Ordovician of the Eastern Baltic palaeobasin and the Tornquist Sea margin of Baltica

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Abstract: This paper summarizes recent knowledge on the palaeontology, biostratigraphy, correlation, sea-level and climate history and isotopic geochemistry of the Ordovician rocks in the western and central parts of the East European Craton, in the area extending from the southern margin of the Fennoscandian Shield to the western margin of the Ukrainian Shield. The regional chronostratigraphic standard is briefly summarized and its correlation to the global standard of the Ordovician is addressed. A two-part correlation chart of 10 areas with unique local Ordovician successions is aligned with the most recent international correlation standard of the Ordovician System and presented against the regular timescale. An updated summary of the evolution of the marine assemblages is provided, the principal gaps in the existing extremely rich palaeontological database are identified and the main bioevents are discussed.

Ordovician rocks are widely distributed in the western and central parts of the East European Craton, extending from the southern margin of the Fennoscandian Shield to the western margin of the Ukrainian Shield. These two shields formed the core of the Baltica Palaeocontinent during the Early Paleozoic. In terms of palaeogeography, the sedimentation occurred in the Baltic Palaeobasin (BPB, also known as the Baltoscandian (Palaeo-)Basin) at the margin of the Tornquist Sea (TSM), the southerly extension along the margin of the Iapetus Ocean that separated the palaeocontinent of Baltica from Avalonia, and a gulf-like extension of the BPB into NW Russia. The present paper summarizes the advances in Ordovician studies in Estonia, Latvia, Lithuania, Russian Kaliningrad Region, Belarus, Ukraine and Moldova.

Knowledge of the whole area addressed in this paper is very uneven. The information from subsurface areas of the narrow Tornquist Sea marginal zone in Ukraine and Moldova is scanty when compared with the highly detailed stratigraphy and very large datasets from the outcrop areas in Estonia and nearby areas of NW Russia. For many decades, the main focus of research that connects this entire vast territory has been stratigraphic correlation, the main topic of this overview paper.

The review is based on the latest formal Ordovician correlation chart compiled in the former USSR for the whole East European Platform that was published in 1987 (Decisions 1987) and its emended English version (Männil and Meidla 1994), but also on the emended versions of the more recent stratigraphic charts in Estonia (Nõlvak *et al.* 2006; Meidla *et al.* 2014), Latvia (Lukševičs *et al.* 2012; Nikodemus *et al.* 2018), Lithuania (Laškovas 2000, 2005) and Belarus (Kruchek *et al.* 2010) and the correlation chart in the explanation to the Kaliningrad sheet of the State Geological Map of Russia (Lukyanova *et al.* 2011), summarizing the most recent advances of research in these areas. New data on bio- and chemostratigraphy (e.g. Kaljo *et al.* 2008; Ainsaar *et al.* 2010, 2020; Meidla *et al.* 2020) are added, as well as the recent interpretations of the climate and sea-level history.

The Ordovician rock successions of 10 areas are addressed. The present updated version of the territorial subdivision covers most of the territory treated by Männil and Meidla (1994) but in slightly more detail. The stratigraphy in the Kaliningrad Region is addressed separately from west Lithuania and SE Latvia is separated from Middle Lithuania. The subdivision into subareas reflects quite well the principal palaeodepth zonation of the palaeobasin as described below but is in places also influenced by the state boundaries.

A glimpse into the history of stratigraphical studies in the region

The tradition of using Ordovician limestone as a building material reaches back several millennia in

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Estonia. The scientific study of the Ordovician rocks in the western part of the East European Platform was initiated only in the nineteenth century in the outcrop belt of Ordovician strata extending from the western Estonian islands to the vicinity of the Ladoga Lake in the St Petersburg region of Russia. The regional stages proposed by Schmidt (1858, 1881) were generally accepted in Estonia as the principal subdivision for both research and geological exploration purposes and later introduced to the neighbouring areas. Until the mid-twentieth century, studies were mainly restricted to the outcrop areas, addressing rocks, stratigraphy, palaeontology and mineral occurrences. The beginning of investigations of the subsurface areas and the recognition of very limited exposure of the Ordovician strata in Ukraine took place in the middle of the twentieth century.

The more recent advances in Ordovician stratigraphy were summarized in correlation charts during the second half of the twentieth century, published in succession since 1965. Even the first one (Decisions 1965) applied the Baltic regional stages as the chronostratigraphic framework in the whole area addressed in this paper and also for NW Russia. The stage classification was complemented in 1984 (Decisions 1987) and this emended classification was also used by Männil and Meidla (1994).

Outline of palaeogeography and regional geology

The distribution area of Ordovician strata extends from the Baltic Sea islands and Finnish Gulf in the north to Ukraine and Moldova in the south. In the northern near-coastal area of Estonia and further to the east, the strata are exposed in the impressive sections of the Baltic–Ladoga Klint. The riverbanks, coastal sections, and limestone quarries and open cast mines expose the Ordovician strata in a limited thickness owing to their nearly horizontal position. Limited exposure of the Ordovician strata is also known in Ukraine. The remaining part of the region considered in this paper represents a subsurface distribution area of the Ordovician, with variable burial depths of the Ordovician strata, locally exceeding 2 km (in the Kaliningrad Region of Russia).

The traditional western boundary of Baltica, the Teisseyre–Tornquist Lineament, is traced across Poland and extends into the westernmost Ukraine and NE Romania near the border with Moldova. This is a traditional boundary and more recent data move the location of the Caledonian tectonic suture (the collision front of Avalonia and Baltica) farther to the SW in Poland. South of Poland, this suture is buried beneath the Alpine–Carpathian Deformation Front (Mazur *et al.* 2018; Poprawa 2019). The area dealt with in this paper represents a passive margin of the Tornquist Sea in the Early Ordovician but was gradually affected in the later part of the Ordovician, owing to collision of Baltica, Laurentia and Avalonia.

The near-coastal zone of deposition along the margin of Baltica was relatively narrow within present-day Ukraine and Moldova, widening towards the north, where it formed the BPB, penetrating deep into the interior of the palaeocontinent as a semi-restricted gulf-like basin. The BPB continues to Scandinavia (mainland Sweden, Norway and the islands of Gotland, Bornholm, Öland and Åland, where the distribution of strata is incomplete because of erosion) and also reaches northwestern and central areas of European Russia. The Ordovician succession is relatively complete within the BPB. In SW Belarus and farther south, the succession gradually becomes progressively less complete, with only middle-Upper Ordovician represented in western Ukraine and Moldova.

Across the East European distribution area, the Ordovician succession begins with sandstones, including common fragments of linguliformean brachiopods. In the northern Estonian part of the BPB, the shells form coquinas of the Cambrian–Ordovician phosphorite deposit. The Lower Ordovician is characterized by the lack of carbonate rocks, except for its uppermost part, and is of very limited thickness almost everywhere but the offshore part of the BPB (western Latvia and western Lithuania). The middle part of the Lower Ordovician comprises argillites and/or clays. A thin overlying unit of glauconite-rich sandstone (Leetse Formation) represents a distinct marker horizon in the upper part of the Lower Ordovician. It is confined to the mid-upper shelf zone in northern and central Estonia but is also distributed across eastern Latvia, central and eastern Lithuania, and NW and SW Belarus up to western Volyn. The sandstones are everywhere almost simultaneously grading upwards into carbonate strata.

The main part of the Ordovician succession, beginning from the topmost Lower Ordovician, is dominated by various limestones and marls, occasionally dolomitic, with rare units of dolomites and argillites. The lower part of the carbonate succession was formed in an extensive shallow sediment-starved basin, with numerous hiatuses and episodes of deposition of glauconite and ferruginous ooids in near-shore areas. More continuous sedimentation was characterizing only the deeper parts of the BPB (western Latvia and western Lithuania). The sediment accumulation rates gradually increased across the BPB during the late Middle Ordovician. Further south of the BPB, the marginal areas of Baltica were repeatedly subjected to tectonic movements and erosion, making the preserved Ordovician succession progressively more incomplete towards the south. Only a few lenses of Upper Ordovician limestones and sandstones of marginal marine origin are preserved in western Ukraine and Moldova.

The lower part of the Upper Ordovician succession is characterized by extensive distribution of kukersite oil shale associated with limestones in NW Estonia and further to the east while the accumulation of carbonate sediments continued across the rest of the BPB. The succession directly above the kukersite-bearing strata contains evidence of volcanism at the Iapetus margin of Baltica, in the form of K-bentonites that occur in Estonia, Latvia, Lithuania and the Kaliningrad Region. A few K-bentonites are also known from the upper Katian of Estonia. The Upper Ordovician carbonate succession also contains reef units at several levels. A few carbonate stromatactis mounds are also identified in the uppermost Katian of central Estonia. The Katian–Hirnantian transition in northern Estonia is characterized by a reef unit overlain by a transgressive succession with a hiatus that is recognizable almost everywhere across the BPB and TSM, with the exception of the Baltic Sea area west of the Kaliningrad Region where the studied area's only record of the graptolites *Metabolograptus extraordinarius* and *M. persculptus* is known (Ulst 1992). The presence of time-equivalents of the *persculptus* zone is still anticipated in numerous sections.

The overall character of the sedimentary succession is thought to reflect the plate tectonic drift of the palaeocontinent from higher southern latitudes in the Early Ordovician towards the southern tropical zone in the Late Ordovician (Cocks and Torsvik 2021). The replacement of the siliciclastic deposits in the basal part of the Ordovician System with cool-water carbonate sediments and the later change to the Upper Ordovician tropical carbonate rocks with occasional reefs is generally ascribed to this drift (Nestor and Einasto 1997). A distinct ecological zonation of the BPB, with more clay-rich and monotonous deposits in the basin depression areas and packstones to grainstones with occasional coarse siliciclastic supplement and dolomites more nearshore, reflects the depth zonation of the palaeobasin.The principal features of this pattern within the BPB were first recognized as the difference between northern Estonia and the zone extending from Sweden to western Latvia (Männil 1966). A transitional area between the two principal zones was subsequently documented by Põlma (1967). The boundaries of the main zones in Estonia are nearly parallel to the outcrop belt (extending in the west–east direction) but turn to the meridional position in Latvia and Lithuania (see Fig. 1). Northern Estonia, eastern Latvia and eastern Lithuania, together with NW Belarus, represent shallow to mid-shelf carbonate facies. Southern Estonia, western Latvia, western Lithuania and the Kaliningrad region represent the basinal facies with mostly argillaceous red or grey limestones and some clay-dominated intervals. The transitional area between the main belts completes the pattern (areas 2, 5 and 6; Männil and Meidla 1994).

Fig. 1. Distribution of Ordovician strata along the Tornquist Sea margin of Baltica. Numbers for areas: 1, northern Estonia; 2, central Estonia; 3, Livonian Basin; 4, Kaliningrad Region; 5, eastern Latvia; 6, Middle Lithuanian Depression; 7, eastern Lithuania and NW Belarus; 8, SW Belarus; 9, western Volyn; 10, Podillya, eastern Volyn and Moldova. Abbreviations: E, Estonia; La., Latvia; Li., Lithuania; K., Kaliningrad Region of Russia; M. Moldova. Bold line, erosional boundary of the Ordovician strata; solid line, boundary between the areas; dotted line, erosional boundary of the Ordovician strata within Russia; bold dashed line, Teisseyre–Tornquist Lineament.

