where it correlates with the upper Jaani Fm (with the Ninase and Paramaja Mbs). Consequently, the base of the Jaagarahu Fm and the traditional base of the Jaagarahu RS are diachronous.

The gap below the Kesselaid Mb (below the basal Muhu Fm; Fig. 2) is supported by data from the Salevere section in western continental Estonia, where *J. s. rhenana* and *Oz. martinssoni* (*Ozarkodina* sp. (aff. *gulletensis*) in Einasto and Männik 1991) appear together in the lowermost part of that member. Based on data from the Viki core section (Männik 2010), the Kesselaid Mb in Salevere correlates with the *Con. tuba* ChZ, suggesting that at least the lower *J. s. rhenana* CZ is missing in that section.

Based on chitinozoan data from the deeper part of the palaeobasin (e.g. Ohesaare and Ruhnu-500 cores), V. Nestor (1994, 2012) suggested that the lower boundary of the Jaagarahu RS corresponds to the base of the *Cingulochitina cingulata* ChZ. In the Ohesaare core, the bases of the *Cin. cingulata* ChZ (marked by the appearance of *Cin. cingulata* (Eisenack) at 299.85 m; Nestor 1994) and the Lower *K. walliseri* CZ (defined by the appearance of *K. walliseri* (Helfrich) at 301 m; Männik, unpublished data) lie very close to each other. In the Viki core section (Männik 2010; Nestor 2010), *Cin. cingulata* and *K. walliseri* also appear almost at the same level. However, this level does not fit the traditional base of the Jaagarahu RS (as shown in Nestor 1997, table 8) but corresponds instead to the boundary between the Vilsandi and Maasi beds. In the Riksu core section, *K. walliseri* appears within the Sõrve Fm (in the Middle Riksu Beds as shown by Nestor et al. 2001), in an interval corresponding to the *Cin. cingulata* ChZ. In the Riksu section, the lower boundary of the Jaagarahu RS is correlated with a level within the *Con. tuba* ChZ and *J. s. rhenana* CZ (Nestor et al. 2001). If the base of the *Cin. cingulata* ChZ is taken as the lower boundary of the Jaagarahu RS, the strata corresponding to the Vilsandi Beds of the Jaagarahu Fm (traditionally assigned to the lower Jaagarahu RS; e.g. Nestor 1997 and references therein) and their equivalents in the lower part of the Muhu Fm (Kesselaid Mb) should instead be correlated with the upper Jaani RS. This possibility was first suggested by Perens (1995).

The data above demonstrate that the lower boundary of the Jaagarahu Fm, as well as the traditional base of the Jaagarahu RS as used until now, are diachronous. However, since the lower boundary of the RS almost correlates with the FAD of *J. s. rhenana* in the Jaagarahu core (the hypostratotype of the Jaagarahu RS), we propose this biostratigraphic marker as the foremost suitable level for tracing the base of the Jaagarahu RS (Fig. 2).

Base of Paadla Regional Stage and Wenlock–Ludlow boundary

The lower boundary of the Paadla RS was initially defined based on lithological criteria: it coincides with the top of the Soeginina mottled early diagenetic (lagoonal) dolostones, which are transgressively overlain by argillaceous limestones and dolostones containing *Didymothyris didyma* (Dalman) and *Ilionia prisca* (Hisinger) (Nestor 1997). Nestor and Nestor (1991), based on chitinozoan ranges in the Ventspils (Latvia) and Ohesaare core sections, concluded that the Rootsiküla and Paadla RSs are separated by a considerable gap in the carbonate sections in Estonia, corresponding to the lower part of the Ludlow, equivalent to the *Noediversograptus nilssoni* and most of the *Lobograptus scanicus* GZs, and consequently, the base of the Paadla RS lies close to the base of the Ludfordian in Estonian successions.