The same pattern serves as the basis for subdividing the region into areas 1–10 (Fig. 1). The subdivision within Estonia, Latvia and Lithuania reflects the principal facies zonation. The mid-shelf zone of the BPB comprises northern Estonia (1) together with eastern Lithuania and NW Belarus (7). The deeper shelf (depression) zone, known also as the Livonian Basin (LB), comprises southern Estonia, western Latvia and western Lithuania (3) together with the Kaliningrad Region (4). The transition zone between the main belts includes central Estonia (2), eastern Latvia (5) and central Lithuania (6). The TSM represents the southern extension of the BPB and is divided into SW Belarus (8), western Volyn (9) and eastern Volyn, Podillya and Moldova (10).

Regional chronostratigraphy and correlation with the global standard

For more than a century, the regional stages (henceforth 'RS') have been the basic chronostratigraphic units for subdividing the Ordovician succession within the outcrop area of Ordovician strata of the East European Craton. The origin of the concept has usually been attributed to F. Schmidt, although the modern stage terminology was introduced much later. The main features of the stage-level regional chronostratigraphic classification of the Ordovician System were summarized by Männil (1966). Only a few changes have been introduced since then: the Ceratopyge RS was renamed as the Varangu RS (Männil 1990), the Latorp RS was subdivided into the Hunneberg and Billingen RSs (Hints *et al.* 1994) and the Haljala RS merges the former Idavere and Jõhvi stages (Jaanusson 1995). Regional boundary stratotype sections and points have been proposed for a few stages but the same practice cannot be widely applied owing to stratigraphic hiatuses at the bases of most of the regional stages in the outcrop area, and thus most regional stages have unit stratotypes and are in practice commonly recognized by their content rather than their boundaries.

Correlation with the global standard

The *boundary of the Tremadocian Stage and the Ordovician System* was correlated with the base of the *Cordylodus proavus* conodont zone (CZ hereafter) in the BPB for many decades and approximated to the lower boundary of the Pakerort RS in older correlation charts. In the global boundary stratotype section, the base of the Tremadocian coincides with the first appearance datum (FAD) of *Iapetognathus preaengensis* (*I. fluctivagus* in Cooper *et al.* 2001), but only a few specimens of *Iapetognathus* sp. have so far been found in the BPB and none are recorded from the TSM. Therefore, the best approximation for the lower boundary is the FAD of *Cordylodus lindstromi* (Puura and Viira 1999). This level is drawn within the Kallavere Formation in northern Estonia but seems to be confined to a hiatus in other areas (Männil and Meidla 1994).

The *boundary of the Floian Stage* coincides with the FAD of *Tetragraptus approximatus* in the global boundary stratotype section (Bergström *et al.* 2004), corresponding to a level within the *Paroistodus proteus* CZ in the BPB (Pärnaste and Viira 2012). The latter species occurs within the Leetse and Zebre formations in Estonia, Latvia and western Lithuania (Ulst *et al.* 1982; Männil and Meidla 1994; Meidla 1997). In other areas, this boundary is associated with a hiatus (Männil and Meidla 1994).

The *boundary of the Dapingian Stage* (and the Middle Ordovician) is marked by to the FAD of *Baltoniodus triangularis* (Wang *et al.* 2009). The base of this CZ coincides with a well-known marker discontinuity known as ‘Püstakkiht’ (∼ ‘gable layer’) in Estonia, ‘Steklo’ (‘Glass’) in Russia or ‘Blommiga Bladet’ (‘Flowery Sheet’) in Sweden – and is drawn above the base of the Toila Formation in northern Estonia. South of the outcrop belt, this level is close to the base of Kriukai Formation (Ulst *et al.* 1982; Viira 2011) and drawn within the Dr̦aseikiai Formation in eastern Latvia, eastern and central Lithuania (see details below). Farther to the south, the boundary seems to be marked by a minor hiatus (Männil and Meidla 1994).

The *boundary of the Darriwilian Stage* is marked by the FAD of *Levisograptus austrodentatus* (Mitchell *et al.* 1997). This species has been identified in the Šakyna Formation of the LB (Paškevičius 1997) and the boundary is tentatively drawn in the upper part of the Kriukai, Dr̦aseikiai and Pribug formations (Männil and Meidla 1994). In the type area of the Ordovician RSs (northern Estonia), this boundary is drawn within the *Baltoniodus norrlandicus* CZ in the uppermost part of the Volkhov RS.

The *boundary of the Sandbian Stage* (and the Upper Ordovician) is marked by the FAD of *Nemagraptus gracilis* in the stratotype section (Bergström *et al.* 2000). The distribution of this species in Estonia and Latvia is summarized by Nõlvak and Goldman (2007). It occurs in the middle and upper parts of the Viivikonna Formation (northern Estonia) and the Dreimaņi Formation (Latvia and southern Estonia). Männil (1986, fig. 2.1.1) noted the first *Nemagraptus* in the Uhaku RS and tentatively correlated the lower boundary of the *N. gracilis* graptolite zone (GZ) with the boundary of the Kukruse RS. Goldman *et al.* (2015) argued that the occurrence of *N. gracilis* in the middle part of the Dreimaņi Formation should be interpreted as a ‘late occurrence’ and left the stage boundary in the same position. There is likewise no perfect marker for this boundary in the conodont succession (Paiste *et al.* 2022) but the base of the *Eisenackitina rhenana* chitinozoan subzone may serve as a tentative marker (Hints *et al.* 2007). The base of the Sandbian remains tentative also within the TSM area.

The *boundary of the Katian Stage* is marked by the FAD of *Diplacanthograptus caudatus* (Goldman *et al.* 2007), but the interval is poor in graptolites and conodonts in the regions addressed in this paper. The boundary can still be identified using the secondary marker, the Guttenberg δ^{13}C excursion (GICE), located slightly above the boundary in the stratotype section. The base of the Katian lies within the upper part of Kahula and Adze (or Blīdene) formations within the BPB but is less well constrained in other areas.

The *boundary of the Hirnantian Stage* is marked by the FAD of *Metabolograptus extraordinarius* (Chen *et al.* 2006). The only section with a record of this graptolite species is located in the Baltic Sea area, west of the Kaliningrad Region (Ulst 1992), where the distribution of other fossil groups is unknown. Conventionally, the base of the

Hirnantian is considered to coincide with the base of the Porkuni RS (e.g. Kaljo *et al.* 2008). The latter is often identified using the *Conochitina taugourdeaui* chitinozoan zone (Hints *et al.* 2000) and the beginning of the Hirnantian δ^{13}C excursion (HICE). However, in some sections the succession of events is difficult to interpret (Bauert *et al.* 2014; Meidla *et al.* 2020; see also below) and the correlation of this boundary with the global standard needs to be verified. The Hirnantian corresponds to a hiatus in the areas south of the BPB.

The *lower boundary of the Rhuddanian Stage and the Silurian System* is marked by the FAD of *Akidograptus ascensus* (Melchin and Williams 2000). In the area addressed here, this species is known only from one offshore section in the southeastern part of the Baltic Sea (Ulst 1992). In the onshore sections, the Hirnantian–Rhuddanian transition lacks good index taxa. The base of the Silurian System has for a long time been correlated with the significant hiatus at the boundary between the Porkuni and Juuru RSs corresponding to the maximum regression related to the Hirnantian glaciation and the major faunal overturn. However, recent chemostratigraphic data show that the falling limb of HICE reaches into the basal part of the Juuru RS (Ainsaar *et al.* 2010, 2015; Bauert *et al.* 2014; Meidla *et al.* 2020). This suggests that the Ordovician–Silurian boundary is probably located within the beds formerly considered as basal Silurian.

Regional stages

The regional stages have been the basic chronostratigraphic units of the Ordovician succession of the East European Craton almost from the beginning of studies in the middle of the nineteenth century. The definitions of stages were originally based on a combination of palaeontological and lithological features of rock units with distinctive lithologies within the outcrop area, with the carbonate macrofauna as the main basis for the subdivision. Since the beginning of extensive drilling activities in the middle of the twentieth century, the stage classification has also been extended into the subsurface area of Estonia, other areas of the BPB and the TSM. The definitions of the stages have ‘evolved’ remarkably during the last decades and the ties to the graptolite zonation and microfauna, in particular conodonts, are well developed. The rich dataset allows the spatial distribution of the formations to be traced and this generally supported the use of ‘stages’ of an integrative nature, although problems with chronostratigraphic correlation between the formations of the outcrop belt and the subsurface are still not properly resolved at some levels. Since the middle of twentieth century, the stages have been treated largely as sets of lateral formations (or members, or their parts) having, according to the faunal evidence, roughly similar ages. This approach was reasonable given the availability of a huge number of core sections of which the absolute majority could not be properly investigated palaeontologically. Largely the same principles are still actively used in Belarus, but Estonia, Latvia and Lithuania have decided to adopt the principles of the International Stratigraphic Guide.

In its near-present form, the Ordovician regional stage classification was accepted in 1984 as the standard for correlation of the Ordovician strata within most of the western East European platform. Today, the Ordovician sequence of the BPB and TSM is subdivided into 19 regional stages, from the upper part of the Pakerort RS to the lower part of the Juuru RS (Meidla *et al.* 2014).

The *Pakerort RS* was originally defined as the lowermost RS of the Ordovician System characterized by, for example, *Rhabdinopora flabelliforme*, *Ungula ingrica* and *Obolus apollinis* (Männil and Meidla 1994). Its boundary is drawn at the base of the *Cordylodus andresi* CZ. The systemic boundary is traced according to the FAD of the conodont *Cordylodus lindstromi* (see Section ‘Correlation with the global standard’) and is located in the middle–upper parts of the Pakerort RS in northern Estonia (Heinsalu and Viira 1997), within the Kallavere Formation. In Latvia and Lithuania, the Kallavere and Salantai formations yield *Cordylodus angulatus* and are attributed to the Ordovician. South of BPB, the systemic boundary is mostly marked by a remarkable hiatus, except for the West Volyn where it is tentatively drawn within the Vyzhivka Formation. The thickness of the Pakerort RS within BPB may occasionally reach 16 m (Männil and Meidla 1994).

The *Varangu RS* comprises clays and argillites and can be recognized primarily by conodonts, corresponding closely to the *Paltodus deltifer* CZ (Heinsalu and Viira 1997). The thickness within the BPB usually does not exceed 10 m; south of the BPB the Varangu RS is missing because of a hiatus (Männil and Meidla 1994).

The *Hunneberg RS* was introduced to the area in 1994 (Hints *et al.* 1994), following, with some delay, the changed stratigraphic practice in Sweden where the former Latorp Stage was subdivided into the Hunneberg and Billingen stages (Tjernvik 1956). In the type area (Sweden), the stage comprises the *Megistaspis armata* and *Megistaspis planilimbata* trilobite zones but trilobites are scarce in the sandstones of northern Estonia. The stage boundary is drawn here near the base of the *Paroistodus proteus* CZ. *Tetragraptus phyllograptoides* has also been documented in the claystones of the same interval in western Latvia (Meidla 1997). The thickness of the Varangu RS usually does not exceed 4 m in the northern areas of the BPB but may reach 46 m in western Latvia (Meidla 1997). This RS corresponds to a hiatus south of the BPB. In Belarus, the 'Latorp Stage' is still used in the correlation charts (e.g. Kruchek *et al.* 2010).

The *Billingen RS* was also introduced for the BPB in 1994 (Hints *et al.* 1994). In Sweden, this RS corresponds to the *Megistaspis dalecarlicus* and *M. estonica* trilobite zones and its base is drawn near the base of the *Prioniodus elegans* CZ. The upper part of RS corresponds to the *Oepikodus evae* CZ (Meidla 1997). The thickness of RS is limited to a few metres in the northern part of BPB and in western Volyn but may reach up to 20 m in western Latvia (Ulst *et al.* 1982).

The *Volkhov RS*, with its type section on the Volkhov River, east of St Peterburg (NW Russia), was initially defined as limestones corresponding to the trilobite succession from the base of the *Megistaspis lata* zone to the top of *Megistaspis limbata* zone. Compared with the underlying strata, this RS contains a more abundant macrofauna. The lower boundary of the RS coincides in northern and central Estonia with the characteristic discontinuity surface serving as a regional marker horizon ('Püstakkiht', see Section 'Correlation with the global standard') and with the base of the *Baltoniodus triangularis* CZ (Meidla 1997), marking also the base of the Middle Ordovician in the whole region. The thickness of the RS in the outcrop area is up to 2.8 m but may reach 30 m in the Jelgava depression (Männil and Meidla 1994).

The *Kunda RS* was originally distinguished as a limestone unit characterized by the trilobite succession from the base of the *Asaphus expansus* zone to the top of *Megistaspis gigas* zone and containing a rich assemblage of macrofossils. Its base, currently drawn near the base of *Lenodus variabilis* CZ, is thought to correspond to the base of *Cyathochitina regnelli* chitinozoan zone (Nõlvak *et al.* 2006). The thickness of the RS varies usually between 1 and 9 m in the outcrop area but may reach up to 40 m in the subsurface.

The *Aseri RS* was formerly distinguished in the trilobite succession as an interval from the base of the *Asaphus (Neoasaphus) platyurus* zone to the top of *Asaphus (Neoasaphus) kowalewskii* zone, but in practice it was also distinguished according to a remarkable macrofaunal change at its base, *inter alia* by the disappearance of *Megistaspis* and appearance of *Asaphus (Neoasaphus)*, *Echinosphaerites* and others (Männil and Meidla 1994; Hints 1997). The base of the RS is drawn above the base of the *Eoplacognathus suecicus* CZ. The thickness of the RS mostly does not exceed 3 m, but may be higher in the subsurface areas (Männil and Meidla 1994).

The *Lasnamägi RS* comprises mostly grey or in some areas also red-coloured limestones. The unit was originally distinguished as the Building Limestone in the type area (Jaansoon-Orviku 1927; Rõõmusoks 1970), but is now limited to the lower half of its previous extent (Decisions 1987). The boundary of the RS coincides, according to the present understanding, with the base of the *Eoplacognathus foliaceus* Subzone of the *Pygodus serra* CZ and is also macrofaunally fairly distinct (Männil and Meidla 1994). The thickness of the RS does mostly not exceed 10 m.

The *Uhaku RS* represents a limestone and marl unit with a boundary drawn, after a remarkable revision (Decisions 1987), at the base of *Gymnograptus linnarssoni* GZ and the *Eoplacognathus robustus* subzone of the *Pygodus serra* CZ (Hints 1997). In the type area, the lower part of the RS was formerly attributed to the Lasnamägi RS. *Gymnograptus linnarssoni* is also known in Scandinavia and in the Moscow Basin. The thickness of the RS varies mostly between 8 and 18 m (Männil and Meidla 1994).

The *Kukruse RS* is a limestone unit that contains kukersite oil shale seams or supplement of kukersine (organic matter from near-coastal algal mats) in limestones of the outcrop belt and its nearest vicinity. The boundary of the RS has been repeatedly modified. A bed-by-bed stratification (with indexation of individual beds or their sets: capitals A–P and Roman numbers I–X) has been introduced in the type area. The lower boundary of the RS matches that of the *N. gracilis* GZ although the index species has never been found in the lower part of the RS (see Section 'Correlation with the global standard'). In the type area, the boundary of the RS is confined to the first commercial kukersite bed ('A') but a major change in the composition of the macrofauna is noted at a slightly higher level (in the kukersite bed 'C'). Outside the distribution area of the commercial kukersite seams, in the basal part of the RS, ostracods (e.g. *Baltonotella kuckersiana* and *Euprimites locknensis*) have been used for identifying the lower boundary of the RS (Hints 1997). The thickness of the RS is mostly 15–24 m but may locally exceed 30 m in NE Estonia.

The *Haljala RS* was formally introduced in 1995 by merging variably argillaceous limestones of the former Idavere and Jõhvi stages that were difficult to differentiate biostratigraphically in the subsurface areas (Hints 1997). However, 'Idavere' and 'Jõhvi' are still used as stages in Belarus (Kruchek *et al.* 2010). The boundary of the RS is drawn within the *Baltoniodus gerdae* subzone of the *Amorphognathus tvaerensis* CZ. Because of a hiatus in the boundary interval of the Haljala RS, the unit is macrofaunally fairly distinct in the outcrop area, particularly in the trilobite and brachiopod record. The lower boundary is identified in other areas based on the more complete sections of central Estonia (northern part of

Tartu County) where the base of *Angochitina granulifera* Chitinozoan Zone has been proposed as a marker for this boundary (Hints 1997). This RS contains the Grefsen and Sinsen K-bentonite complexes (according to Bergström *et al.* 1995), up to 20 K-bentonite beds, most numerous in NW Estonia. Some of the beds are also traceable to Latvia and to Lithuania. The thickness of the RS reaches up to 20 m within the BPB.

The *Keila RS* is distinguished in the type area as bioclastic and micritic limestones containing a distinctive reef unit in NW Estonia (Vasalemma Formation; Kröger *et al.* 2014). In the subsurface area, this RS also contains marls, dolomites, calcareous siltsones and claystones. The lower boundary of the RS is drawn at the level of the Kinnekulle K-bentonite bed located at the appearance level of the short-ranged chitinozoan species *Angochitina multiplex* (Hints and Meidla 1997). The thickness of the RS is highly variable, from 2 to almost 30 m within the BPB and the TSM (Männil and Meidla 1994).

The *Oandu RS* is a thin unit of argillaceous limestones and marls that are faunistically very distinct from the underlying strata in the outcrop belt and its vicinity, containing *Toxochasmops extensus*, *Howellites wesenbergensis*, *Sowerbyella (Sowerbyella) tenera* and many other macro- and microfossils (Hints *et al.* 1989; Männil and Meidla 1994; Meidla 1996). This RS contains the short range of *Amorphognathus ventilatus* (Männik and Viira 2012) and its boundary can be identified by the appearance of a new ostracod assemblage containing *Pelecybolbina illativis*, *Disulcina perita perita* and many others (Meidla 1996). The thickness of the RS varies between 0.3 and 8 m within the BPB (Männil and Meidla 1994).

The *Rakvere RS* was introduced as a unit of finely micritic limestones with scarce macrofauna in the outcrop area and comprises marls and argillaceous limestones in the subsurface areas. The boundary of RS lies in the basal part of the *Amorphognathus superbus* CZ and can be traced also in the ostracod record by the appearance of *Pelecybolbina pelecyoides* and others (Meidla 1996). Based on the scanty graptolite record, this RS could be attributed to the *Dicranograptus clingani* (Nõlvak *et al.* 2006) or *Pleurograptus linearis* (Hints and Meidla 1997) GZs. The thickness of the RS is highly variable from 1.5 to 28 m within the BPB (Männil and Meidla 1994).

The *Nabala RS* comprises various limestones that probably correspond to part of the *Pleurograptus linearis* GZ and are characterized by the appearance of new brachiopod and ostracod species (Hints and Meidla 1997). However, its lower boundary is more reliably traced within the BPB by the appearance of the chitinozoan species *Armoricochitina reticulifera* (Nõlvak *et al.* 2006). The lower boundary of the *Amorphognathus ordovicicus* CZ is very probably drawn within the Nabala RS. Its thickness is highly variable, from 2.5 to 35 m (Männil and Meidla 1994).

The *Vormsi RS* is mostly represented by limestones, marls and argillites, being characterized by sharp lateral facies changes within the BPB. It corresponds to the lower part of *A. ordovicicus* CZ. The lower boundary of the RS is lithologically sharp and macropalaeontologically distinct in the type area (with appearing species, e.g. *Eoplectodonta schmidti, Equirostra gigas* and *Triplesia insularis*) but much less obvious in the subsurface areas (Hints and Meidla 1997). It has sometimes been merged with the underlying Nabala RS in Lithuania and Poland (e.g. Laškov *et al.* 1984; Modliński 1984). This RS is absent in western Volyn. The thickness varies mostly from 0.8 to 25 m (Männil and Meidla 1994).

The *Pirgu RS* is an extensive and variable unit of complicated structure, being mostly characterized by limestones and marls that turn brownish red in the deeper shelf settings (in southern Estonia, western Latvia and western Lithuania). Occasional small reefs are documented in northern Estonia and a few carbonate mounds are known in central Estonia. Some K-bentonites (up to four?) are present in this RS (Estonia and Latvia) but their correlation potential remains uncertain. The shelly fauna comprises three different lateral assemblages within the BPB, with the richest and most diverse mid-shelf assemblage in the type area and an impoverished one in the red limestones and grey marls of the deeper shelf settings (Hints and Meidla 1997). The lower boundary of the RS is indistinct in the distribution of shelly fauna but the utility of the disappearance level of the chitinozoan *Acantochitina barbata* has been demonstrated in grey-coloured syuccessions (Nõlvak *et al.* 2006). This RS is tentatively correlated with the *Dicellograptus complanatus* and *D. anceps* GZs and corresponds to the middle–upper parts of the *A. ordovicicus* CZ. The thickness of the RS is 35–50 m in the type area and 10–70 m in other areas. This RS is absent in SW Belarus, Ukraine and Moldova (Männil and Meidla 1994).

The *Porkuni RS* was established as a unit of dolomites and an overlying reef complex in the type area. In the subsurface area of the BPB, it is replaced by various limestones and dolomites with siliciclastic supplement, oolitic and finely laminated marginal-marine strata. The faunal assemblages in the type area have numerous genera in common with the underlying strata while the strata in southern Estonia, western Latvia and western Lithuania are characterized by the markedly different *Hirnantia* fauna (e.g. *Hirnantia sagittifera* and *Dalmanella testudinaria*) and the Hirnantian *Harpabollia* *harparum* ostracod assemblage (Hints and Meidla 1997; Meidla *et al.* 2020). The boundary of the RS matches the base of the *Spinachitina taugourdeaui* chitinozoan zone (Nõlvak *et al.* 2006; Hints and Männik 2014), although the species is very rare in the dolomites of the type area. In deeper shelf settings, the appearance of *S. taugourdeaui* seems to precede the appearance of the typical *Hirnantia* fauna (Meidla *et al.* 2020). This RS corresponds to the upper part of the *A. ordovicicus* CZ and is tentatively correlated with the *Metabolograptus extraordinarius* GZ and the lower part of *N. persculptus* GZ (see Section 'Correlation with the global standard'). This RS was for a long time considered the topmost Ordovician within the BPB but contains only the lower and middle parts of the early to mid-Hirnantian HICE isotopic excursion and hence does not represent the youngest Ordovician (Meidla *et al.* 2020). The thickness of the RS does usually not exceed 15 m but may locally reach up to 30 m in western Latvia. This RS is absent in SW Belarus, Ukraine and Moldova (Männil and Meidla 1994).