Comparison of $\delta^{13}C$ data from the Priekule (Latvia) and Ohesaare cores confirmed a considerable gap below the Sauvere Beds in the latter section (Kaljo et al. 1997), although the same authors also proposed that '… transgressive parts of this long interval might be represented by some strata at the corresponding levels in the Sauvere Beds...'. The co-occurrence of *Angochitina elongata* Eisenack, *Conochitina latifrons* Eisenack, and *Phlebolepis ornata* Märss in the lower Torgu Fm (Paadla RS) in the Ohesaare core indicates that the upper part of the Gorstian (the *L. scanicus* GZ) is represented at least in southwestern Saaremaa (Viira and Aldridge 1998). Additionally, comparison of conodont data from Saaremaa and Gotland (Sweden) confirms the existence of a gap below the Paadla RS, but also suggests that the Gorstian is still partly present in the region (Jeppsson et al. 1994). The occurrence of *Ph. ornata* in the Sauvere Beds in several outcrop sections (Kandla, Kärla, Kogula) on west-central Saaremaa (Märss 1986) suggests that the upper part of the *Kockelella variabilis variabilis* CZ, comprising the upper Gorstian (Jeppsson et al. 2006; Märss and Männik 2013; Männik 2014), is preserved also in the outcrop area of the Paadla RS. The data above indicate that the base of the Paadla RS corresponds to a level within the upper Gorstian.

Conventionally, the boundary between the Rootsiküla and Paadla RSs has been correlated with the Wenlock–Ludlow boundary in Estonia (Nestor 1997 and references therein). Viira and Einasto (2003) concluded – based mainly on cyclostratigraphic reconstruction, but also on the distribution of some conodonts – that the topmost part of the Rootsiküla Fm and the Rootsiküla RS (the Soeginina Beds) are of early Ludlow age. This was previously suggested by Kaljo et al. (1997), based on correlation of $\delta^{13}C$ curves from the Ohesaare and Priekule cores, which indicated that the upper part of the Rootsiküla RS likely belongs to the Ludlow, within the *Neodiversograptus nilssoni* GZ. As the Rootsiküla RS has traditionally been considered to be of late Wenlock (Homerian) age and the Paadla RS of Ludlow age, Viira and Einasto (2003), when re-dating the uppermost Rootsiküla RS, proposed to move the Soeginina Beds from the Rootsiküla RS to the Paadla RS and, accordingly – and somewhat surprisingly – from the Rootsiküla Fm to the Paadla Fm (as indicated e.g. in Hints 2008, fig. C2). However, although the relatively poor conodont faunas in the Soeginina Beds contain some elements characteristic of the Paadla RS (e.g. *Oulodus siluricus* (Branson and Mehl; Viira and Einasto 2003; Jarochowska et al. 2017), they generally do not differ markedly from those in the underlying strata. Instead, a distinct change in the conodont succession, along with a marked increase in diversity and abundance, occurs just above the boundary between the Soeginina and Sauvere beds, in the lower part of the Paadla RS (Männik and Viira 1993; Märss and Männik 2013).

In the present paper, the traditional definition of the Rootsiküla and Paadla RSs (Nestor 1997) is followed, and the Soeginina Beds – although probably of earliest Ludlow age based on $\delta^{13}C$ data – are attributed to the uppermost part of the Rootsiküla Fm. Hence, the Wenlock–Ludlow boundary is tentatively correlated with the boundary between the Vesiku and Soeginina beds, within the upper Rootsiküla RS (Fig. 2).

Two new units, the Anikaitse and Iide beds, have been proposed as subdivisions of the Rootsiküla Fm. The Anikaitse Beds were described on eastern Saaremaa, between the Vesiku and Soeginina beds, and dated to the latest Wenlock (Viira and Einasto 2003), but the distribution area of this proposed unit and its correlation with core sections were insufficiently addressed. Kiipli et al. (2011, p. 209) proposed the name 'Iide Beds' for microbedded limestone of the Ančia Mb in the Ohesaare core (depth interval 150.5–161.5 m), corresponding to the lowermost, transgressive part of the Rootsiküla Fm. Earlier, this interval had been assigned to the Jaagarahu RS (Einasto 1970), divided between the Jaagarahu and Rootsiküla RSs (Nestor 1997), or included entirely in the Rootsiküla RS (Kaljo et al. 1997). However, as the spatial distribution of both units is unclear or very limited in Estonia, their usefulness in regional stratigraphy remains arguable.

Paadla Formation and Paadla Regional Stage

The distribution of vertebrates and conodonts in the Sauvere Beds dates this unit to the late Gorstian. The age of the Himmiste and Uduvere beds in the middle and upper parts of the Paadla Fm is more problematic. The distribution of vertebrates – particularly the occurrence (appearance) of *Phlebolepis elegans* Pander and the lack of *Andreolepis hedei* Gross in the Himmiste Beds – suggests a correlation of these strata with the uppermost Gorstian–lowermost Ludfordian *Phl. elegans* Vertebrate Biozone (VZ). However, the lack of the lower Ludfordian *Ancoradella ploeckensis* and *Polygnathoides siluricus* CZs in the studied Estonian sections suggests that both biozones lie within a gap in the succession (Märss and Männik 2013). These CZs have been identified further south, e.g. in the Pavilosta-51 core in western Latvia, representing the distal, deeper part of the palaeobasin beyond the carbonate shelf in Estonia (Nestor and Einasto 1977). Considering these data, the Himmiste Beds overlying the Sauvere Beds in the succession correspond to the *Phl. elegans* VZ and probably also to the uppermost Gorstian (Märss and Männik 2013).