The *Juuru RS* is dominated by biomicritic limestones of the mid-shelf zone of the BPB but the limestones grade rapidly into black shales in the deeper shelf setting (western Latvia and western Lithuania). The lower boundary of the RS coincides with the major gap, associated with the Hirnantian glaciation and an eustatic regression. The conodont fauna is meagre and the *Akidograptus ascensus* and *Parakidograptus acuminatus* GZs have not been established in the area addressed here, except for in one atypical core from the Baltic Sea area (see Section 'Correlation with the global standard'). All groups of the shelly fauna show nearly full rearrangement at the base of this RS but its lower part contains the falling limb of the HICE that elsewhere is correlated with the *Metabolograptus persculptus* GZ (see Section 4.1). The faunas are relatively scarce in the lower part of the RS, probably owing to slow recovery after the Hirnantian environmental crisis. The lowermost truly Silurian biozonal marker within the region is probably the base of *Belonechitina postrobusta* chitinozoan zone that is tentatively correlated with the *P. acuminatus* GZ (Verniers *et al.* 2008) or with the basal part of the *Cystograptus vesiculosus* GZ (Nestor 2012). The thickness of the Ordovician part of Juuru RS seems to increase southwards within the BPB and may locally exceed 10 m (Bauert *et al.* 2014; Meidla *et al.* 2020).

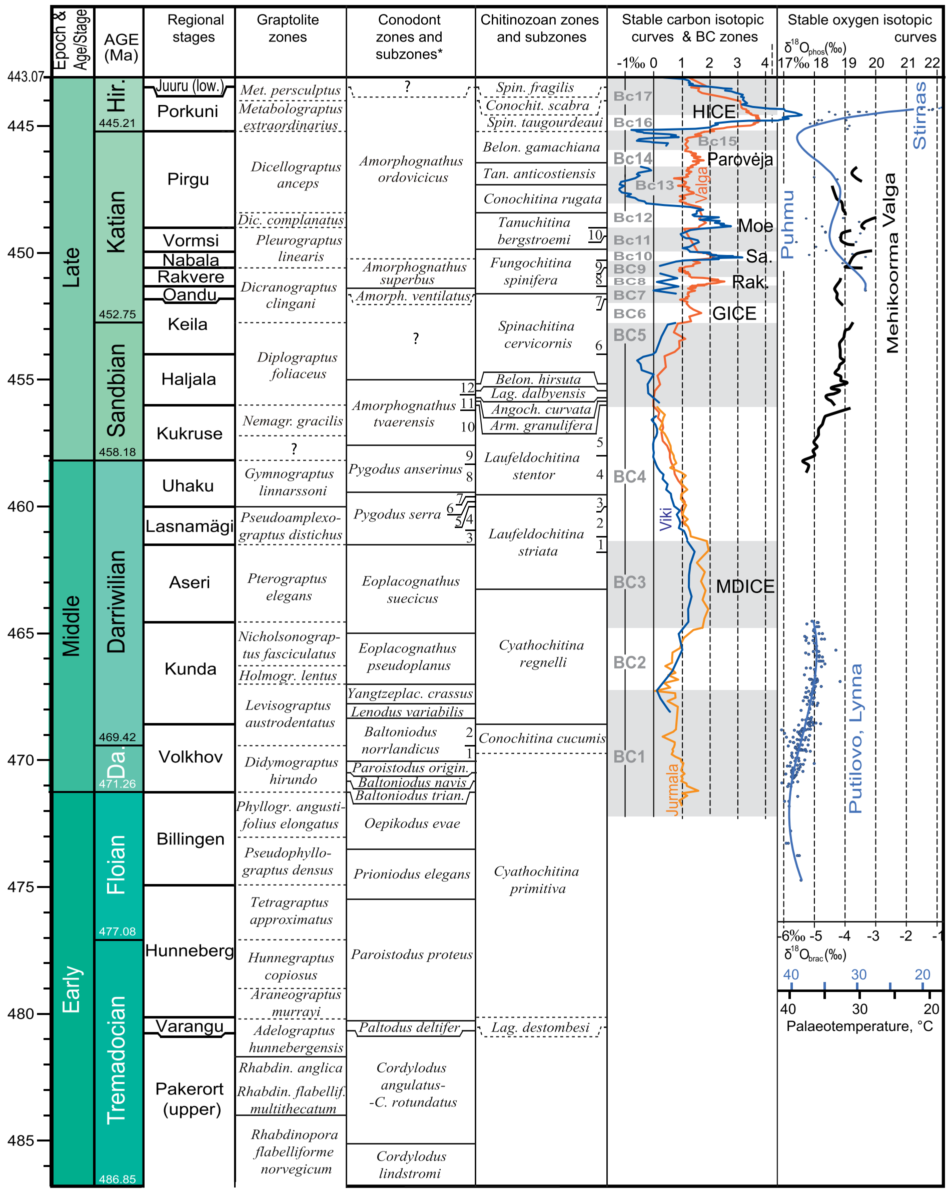
Biostratigraphy

Studies on Ordovician fossils began in the mid-nineteenth century. After the first comprehensive biostratigraphical review by Schmidt (1858), a number of important monographic studies were published by E. Eichwald, C. Pander, A. Pahlen, A. Mickwitz, J. H. Bonnema, R. F. Bassler and others. This documentation was also used in creating and developing the concept of 'stages' ('*Schichten*' by Schmidt 1858, 1881). A large number of monographic studies on Ordovician brachiopods, corals, stromatoporoids, chitinozoans, scolecodonts, ostracods and conodonts were published during the twentieth century by many authors; they are referred to in the major monographic volumes about Estonia (Raukas and Teedumäe 1997), Latvia (Ulst *et al.* 1982), Lithuania (Baltrunas 2004), Belarus (Ropot and Pushkin 1987), Ukraine and Moldova (Shulga 1972).

The initial concept of regional stages was based on the shelly macrofauna but now relies mostly on graptolites and conodonts, and also chitinozoans in the more recent correlation charts. Graptolites are not abundant in the carbonate successions of the TSM and their record within the BPB is confined to the Tremadocian and Darriwilian–Sandbian (Kaljo and Kivimägi 1970, 1976; Männil 1976; Goldman *et al.* 2007; Paškevičius 2011) in near-shore areas while the Lower and Middle Ordovician (except for the redbeds) are fairly well characterized in the deeper shelf setting. Recognition of the Scandinavian graptolite zones that are usually adopted for the correlation charts (see Fig. 2) are largely based on indirect evidence. The conodont zonation, however, is elaborated in detail (Männik and Viira 2012; see also Meidla *et al.* 2014) and is of very high resolution for the Lower and Middle Ordovician (Fig. 2), being based on the North Atlantic conodont zonation established by Bergström (1971). The Baltic chitinozoan biozonation (Nõlvak *et al.* 2006) provides a high-resolution tool across the BPB, particularly in the Middle and Upper Ordovician. A number of other biozonations have been proposed for the BPB. An ostracod biozonation (Meidla 1996; Sidaravičiene 1996) and a partial trilobite zonation (Jaanusson 1982; Meidla 1997; Pärnaste *et al.* 2013) are established and a partial acritarch zonation is proposed (Raevskaya 2005).

Chemostratigraphy

Secular variations in the stable carbon isotopic composition of the carbonate rocks comprise an important tool for the correlation of sections across different facies belts and sedimentary basins. The fluctuations are potentially reflecting the variation of isotopic composition of dissolved inorganic carbon in the original seawater. The Middle and Upper Ordovician sedimentary succession of the BPB is dominated by carbonate rocks and the carbon isotope stratigraphy of this interval is based here on bulk rock δ^{13}C analyses from about 50 drillcore and



Eastern Baltic area and Tornquist Sea margin

Fig. 2. Chronostratigraphy, biozonations, stable carbon and oxygen isotopic curves and stable carbon isotopic zones ('BC…' from 'Baltic Carbon'; Ainsaar *et al.* 2010). Numbers in the columns of biozonations designate the zones and subzones (SZ), as follows. Conodont zonation: *Baltoniodus norrlandicus* zone – 1, *Trapezognathus quadrangulum* SZ; 2, *Lenodus antivariabilis* SZ; *Pygodus serra* zone – 3, *Eoplacognathus foliaceous* SZ; 4, *E. reclinatus* SZ; 5, *E. robustus* SZ; 6, *E. protoramosus* SZ; 7, *E. lindstromi* SZ; *Pygodus anserinus* zone – 8, *Sagittodontia kielcensis* SZ; 9, *Amorphognathus inaequalis* SZ; *Amorphognathus tvaerensis* zone – 10, *Baltoniodus variabilis* SZ; 11, *B. gerdae* SZ; 12, *B. alobatus* SZ (Meidla *et al.* 2014). Chitinozoan subzones (Nõlvak *et al.* 2006): *Laufeldochitina striata* zone – 1, *Cyathochitina sebyensis* SZ; 2, *Conochitina clavaherculi* SZ; 3, lower *Conochitina tuberculata* SZ; *Laufeldochitina stentor* zone – 4, upper *Conochitina tuberculata* SZ; 5, *Eisenackitina rhenana* SZ; *Spinachitina cervicornis* zone – 6, *Angochitina multiplex* SZ; 7, *Ancyrochitina* sp. n. 1 SZ; *Fungochitina spinifera* zone – 8, *Cyathochitina angusta* SZ; 9, *Armoricochitina reticulifera* SZ; *Tanuchitina bergstroemi* zone – 10, *Acanthochitina barbata* SZ. Abbreviations: Ages – Hir., Hirnantian; Da., Dapingian; graptolite zones – *Met., Metabolograptus; Dic., Dicellograptus; Nemagr., Nemagraptus; Holmorg., Holmograptus; Phyllogr., Phyllograptus; flabellif., flabelliforme;* chitinozoan zones – *Spin.*, *Spinachitina*; *Conochit.*, *Conochitina*; *Belon.*, *Belonechitina*; *Tan.*, *Tanuchitina*; *Lag.*, *Lagenochitina*; *Angoch.*, *Angochitina*; *Arm.*, *Armoricochitina.*

outcrop sections from Estonia, Latvia, Lithuania, Sweden and NW Russia (Fig. 2).

The inorganic carbon isotope curve offers positive and negative excursions for correlation of the sections (Ainsaar *et al.* 2010). The isotope curve is relatively smooth in the Dapingian–Sandbian interval, with one distinct long-lasting positive excursion, the MDICE (Middle Darriwilian Isotopic Carbon Excursion) and one negative excursion, the LSNICE (Lower Sandbian Negative Isotopic Carbon Excursion; Bauert *et al.* 2014). The Katian–Hirnantian interval is characterized by frequent fluctuations of the δ^{13}C curve with multiple positive excursions: the GICE (Guttenberg ICE), Rakvere, Saunja, Moe, Parovėja, and the prominent HICE (Hirnantian ICE; Ainsaar *et al.* 2010; Bauert *et al.* 2014). The MDICE, GICE and HICE have been correlated globally between basins on different palaeocontinents, whereas the global correlation of other excursions is not entirely confirmed (e.g. Bergström *et al.* 2015). Based on the variations of δ^{13}C curves, Ainsaar *et al.* (2010) established the Baltoscandian correlation standard with 17 chemostratigraphic zones. The isotope curve of the Dapingian–Sandbian interval has been subdivided into five zones (BC1–BC5) as pre-MDICE, the rising limb of the MDCE, the MDICE plateau, the falling limb of the MDICE until the LSNICE, and post-MDICE. The subdivision of the curve in the Katian interval comprises 10 zones (BC6–BC15), each representing a peak or an inter-peak segment. The HICE has been subdivided into rising (BC16) and falling parts (BC17) of the excursion.

The δ^{13}C bulk carbonate curves of three sections in Figure 2 represent different facies zones and clearly show some facies-related differences in the isotope values. The δ^{13}C values in the shallower platform facies (Viki; Hints *et al.* 2014) are generally lower than in the deeper basinal facies (Jurmala and Valga; Ainsaar *et al.* 2010; Männik *et al.* 2021), except for the excursion peaks in the Upper Ordovician that are clearly amplified. Despite this facies effect, this chemostratigraphic zonation is easily applicable across the BPB and has also been used for intercontinental correlations.

Secular trends in the oxygen stable isotopic composition of different sedimentary components could reflect seawater temperature variations. As the original oxygen isotopic composition of carbonate sediments could be easily altered by diagenesis, the application of oxygen isotopes for Paleozoic chemostratigraphic correlations and palaeoenvironmental studies is more complicated. Brachiopod (Gul *et al.* 2021) and ostracod shells (Brenchley *et al.* 2003) have maintained the primary signal better than whole-rock carbonate but the oxygen isotopic composition of conodont phosphate is a more widely applied palaeotemperature proxy. The three-point moving averages of brachiopod calcite δ^{18}O values from combined Putilovo and Lynna outcrop samples (NW Russia; Rasmussen *et al.* 2016) and Puhmu drillcore samples (Estonia; Kaljo *et al.* 2017), as well as sample-averaged data from the Stirnas drillcore (Latvia; Hints *et al.* 2010*a*) are presented in Figure 2, together with phosphate δ^{18}O three-point averaged curves from the Mehikoorma and Valga drillcores (Estonia; Männik *et al.* 2021). The curves have been tentatively positioned on a palaeotemperature scale (calculated on the basis of seawater $\delta^{18}\mathrm{O} = -1$). The gradual cooling trend in the global sea-surface palaeotemperature throughout the middle to late Ordovician (Trotter *et al.* 2008) is well traced in the combined curves from the BPB (Fig. 2). The only remarkable environmental event, the Hirnantian cooling, is also expressed in the Baltoscandian brachiopod δ^{18}O curve and serves as a chemostratigraphic marker, together with the HICE.

Description of the areas

The description of the areas summarizes the principal features of the rock successions in different parts of the BPB and TSM. The correlation of formations shown in Figures 3 and 4 is usually well constrained (if not otherwise stated). Most of the units are fossiliferous and the faunas are often well described but only the principal features (commonest fossils, principal correlation tie points) are usually mentioned. Additional information can be found in the overview papers (see Sections 'Distribution of the Ordovician strata' and 'Regional stages').

Northern and central Estonia (1, 2)

North Estonia is the historical type area for the majority of the regional stages and correlation to the regional standard is addressed only in a few relevant cases in this section. The present lithostratigraphic subdivision was introduced since the pioneering paper by Orviku (1940) and elaborated in more detail in the middle of the twentieth century. Except for the mainly siliciclastic Lower Ordovician, wackestones and packstones with abundant skeletal debris of several invertebrate groups and algae are characteristic of this succession. Several correlation charts have been published since 1965 (the latest one by Männil and Meidla 1994).

The *Lower Ordovician* succession in northern and central Estonia (Fig. 3) consists of thin lenses of clastic rocks and claystones, with maximum thickness of the individual units in NW Estonia (Heinsalu and Viira 1997; Meidla 1997). The Ordovician succession begins with the upper part of the *Kallavere Formation*, which is a brownish grey medium-

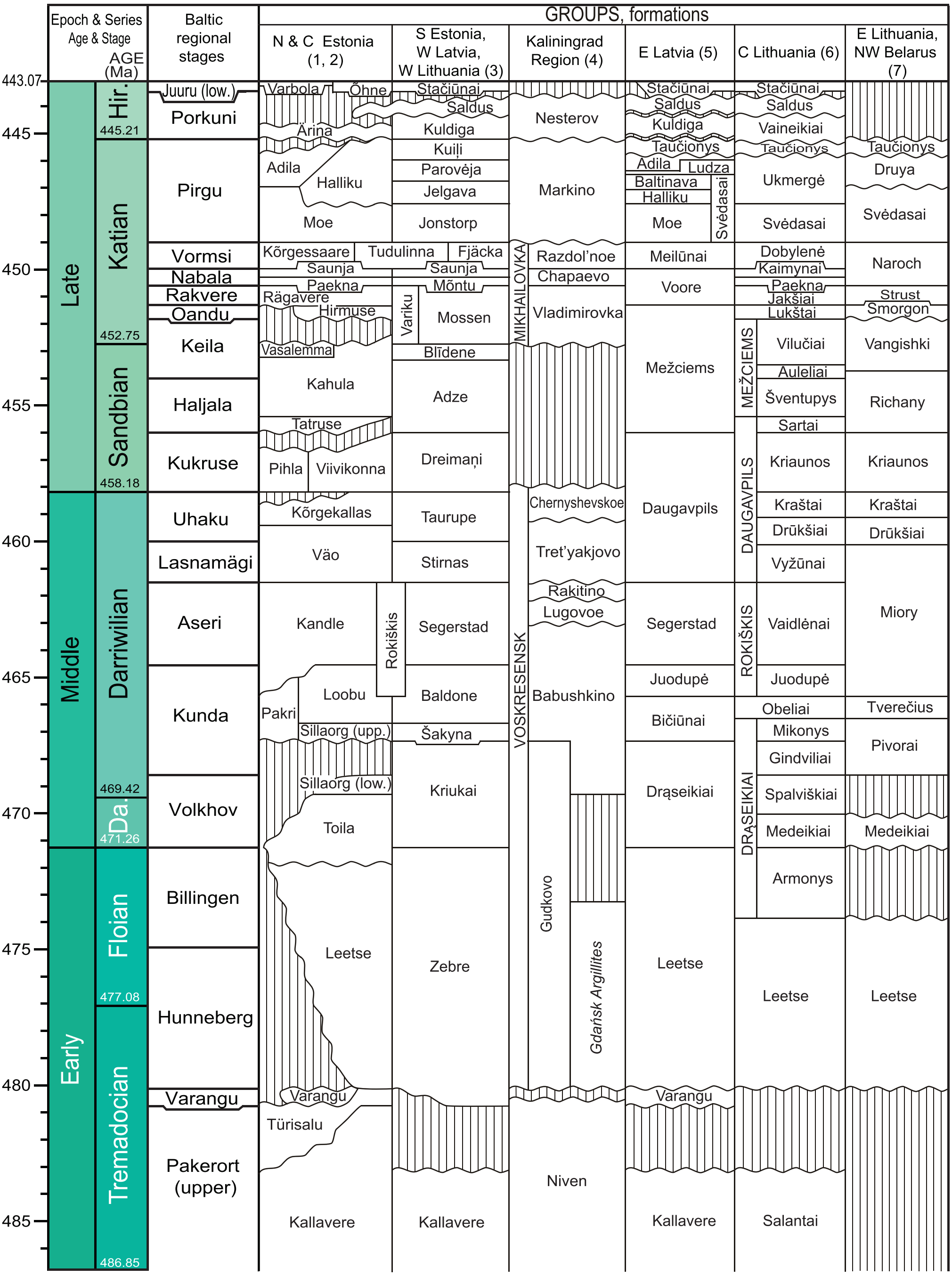


Fig. 3. Correlation of the regional successions with the chronostratigraphic standard within the Baltic Palaeobasin. For abbreviations see Figure 2.

grained weakly cemented quartzose sandstone (mostly 4–10, locally up to 20 m). This unit is successively overlain by the dark brown bituminous argillites assigned to the *Türisalu Formation* (up to 6 m), and light grey clays of the *Varangu Formation* (up to 4 m), both rapidly thinning out southwards.

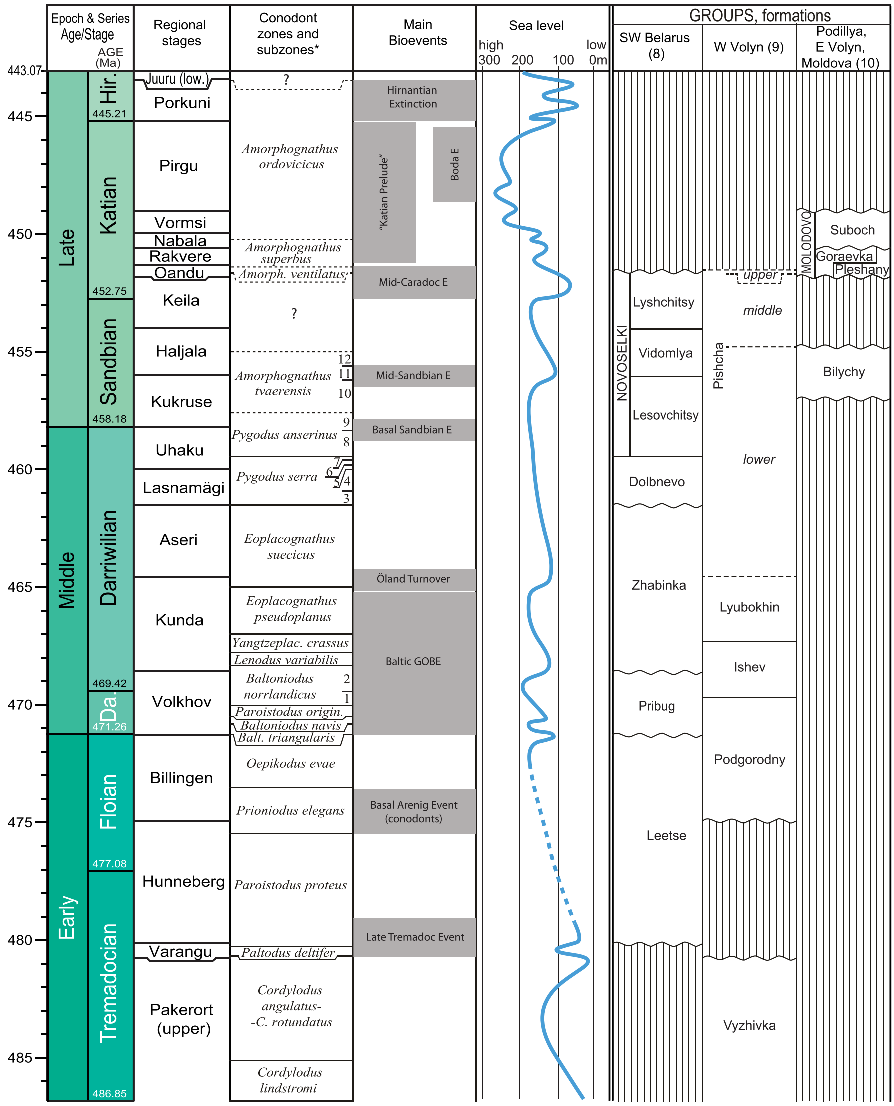


Fig. 4. Main bioevents, the regional sea-level curve (modified from Dronov *et al.* 2011) and correlation of the regional successions with the chronostratigraphic standard and conodont zones along the southern Tornquist Sea margin of Baltica. For conodont subzones and abbreviations see Figure 2.