Alternatively, based on the identification of the conodont *Jeppssonia crispa* (Walliser) in several sections of the Himmiste Beds (e.g. Viira and Aldridge 1998), this unit could also be dated as late Ludfordian and correlated with the *Formosograptus formosus* GZ (Corradini and Serpagli 1999; Cramer et al. 2011). It has been shown, however, that *J. crispa* may have a considerably longer stratigraphic range in the Baltic region than elsewhere (Viira and Aldridge 1998; Viira 1999; Kaljo et al. 2015), with the oldest identifications reported from the lowermost Paadla Fm (Sauvere Beds; e.g. the Kärla section on Saaremaa; Viira and Aldridge 1998) and co-occurring with *Phlebolepis ornata* in strata of late Gorstian age. In the Riksu core, southwestern Saaremaa, *J. crispa* has been identified from below the FAD of *Phl. ornata* (identified as *Ozarkodina snajdri* s.l.; Nestor et al. 2001; Märss and Männik 2013). However, *J. crispa* belongs to closely related taxa together with *J. snajdri snajdri* (Walliser) and *J. s. parasnajdri* (Viira and Aldridge), forming the so-called *J. snajdri–crispa* lineage, which is known to appear in the upper Gorstian (Aldridge 1985; Jeppsson et al. 1994; Paškevičius et al. 1994) and extend stratigraphically upward to at least the lower Přídolí (Corradini et al. 2015). The Pa elements that are critical for the recognition of these taxa are morphologically highly variable (e.g. Viira and Aldridge 1998), which makes their reliable identification complicated and highly subjective, particularly in samples with few specimens. For example, Viira and Aldridge (1998) identified *J.* cf. *s. snajdri* in the Ohesaare core from the interval 106.25–113.35 m, *J. crispa* from 95.95–100.80 m, and *J. s. parasnajdri* from 61.20–93.40 m. C. Corradini, who restudied the collection in 2014, agreed that *J. s. parasnajdri* occurs in the interval 61.20–93.40 m but identified *J. crispa* in the interval 61.20–100.80 m and did not recognise *J. s. snajdri*. Hence, it is evident that the use of these taxa in stratigraphy should be treated with caution.

The age of the Uduvere Beds is poorly constrained. The occurrence of *Andreolepis hedei* suggests a Ludfordian age for these strata. Märss and Männik (2013) correlated the Uduvere Beds with the *J. s. snajdri* CZ. However, this interpretation disagrees with the geochemical data indicating that the strata hosting the Mid-Ludfordian (Lau) $\delta^{13}C$ excursion are missing in Estonia (Kaljo and Martma 2006). Moreover, the occurrence of *A. hedei* in the Uduvere Beds – considering that the species became extinct during the Lau Event together with *Pol. siluricus* Branson and Mehl (Eriksson et al. 2009) – indicates that they cannot be younger than early Ludfordian. Recent detailed comparison of vertebrate assemblages from Gotland and Estonia also suggests that the Uduvere Beds correlate with an interval in the lower Ludfordian, below the Mid-Ludfordian $\delta^{13}C$ excursion, and might be equivalent to part of the När Fm, Gotland, Sweden (Bremer et al. 2020).

In general, these data agree with the conclusions of Jeppsson et al. (1994) who, based on the occurrence of *Coryssognathus dubius* (Rhodes) and the lack of *Pol. siluricus* in the Uduvere Beds, correlated this unit with the youngest part of the *Ancoradella ploeckensis* CZ, an interval in which specimens of *A. ploeckensis* are very rare. Insufficient sample size may explain why this conodont has not been found in the Uduvere Beds. Based on the considerations above, the Uduvere Beds are tentatively correlated with the upper *A. ploeckensis* CZ in the updated correlation chart (Fig. 2).