The overlying *Leetse Formation* is a distinctive marker unit of dark green glauconite-rich quartzose sandstones (up to 4.5 m in northern Estonia but <1 m in central Estonia). The contact between the sandstone and overlying carbonate strata of the Toila Formation is sharp, with only slightly elevated carbonate content in the topmost 0.5 m of the sandstones.

The *Middle Ordovician* boundary is drawn in the lower part of the *Toila Formation* that consists of pure and argillaceous glauconite-containing limestones (partly packstones interpreted as storm beds; up to 4 m) that are dolomitized in NE Estonia. The overlying thin and discontinuous bed of argillaceous limestone with abundant ferriferrous ooids (*Sillaoru Formation*, up to 1 m) and variegated pure or argillaceous limestones with glauconite grains, ferruginous ooids and common cephalopod remains (*Loobu Formation*, up to 8 m) grade laterally into hard thick-bedded sandy limestones in NW Estonia (*Pakri Formation*, up to 4 m) or into the lower part of a grey–red mottled limestone unit with ferriferrous ooids (the *Rokiškis Formation*, up to 15 m) in central Estonia (Meidla 1997). The upper half of the Middle Ordovician comprises a succession of limestones with variable concentration of ooids (*Kandle Formation*, up to 8 m, equivalent to the upper part of the red mottled Rokiškis Formation in central Estonia), hard grey limestones of the *Väo Formation* (4–10 m) and a unit of rhythmic alternation of argillaceous limestones and marls (*Kõrgekallas Formation*, 1–18 m; Hints 1997). All Middle Ordovician formations have reduced thicknesses in NW Estonia.

The *Upper Ordovician* succession begins with the *Viivikonna Formation* (thickness 5–30 m, decreasing west- and southwards), a distinctive limestone unit with commercial kukersite oil shale seams at its base in NE Estonia (up to 2.9 m, the Estonian Deposit) and further seams in the subsurface of northern-central Estonia (the Tapa Deposit). This unit grades westwards into hard bioclastic limestones of the *Pihla Formation* (up to 6 m; Hints 1997). Both are overlain, with a hiatus, by hard bioclastic limestones of the *Tatruse Formation* (up to 8 m), sometimes with some quartz supplement in its basal part. The overlying variably argillaceous limestones of the *Kahula Formation* (up to 25 m; Hints 1997; Hints and Meidla 1997) contain numerous (over 20 in NW Estonia) K-bentonite interbeds attributed to the Grefsen, Sinsen, Kinnekulle and Grimstorp complexes (Bergström *et al.* 1995). The Kinnekulle Bed is the thickest one, up to 27 cm (Hints *et al.* 1997). In NW mainland Estonia, the upper part of the Kahula Formation grades laterally into the *Vasalemma Formation* comprising up to 15 m of reef limestones (framestones, bafflestones) and massive cystoid limestones (Kröger *et al.* 2014). The GICE is not recorded in these areas because of a hiatus above the Kahula and Vasalemma formations.

The Vasalemma and Kahula formations are overlain by a thin (up to 4 m) unit of marls and argillaceous limestones (*Hirmuse Formation*), topped by finely micritic limestones (mostly mudstones) of the *Rägavere Formation* (2–27 m). Another unit of similar micritic limestones, the up to 28 m thick *Saunja Formation*, is separated from the Rägavere Formation by variably argillaceous wackestones of the *Paekna Formation* (up to 16 m). The Saunja Formation is overlain by argillaceous wackestones of the *Kõrgessaare Formation* (9–22 m), grading southwards into a red-mottled marlstone unit, the *Tudulinna Formation* (5–20 m; Hints and Meidla 1997).

The pre-Hirnantian of northern Estonia comprises a succession including the *Moe Formation* (up to 40 m of micritic limestones with a few small reefs) and the *Adila Formation* (up to 12 m of argillaceous wackestones). In central Estonia, these units are separated by a tongue of marls and argillaceous limestones, the *Halliku Formation* (thickness up to 25 m, increasing in southern direction; Hints and Meidla 1997).

The Adila Formation is overlain by the *Ärina Formation* consisting of a basal dolomite and overlying reef limestones, cystoid grainstones and slightly bituminous limestones, interpreted as the back-reef facies, sometimes overlain by a thin bed of sandy limestone (Hints and Meidla 1997). This unit contains the lower part of the rising limb of the HICE. The unit is thinning out in central Estonia where the Adila Formation may locally be overlain by laminated sandy or oolitic limestones of the *Saldus Formation* (up to 5 m). The Ordovician–Silurian boundary is tentatively drawn above the HICE, in the lower part of the *Varbola Formation*, a succession of argillaceous limestones (wackestones to packstones) in northern Estonia and within marlstones and micritic limestones of the *Õhne Formation* in central Estonia, as suggested by the isotopic correlation (Bauert *et al.* 2014; Ainsaar *et al.* 2015; Meidla *et al.* 2020).

Southern Estonia, western Latvia and western Lithuania (Livonian Basin; 3)

This subregion is located south of the Ordovician outcrop area in Estonia and is separated from eastern Latvia and SE Lithuania by the Lower Nemunas Elevation (Paškevičius 1997). The Ordovician rocks are lying at a depth of *c.* 200–2000 m in the subsurface (Laškovas 2000) and their thickness reaches 250 m in the Jelgava Depression.

The lithology, fossils and stratigraphy of the Ordovician succession in this area was described for the first time only in the mid-twentieth century (Alichova 1960; Rõõmusoks 1960; Ulst 1960; Paškevičius 1961). Evolution of the BPB was first described by Männil (1966) and this led to the compilation of several stratigraphic charts in the 1970–1980s (see Section ‘Distribution of the Ordovician strata’). Overviews of the Ordovician succession and stratigraphy of the LB (e.g. Paškevičius 1997; Raukas and Teedumäe 1997; Laškovas 2000) are complemented by numerous research papers published in recent decades (e.g. Meidla *et al.* 2014 and references therein). The lithostratigraphic framework is composed of a mixture of units defined in drill cores within Latvia and Lithuania but a few also in Sweden and Estonia. Compared with northern Estonia, the rocks are more argillaceous, mainly mudstones and wackestones, and the skeletal material is dominated by trilobite debris (Põlma 1972). In the Darriwilian and late Katian, red-coloured rocks are typical of the area and a few thin lenses of dark organic-rich shales occur.

The *Lower Ordovician* of the LB begins with siliciclastic rocks, conventionally assigned to the

Kallavere Formation (dark sandstones of variable grain size, with remains of linguliformean brachiopods), in some sections overlain by organic-rich mudstone with graptolite fragments. The age of the Kallavere Formation is unclear in the area but the *C. angulatus* CZ is recorded in its assumed lateral equivalent (the Salantai Formation). The overlying *Zebre Formation* (up to 46 m) is composed of greenish-grey and reddish-brown mudstones with occasional dark shale interbeds, glauconitic sandstone and dolomite. The Zebre Formation correlates with the upper Tremadocian and Floian (Varangu, Hunneberg and Billingen RSs), based on conodonts, graptolites and rare trilobites (Ulst *et al.* 1982; Paškevičius 1997; Viira 2011).

The *Middle Ordovician* succession starts with red-coloured marls and argillaceous limestones of the *Kriukai Formation* (up to 32 m), dated by trilobites and conodonts as Dapingian (Volkhov RS) and containing a turbidite sandstone bed (‘Volkhov Oil Collector’) in western Latvia (Põldsaar *et al.* 2019). The overlying *Šakyna Formation* (up to 25 m) comprises grey marls and limestones rich in fossils, including *Levisograptus austrodentatus* and several trilobites, conodonts and ostracods, suggesting an early Darriwilian age (Kunda RS by most authors). The succeeding *Baldone Formation* (up to 20 m), mottled reddish-brown to greenish-grey argillaceous limestones, is also assigned to the Kunda RS, based on trilobites and conodonts. Some authors subdivide the Baldone Formation into several formations (e.g. Paškevičius 1997).

The middle and upper Darriwilian (Aseri, Lasnamägi and Uhaku RS) is represented by the *Segerstad* (up to 4 m), *Stirnas* (up to 15) and *Taurupe* (up to 18–24 m) formations in the LB, consisting of reddish-brown, mottled red to grey, and light grey partly argillaceous limestones, respectively. Their age is confirmed by graptolite, conodont and chitinozoan biostratigraphy (e.g. Goldman *et al.* 2015).

The *Upper Ordovician Dreimaņi Formation* (up to 18 m) comprises argillaceous limestones with characteristic abundant (20–30%) pyritized skeletal grains and contains rare specimens of *N. gracilis*. The overlying *Adze Formation* comprises grey argillaceous limestones and marls (up to 15 m, corresponding to the Haljala and lower Keila RS) and contains up to 11 thin K-bentonite layers including the Kinnekulle Bed. Chitinozoan biostratigraphy is very detailed in the lower part of this unit.

The base of Katian is probably located within the *Blīdene Formation* (Goldman *et al.* 2015), a relatively thin unit (up to 3.5 m) of greenish-grey marls and calcareous clays rich in well-preserved shelly faunas (brachiopods, trilobites, ostracods etc.). The overlying *Mossen Formation* consists of a basal black shale grading into dark mudstones and marls and it contains graptolites of the *Dicranograptus clingani* GZ, i.e. the Keila to Rakvere RSs. The overlying *Mõntu* and *Saunja formations* contain argillaceous limestone and lime mudstone with rare glauconite and comprise the Nabala RS. Formerly this interval was referred to as the Voore Group containing also the Dzerbene and Skrunda formations (Ulst *et al.* 1982; Männil and Meidla 1994). The overlying *Fjäcka Formation* (up to 6 m) reflects a transgressive episode when back shales, grading proximally into grey mudstone with some limestone interbeds, reached the LB. The late Katian Pirgu RS contains occasional carbonate mounds and comprises four successive formations within the LB. The mainly red-coloured argillaceous limestones and marls of the *Jonstorp Formation* (up to 18 m) are overlain by mottled marls of the *Jelgava Formation* (up to 14 m). The *Parovėja Formation* (up to 36 m) is characterized by two packages of light beige cryptocrystalline nodular lime mudstone with pyritic spots separated by an interval of variegated marl or argillaceous limestone. The overlying *Kuiļi Formation* comprises red-coloured or mottled marls and limestones.

The base of the Hirnantian is conventionally correlated with the base of the onlapping *Kuldiga Formation* (up to 18 m) composed of dolomitic marls and limestones, with an admixture of quartz silt and sand. The lower part of this formation hosts the rising limb of the HICE and the thin *Spinachitina taugourdeaui* chitinozoan zone near its base. The upper part is characterized by a rich fossil assemblage representing the *Hirnantia* fauna (Hints *et al.* 2010*a*; Truuver *et al.* 2021 and references therein). The overlying *Saldus Formation* (mostly up to 13.5 m but occasionally more than 30 m in western Latvia) is characterized by grey marls, sandy limestones and oolitic grainstones in the lower part and laminated marls and siltstones in the upper part. The overlying lime mudstones of the *Stačiūnai Formation* (up to 32 m in southern Lithuania) are poorly fossiliferous but contain the declining limb of the HICE in its lower part, suggesting that the boundary of the Silurian System lies within the Stačiūnai Formation (Meidla *et al.* 2020; Truuver *et al.* 2021).

Kaliningrad Region (4)

The Ordovician is buried to a depth of up to 2500 m in this area. The stratigraphic subdivision of the Ordovician in this area was formerly the same as in the LB but new formations were proposed in course of the geological mapping by Zagorodnykh *et al.* (2001) (see Fig. 3). The thickness of the Ordovician is 60–150 m in the area and limestones dominate. The groups and formations are characterized below following Lukyanova *et al.* (2011); their chronostratigraphic age estimates are based on graptolites, acritarchs, brachiopods (*ibid.*) and conodonts (Tolmacheva 2011). The latter study adjusts ages of several formations considerably and therefore an emended subdivision is presented here for the first time.

The *Lower Ordovician* section in the area begins with the *Niven Formation* consisting predominantly of quartzose sandstones, with some siltstones and clays containing obolid fragments (up to 48 m) and a basal conglomerate. Within the neighbouring Baltic Sea area, the formation contains pebbles of organic-rich argillites and is more coarse-grained. The unit was established as an equivalent of the Pakerort RS. As only the upper part of this RS is attributed to the Ordovician in the type area, the boundary of the Ordovician System is tentatively drawn within the Niven Formation.

The *Middle Ordovician Voskresensk Group* is overlying the Niven Formation with a hiatus and comprises the Gudkovo, Babushkino, Lugovoe, Rakitino, Tret'yakovo and Chernyshevskoe formations. The basal *Gudkovo Formation* comprises glauconite–quartzose sandstones of a very limited thickness (up to 2 m, occasionally missing) that grade westward into an informal unit, the Gdańsk Argillites (calcareous argillites, 20–25 m), dated by graptolites as being of Hunneberg or early Billingen Age. Tolmacheva (2011) dated the top of Gudkovo Formation as being of middle Kunda Age, hence the Gudkovo Formation and Gdansk Beds are not lateral equivalents as suggested by Lukyanova *et al.* (2011). The overlying *Babushkino Formation* has a hiatus at its base and a wide distribution area that also reaches the near-coastal marine areas. It comprises reddish brown limestones containing black coalified organic matter (up to 8 m onshore Kaliningrad Region, up to 10 m in the Baltic Sea). The originally proposed Volkhov Age was adjusted by Tolmacheva (2011) as late Kunda to early Aseri in onshore wells. The occurrence of *Megistaspis limbata* in the basal part of the Formation within the marine area (Lukyanova *et al.* 2011) suggests that the lower boundary of the formation is strongly diachronous. The overlying *Lugovoe Formation*, brownish grey or dark grey bioclastic limestones and dolomites (up to 7 m), was originally suggested to be of Kunda Age but was dated by Tolmacheva (2011) as being of late Aseri Age. The succeeding *Rakitino Formation* (Segerstad Formation in Lukyanova *et al.* 2011 and Männil and Meidla 1994) rests on the partly eroded Lugovoe Formation and comprises brownish grey dolomitized limestones (wackestones to packstones; up to 2.5 m but occasionally missing). Being initially suggested to correspond to the Kunda RS the unit is now attributed to the upper part of the Aseri RS (Tolmacheva 2011). The two latter formations are merged in the sections of the neighbouring marine area.

The Middle Ordovician succession is terminated by the Tret'yakovo and Chernyshevskoe formations that are merged together in the western offshore sections. The *Tret'yakovo Formation*, comprising 3–6 m of mottled limestones containing siliceous concretions and a layer rich in ferriferrous ooids at the base, is overlying the Rakitino Formation with a hiatus. The succeeding *Chernyshevskoe Formation*, consisting of grey limestones (packstones) with a rich macrofauna (up to 17 m), is dated by conodonts as late Uhaku to early Kukruse Age (Tolmacheva 2011). The boundary of the Upper Ordovician is tentatively drawn within the upper half of this formation.

The *Upper Ordovician* is incomplete; the strata above a considerable hiatus are referred to as the *Mikhailovka Group*, consisting of the *Vladimirovka* (black silty clays, up to 6 m, =Mossen Formation by Männil and Meidla 1994), *Chapaevo* (green or grey marls with bituminous spots, up to 5 m) and *Razdol'noe* (black silty clays, up to 6 m, =Fjäcka Formation by Männil and Meidla 1994) formations. The latter unit has not been recorded in the western offshore sections. The adjusted correlation of the two latter formations in Figure 3 is supported by brachiopods.

The Pre-Hirnantian *Markino Formation*, consisting of up to 15 m of greenish grey bioturbated marls, is overlain by the *Nesterov Formation*, up to 9 m of brownish or greenish grey limestones, with a concentration of layers of conglomeratic sandstone in its lower part that has yielded Hirnantian macrofauna. The lower boundary of the Silurian System seems to be marked with a extensive hiatus as the base of limestones of the overlying Shmelevka Formation, and is dated by graptolites as Mid-Rhuddanian (Lukyanova *et al.* 2011).

East Latvia (5)

Ordovician strata were discovered in East Latvia in the early 1960s in the course of early mapping and oil prospecting activities. These studies resulted in distinguishing two principal facies zones (Männil 1966) and recognition of East Latvia as a part of the shallower shelf area of the BPB (Lukševičs *et al.* 2012). The total thickness of the Ordovician in this area reaches 230–240 m (Nikodemus *et al.* 2018). The subdivision (Fig. 3) is nearly similar to that in central Lithuania but the superformations of Lithuania are ranked as formations in Latvia. The description of the rock succession (Fig. 3) is mainly based on Ulst *et al.* (1982) and Männil and Meidla (1994).

The *Lower Ordovician* begins with the *Kallavere Formation*, which is represented here by quartzose sandstones with few dark brown argillites and a conglomerate at the base, with a combined thickness of up to 1 m. The unit is dated by the zonal conodont *C. angulatus*. A thin (<1 m) unit of sandstones interbedded with grey clays has been tentatively attributed to the *Varangu Formation* in the Ludza-15 core (Ulst *et al.* 1982), where it is separated from the Kallavere Formation by a hiatus. The overlying *Leetse Formation* is a thin (up to 1 m) heterogeneous unit dominated by glauconite sandstones with subordinate carbonates and intersected by an erosional surface. The transgressive *Dr̨aseikiai Formation* is transitional between the Lower and Middle Ordovician and marks the appearance of carbonate rocks, its basal Lower Ordovician part being composed of mottled dolomites with a few scattered glauconite grains, grading upwards into red limestones.

The *Middle Ordovician* begins with red or variegated variably argillaceous limestones constituting the main part of the Dr̨aseikiai Formation that is up to 13.5 m thick (total thickness in eastern Latvia). Some concentrations of glauconite are documented from its upper part. It is overlain by the *Bičiūnai Formation* comprising mainly grey limestones and marls (up to 6 m), in the lower part dolomitic and with some glauconite. The succeeding *Juodupė Formation* is represented by red mottled limestones and marls (up to 11 m) and is overlain by the *Segerstad Formation*, a distinctive unit of brownish-red hard nodular limestone with a consistent thickness (2–4 m) all over Latvia and southern Estonia.

The *Upper Ordovician* is characterized by a remarkable increase in sedimentation rates and thicknesses of individual formations. The Segerstad Formation grades into the *Daugavpils Formation* comprising red-mottled limestones with overlying grey marls and limestones (over 30 m). This formation was previously ranked as a group (Männil and Meidla 1994) consisting of the Vyzhiunai, Kriaunos and Kraštai formations. In some papers (Ulst *et al.* 1982; Lukševičs *et al.* 2012), the Daugavpils Group also included earlier the generally similar but more argillaceous Sartai Formation (up to 20 m). The total thickness of the Daugavpils Formation exceeds 30 m (up to 50 m together with the Sartai Formation) and more than half of it is probably of Middle Ordovician age.

The overlying *Mežciems Formation* (=Mežciems Group in Männil and Meidla 1994; up to 52 m) is dominated by marls, with a gradually increasing abundance of limestone interbeds towards the lower and upper contacts. The succeeding *Voore Formation* (=Voore Group in Männil and Meidla 1994) comprises argillaceous lime mudstones and marls grading into lime mudstones with grey spots of finely dispersed pyrite (up to 50 m). This name was established in Estonia but it is not is used any more.

The Voore Formation is overlain with a hiatus by the *Meilūnai Formation* consisting of grey marls and limestones (up to 29 m) grading in western Latvia into the black shales of the Fjäcka Formation. This unit is overlain by the succession of *Moe* (hard massive limestones with interbeds of algal limestone, up to 30 m), *Halliku* (grey argillaceous limestones, up to 14 m) and *Baltinava* (brownish grey nodular lime mudstones, up to 11 m) formations, all sometimes merged into the *Svedasai Formation* (up to 45 m) in the southern part of the area. This succession contains several erosional surfaces near the base and the top.

The *Ludza Formation*, comprising variegated argillaceous and pure algal limestones (up to 22 m), is overlain by a unit tentatively called the *Adila Formation* but differing from this formation in northern Estonia by its more variable composition. It consists of coarsely nodular limestones, lime mudstones and biohermal limestones (coral and brachiopod boundstones). The Ludza and Adila formations grade southwards into the *Ukmerge Formation*, a unit of argillaceous limestones and marls (up to 20 m).

The *Taučionys Formation* has a rather limited distribution in SE Latvia and comprises grey lime mudstones (up to 8 m). The overlying *Saldus Formation* (dolomitized clastic limestones) has a very limited thickness in this area (up to 2 m).

The hiatus above the Saldus Formation was formerly considered to mark the lower boundary of the Silurian System and represents the maximum of the Hirnantian glacioeustatic regression. In marginal SE Latvia, the Silurian is overlying the Saldus Formation with a remarkable gap that is partly filled by the *Stačiūnai Formation* towards western and NW (Ulst 1976). The formation comprises nodular limestones with grey spots of dispersed pyrite, with a thin (up to 2 m) layer of limestones and marls at its base. Based on comparison with Estonia and western Latvia (Bauert *et al.* 2014; Meidla *et al.* 2020), the lower part of this unit is tentatively attributed to the Ordovician.

Central Lithuania (6), eastern Lithuania and NW Belarus (7)

The Ordovician of Lithuania and NW Belarus has been known since the 1960s and these areas are sometimes addressed together in lithological/palaeogeographical papers and correlation charts. The boundaries of principal facies zones are nearly meridional in Lithuania. Central Lithuania together with marginal eastern Lithuania comprise an eastward shallowing nearshore zone of the BPB. Some more recent overview papers (e. g. Laškovas 2000; Paškevičius 2011) summarize the subdivision of the area but a number of members have recently been raised to the rank of formation while the former formations are occasionally used as superformations (see Fig. 3).

The *Lower Ordovician* sequence in central Lithuania begins with the upper part of the *Salantai Formation* consisting of poorly sorted quartzose sandstones with obolid brachiopods (up to 2 m). It is disconformably overlain by the *Leetse Formation* comprising greenish glauconitic sandstone with siltstone and dolomite interbeds (1–2 m), with a basal conglomerate restricted to SE Lithuania. The Salantai Formation is absent in NW Belarus where the Ordovician succession begins with the Leetse Formation. The Leetse Formation is overlain by the reddish skeletal limestone (packstone) of the *Armonys Formation* (up to 1.5 m).

The *Middle Ordovician* boundary is drawn at the base of greenish and reddish claystones, marls and limestones (packstones) of the *Medeikiai Formation* (up to 5 m) that is overlain by reddish organogenous limestones and marls of the *Spalviškiai Formation* (up to 5.5 m). The Armonys, Medeikiai and Spalviškiai formations were earlier treated as members of the Dr̦aseikiai Formation. The succeeding *Gindviliai Formation* (up to 1 m of grey limestones and marls with glauconite grains) is overlain by reddish organogenous limestones with discontinuities termed the *Mikonys Formation* (up to 1 m). Both are former members of the Bičiūnai Formation. Their lateral equivalent, the *Pivorai Formation* in eastern Lithuania and NW Belarus, is composed of grey limestones and marls with ferriferrous pseudo-ooids and glauconite grains (up to 5 m).