Carbon isotope chemostratigraphy shows that the Mid-Ludfordian (Lau) $\delta^{13}C$ excursion, roughly corresponding to the *N. kozlowski–P. podoliensis* GZ, is missing in all studied sections in Estonia (Kaljo and Martma 2006). This indicates that most of the Mid-Ludfordian corresponds to a gap between the Paadla and Kuressaare RSs in Estonia (Fig. 2). Furthermore, identical conodont and vertebrate faunas in the Paadla and Torgu Fms (e.g. the common occurrence of *Panderodus* ex gr. *greenlandensis* Armstrong and *Pand. serratus* Rexroad in all studied collections, and the occurrence of *Phl. ornata* in the lower and *A. hedei* in the uppermost part of both formations) indicate that they are coeval in Estonia (Märss and Männik 2013). However, based on new bio- and chemostratigraphic data, Kaljo et al. (2022) proposed that strata of mid-Ludfordian age might still be partly preserved in the distalmost sections in Estonia. Further studies are needed to confirm this and to provide reliable dating of the Kihnu Fm.

Age of Kuressaare Regional Stage and Ludlow–Přídolí boundary

The traditional boundary between the Paadla and Kuressaare RSs is lithologically sharp, marked by a bone bed in many core sections (e.g. the Sakla core) and characterised by a distinct turnover among vertebrate faunas, evidently related to a gap in the succession (Märss 1992; Märss and Männik 2013). A gap at this level was also proposed based on sedimentological evidence (Einasto 1991; Nestor and Einasto 1997).

The Kuressaare RS has been indirectly correlated with the upper part of the Ludlow, with the *Formosograptus formosus* GZ (Nestor 1997). The boundary between the Kuressaare and Kaugatuma RSs has been tentatively correlated with the Ludlow–Přídolí boundary, without strong biostratigraphic evidence. Based on the generally accepted idea, the *J. crispa* CZ is the uppermost one of the Ludlow and correlates roughly with the *F. formosus* GZ (Corradini and Serpagli 1999; Cramer et al. 2011). According to Viira (1999), in Estonia *J. crispa* appears in the upper Paadla RS, traditionally correlated with the strata older than the *F. formosus* GZ (Nestor 1997), and also occurs in the lower Kuressaare RS but not higher in succession. Considering the information above, it was proposed that at least part of the Paadla RS probably corresponds to the lower *F. formosus* GZ and that the upper part of the Kuressaare RS above the occurrence of *J. crispa* is of Přídolí age (Männik 2014).

Kaljo et al. (2015), based on a detailed analysis of available bio- and chemostratigraphic information from the Baltic region, concluded that the Kuressaare Fm (and the Kuressaare RS) is of late Ludlow age, at least in the Ohesaare core, and correlates with an interval above the Mid-Ludfordian δ^{13}C excursion. However, it is now known that the range of *J. crispa* reaches the lower Přídolí (e.g. *J. crispa* has been reported to co-occur with *Skalograptus parultimus* (Jaeger), the index taxon for the base of the Přídolí, in the Carnic Alps; Corradini et al. 2015). This is further indication that the upper Kuressaare RS, above the occurrence of *J. crispa*, is most probably of Přídolí age.

There are no reliable biostratigraphic criteria for identifying the Ludlow–Přídolí boundary in the Estonian succession. Nestor (2011, 2012), applying indirect correlations, concluded that the boundary between the East Baltic *Eisenackitina barrandei* and *Fungochitina kosovensis* ChZs approximately corresponds to the series boundary and to the contact between the Kuressaare and Kaugatuma RSs. However, considering the data above in this section, the base of the Kaugatuma RS is younger and the Ludlow–Přídolí boundary in the Estonian succession most likely corresponds to a level within the Kuressaare RS. However, further studies are required to locate its level precisely.

Conclusions

Since the beginning of Silurian research in Estonia almost two centuries ago, a vast amount of information has been accumulated on the lithologies and distribution of faunas within the succession. Based on numerous detailed studies carried out during the second half of the 20th century, a high-resolution stratigraphic framework for the Silurian succession was developed and has been widely adopted in Estonia (Nestor 1997). However, new data collected over the past 25–30 years, particularly regarding microfossils, along with the implementation of a revised international time scale (Melchin et al. 2020), have highlighted the need for an updated regional stratigraphic chart. In this paper, we present a revised version of the regional Silurian stratigraphy and discuss the main changes resulting from recent palaeontological and geochemical analyses. These include the following:

1. The lower part of the Juuru Regional Stage is of Late Ordovician (Hirnantian) age.
2. The age of the base of the Raikküla Regional Stage in terms of global chronostratigraphy remains problematic.
3. The Aeronian–Telychian boundary in Estonia should be sought no higher in the succession than the middle of the Rumba Formation.
4. The lower boundary of the Adavere Regional Stage correlates with a level in the uppermost Aeronian.
5. The former Riksu Formation is now considered to be the proximal, older part of the Sõrve Formation.
6. The lower boundary of the Jaagarahu Formation – and the Jaagarahu Regional Stage as used until now – is diachronous. Based on data from the stratotype region, the best biostratigraphic approximation for identifying the base of this stage is the first appearance datum (FAD) of *J. s. rhenana*.
7. The Wenlock–Ludlow boundary in the Estonian succession correlates with a level in the upper part of the Rootsiküla Regional Stage, tentatively placed at the boundary between the Vesiku and Soeginina beds.
8. The Sauvere and Himmiste beds of the Paadla Formation are of late Gorstian age.
9. The Uduvere Beds correspond to an interval in the lower Ludfordian, below the Mid-Ludfordian δ^{13}C excursion, and are tentatively correlated with the upper *A. ploeckensis* Conodont Zone.
10. The base of the Paadla Regional Stage corresponds to a level in the upper Gorstian, possibly within the lower *Ph. ornata* Vertebrate Zone.
11. There are no reliable biostratigraphic criteria for precisely identifying the Ludlow–Přídolí boundary in the Estonian succession; however, it most likely corresponds to a level within the Kuressaare Regional Stage.

Additionally, the duration and distribution of several gaps in the succession have been revised.

It should be emphasised, however, that the updated scheme presented here reflects the current state of knowledge and the authors' interpretation. As such, it inevitably contains less well-constrained intervals and numerous uncertainties regarding both regional and global correlations.

We have identified several areas where further improvements in regional stratigraphy are needed:

1. Improved and revised definitions of lithostratigraphic units, particularly in the context of geological mapping and applied geology.
2. Development of quantitative approaches and integration of biostratigraphic and chemostratigraphic datasets.
3. Evaluation of whether a broader and more precise application of regional stages is warranted, and whether the principles outlined in the *International Stratigraphic Guide* can be applied at the regional level.
4. The Silurian time scale adopted here for the Baltic Palaeobasin is largely based on the ages of zonal boundaries constructed by Melchin et al. (2020). Radiometric dating of additional levels to further improve the Silurian time scale and datings of the rocks from the Baltic Palaeobasin for validating this correlation are needed.

We hope that the correlation chart presented in this paper not only summarises the current state of knowledge but also represents a step forward. Undoubtedly, future research, new data, and the application of modern methods for investigating and correlating sections will continue to refine the Silurian stratigraphy of the region.

Data availability statement

The data used in this study will be made available on request.

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Eesti Siluri kihtide uuendatud korrelatsiooniskeem

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Viimastel aastakümnetel kogutud geoloogiline informatsioon tingis vajaduse Eestis kasutusel oleva Siluri stratigraafilise skeemi täiendamiseks ja täpsustamiseks. Uue andmestiku analüüsil selgus, et (1) Juuru lademe alumised kihid on Hilis-Ordoviitsiumi Hirnanti vanusega; (2) Raikküla lademe alumise piiri vanus vajab täpsustamist; (3) Aeroni ja Telychi vaheline piir Eestis vastab tasemele Rumba kihistu keskel; (4) Adavere lademe basaalne osa on Hilis-Aeroni vanusega; (5) seni Jaagarahu lademe alumiseks piiriks loetud tase on ajas nihkuv, selle piiri määramise parimaks biostratigraafiliseks tunnuseks on praegu konodondi *J. s. rhenana* ilmumine läbilõikes; (6) Wenlocki ja Ludlow' vaheline piir Eesti läbilõikes vastab tasemele Rootsiküla lademe ülemises osas; (7) Paadla lademe alumine piir korreleerub tasemega Gorsty ülemises osas, tasemega *Ph. ornata* tsooni alumises (?) osas; (8) Paadla kihistu Sauvere ja Himmiste kihid on Hilis-Gorsty vanusega, sama kihistu Uduvere kihid vastavad intervallile Ludfordi alumises osas (osale *A. ploeckensis* konodonditsoonist); (9) Ludlow' ja Přidoli vaheline piir Eesti läbilõikes vastab tõenäoliselt tasemele Kuressaare lademe sees, kuid piiri täpse asendi määramiseks usaldusväärsed tunnused seni puuduvad.