The Mikonys Formation is overlain with a hiatus by grey limestones and marls of the *Obeliai Formation* (up to 1.5 m) in central Lithuania. The equivalent strata in eastern Lithuania and NW Belarus are termed the *Tverečius Formation* and comprise up to 4 m of greenish grey marlstones with fragments of crinoids and pseudo-ooids. The overlying central Lithuanian succession of *Juodupė Formation* (up to 6 m of greenish grey limestones and marls) and *Vaidlėnai Formation* (up to 8 m of red organogenous limestones) above the Obeliai Formation were previously considered as members of the Rokiškis Formation. The overlying *Vyžūnai Formation* (up to 9 m) is composed of greenish marls and limestones, with a conglomerate at the base. The three latter formations grade into the *Miory Formation* in eastern Lithuania and NW Belarus. This unit comprises a succession of greenish marlstones and wavy-laminated limestones, with pseudo-ooids in the lower and upper parts (altogether up to 5.5 m).

The succeeding formations extend from central Lithuania into NW Belarus. Grey limestones and laminated marlstones of the *Drūkšiai Formation* (up to 14 m) are overlain by the *Kraštai Formation* (up to 16 m of grey marlstones and organogenous bioclast-rich limestones). The latter formation comprises the topmost Middle Ordovician. The Vyžūnai, Drūkšiai and Kraštai formations together with the Upper Ordovician Kriaunos and Sartai formations are sometimes treated as the *Daugavpils Group*.

The *Upper Ordovician* begins with the widely distributed *Kriaunos Formation* (up to 9 m) composed of grey marls and limestones with numerous discontinuities. Higher up, the successions within central Lithuania and in other areas are different again.

In central Lithuania, the Kriaunos Formation is overlain by the *Sartai Formation*, wavy laminated grey limestones and marls with K-bentonite layers (up to 6.5 m). The succeeding *Šventupys Formation*, up to 17 m of grey marls with thin K-bentonite layers, is overlain by the *Auleliai Formation* (up to 19 m of mudstones with K-bentonite layers in the lower part) and the *Vilučiai Formation* (up to 20 m of black shales and mudstones). The Šventupys, Auleliai and Vilučiai formations are attributed to the *Mežciems Group*. Grey claystones and black shales with limestone interbeds comprise the *Lukštai Formation* (up to 4.5 m) that is overlain by the *Jakšiai Formation* of very different composition (up to 4 m of grey lime mudstones). The succession continues upwards with the *Paekna Formation* (up to 16 m of argillaceous limestones/wackestones), nodular limestones of the *Kaimynai Formation* (up to 12 m), horizontally laminated marlstones and limestones of the *Dobilynė Formation* (up to 15 m), the *Svėdasai Formation* (up to 30 m of grey nodular wackestones with K-bentonite layers) and the slightly more argillaceous *Ukmergė Formation* (up to 22 m of interbedded nodular limestones and marls). Yellowish grey lime mudstones (up to 11 m) of the *Taučionys Formation* are overlain by up to 3 m of grey marls of the *Vaineikiai Formation*, representing a transition to the Hirnantian, and by ooidal limestones of the *Saldus Formation* with a similar thickness. The overlying limestones of the basal *Stačiūnai Formation* are probably of Ordovician age, like in western Latvia.

In eastern Lithuania and NW Belarus, the Kriaunos Formation is overlain by the *Richany Formation* (up to 12 m of grey clayey wackestones and marls) and greenish limestones (wackestones) of the *Vangishki Formation* (up to 12 m). The succeeding *Smorgon Formation* is very distinct, comprising up to 8 m of grey lime mudstones that are overlain by dark grey mudstones of the *Strust Formation* (up to 25 m). The *Naroch Formation* is composed of nodular limestones with marl interbeds (up to 30 m), being overlain by the *Svėdasai Formation* that extends also into central Lithuania (see above) and up to 16 m of greenish limestone of the *Druya Formation*. The top of the Ordovician succession comprises the Taučionis Formation in this area (see above). The gap above this formation corresponds to the Hirnantian, Rhuddanian and possibly also a part of the Aeronian.

SW Belarus (8)

The suggested presence of Ordovician strata in the bedrock succession of Belarus (Makhnach 1958) was palaeontologically confirmed shortly afterwards (Alichova 1960). More extensive palaeontological and stratigraphic studies were initiated in the 1970s. Detailed investigation of the faunas (see Ropot and Pushkin 1987 for details) led to the development of the modern stratigraphic classification (see Kruchek *et al.* 2010 for the latest version). The formations are mainly dated by macrofossils and their correlation to the BPB section is poorly constrained. In most cases, correlation just follows that of Männil and Meidla (1994). The overview of the section below (Fig. 3) is based on the two latter papers (if not otherwise stated).

The distribution area of the Ordovician in SW Belarus comprises a part of the Podlaska-Brest (Podlyassko-Brest) Depression where the Ordovician strata occur in the subsurface at more than 800 m depth.

The *Lower Ordovician* is represented only by quartz–glauconite sandstones of the *Leetse Formation* (up to 2 m).

The *Middle Ordovician* lies on an erosional surface. The *Pribug Formation* is represented by hard grey heavily dolomitized limestone with abundant glauconite and numerous glide planes (2–3 m) and is well dated by *Ranorthis carinata* as being of Volkhov age. The eroded top of this formation is overlain by the brownish red limestones of the *Zhabinka Formation* (up to 4 m). The limestones contain dolomite laminae with ferriferrous pseudo-ooids near the base. The formation is cut by an erosional surface and overlain by the *Dolbnevo Formation*, grey limestones and marls (wackestones to packstones), often crinoidal limestones with small pyritized bioclasts (up to 4 m).

The following three formation were earlier (Ropot and Pushkin 1987; Männil and Meidla 1994) considered members of the youngest Ordovician unit in Belarus, termed the Novoselki Formation, but they were raised to formational rank by Kruchek *et al.* (2010). The *Lesovchitsy Formation* is a boundary unit between the Middle and Upper Ordovician comprising up to 12 m of grey massive seminodular limestones, often crinoid-rich and with pyritized bioclasts.

The *Upper Ordovician* begins with the upper part of the Lesovchitsy Formation that is overlain by the *Vidomlya Formation*, a unit of alternating grey massive crinoidal limestones (wackestones to packstones) and dark marls rich in bioclasts (up to 13 m). The unit differs from the underlying strata by a higher clay content and more variable composition of the bioclastic material (crinoidal clasts accompanied by bryozoan, brachiopod and trilobite material). The Ordovician succession ends with the *Lyshchitsy Formation*, consisting of grey to greenish-grey bioclast-rich limestones and marls (up to 7 m) that are more argillaceous than the underlying unit. Crinoidal bioclasts are still dominating but the proportion of other groups is growing. The hiatus between the Lyshchitsy Formation and overlying greenish-grey to dark grey clays and marls of Silurian age comprises most of the Katian, Hirnantian, Rhuddanian and Aeronian.

Western Volyn (9)

The western Volyn in western Ukraine represents a southern continuation of the BPB. The Ordovician was recognized here for the first time in the 1960s. The overview of the succession below (Fig. 4) is based on Pomyanovskaya (1972), Decisions (1987) and Männil and Meidla (1994).

The *Lower Ordovician* begins with the *Vyzhivka Formation*, consisting of quartzose sandstones with intercalations of argillites and clays (over 30 m). The formation has a transitional lower boundary and is only tentatively distinguished from the underlying strata, based on the presence of *Obolus apollinis*. Its Ordovician age, however, remains unresolved as *O. apollinis* also occurs in the *Cordylodus proavus* to *C. intermedius* CSs (Mens *et al.* 1993).

The Vyzhivka Formation is overlain with a hiatus by the *Podgorodny Formation* that represents the transition from the Lower to Middle Ordovician. The correlation of weakly cemented quartz–glauconite sandstones with occasional calcareous nodules and a basal conglomerate to the regional standard is well supported by conodonts, showing that the unit corresponds to the Billingen and lower Volkhov RSs (Decisions 1987). The basal conglomerate is composed of sandstone and quartzite pebbles.

The *Middle Ordovician Ishev Formation* is represented by up to 6 m of mostly red coarsely crystalline limestones with a gradual lower boundary and it contains brachiopods and conodonts indicative of the Volkhov to Kunda RSs (SARV 2022). It is overlain by the *Lyubokhin Formation*, consisting of grey or red mottled limestones with ferriferrous ooids (up to 6 m) that are tentatively correlated with the Kunda to Lasnamägi RSs.

The *Middle–Upper (?) Ordovician Pischa Formation* is conformably, with a gradual transition overlying the Lyubokhin Formation. It consists of grey and mottled limestones and marls having a remarkable thickness (probably over 40 m) and with a tentative tripartite subdivision, mainly based on fossils. Accumulations of ferriferrous and chamosite ooids occur in the lower and topmost parts of the unit. The upper half of the formation is dominated by nodular limestones and contains accumulations of sponge fossils. The base of the unit is dated as upper Darriwilian (Aseri RS) based on the occurrence of *Baltoniodus prevariabilis*. The top part containing *Amorphognathus tvaerensis*, *Platystrophia lynx* and *Howellites vilniusensis* is attributed to the lower Katian (Oandu to Rakvere RS). The Pischa Formation is overlain by Llandovery sediments, with a considerable hiatus.

Podillya, eastern Volyn and Moldova (10)

The very incomplete Ordovician succession of this area (Fig. 4) rests on Precambrian or Terreneuvian strata and a major hiatus separates it from the overlying strata. A part of this succession crops out in the valleys of the Dniestr River and some of its tributaries. The strata are dipping to the west and the section is more complete in the westerly areas bordering the ancient Baltica (Poprawa *et al.* 2018). The summary below is based on Tsegelnyuk (1972), Bukachuk (1972), Decisions (1987) and Männil and Meidla (1994). The terminology of the geostructural zonations of Ukraine was adjusted following Shpak and Teslenko (1997) and Poprawa *et al.* (2018).

The *Upper Ordovician Series* is the only part of the system represented in this area. It comprises the Bilychi, Goraevka, Pleshany and Suboch formations (Decisions 1987; Männil and Meidla 1994). The three latter units are attributed to the Molodovo Group that formerly was treated also as a stage (e.g. Tsegelnyuk 1972; Abushik and Sarv 1983) or a series (e.g. Tsegelnyuk *et al.* 1983).

The *Bilychi Formation* is known only from the subsurface of the Lvov–Volyn Depression and comprises up to 7 m of grey limestones dated by brachiopods as the lowermost Upper Ordovician (Kukruse to lower Haljala RSs).

The *Pleshany Formation* forms the only remaining part of the Ordovician subsurface succession of SE Moldova as the area was subjected to subaerial erosion during most of the Ordovician Period. The unit consists of light grey sandstones with some intercalations of siltstones and argillites (up to 26 m). This unit is thought to be equivalent to the *Goraevka Formation* forming the lower part of the Ordovician succession in the Pre-Carpathian Foredeep and comprising up to 3 m of grey calcareous quartzose sandstones with limestone pebbles. The latter formation is exposed on the Volyn–Podillya Platform and extends also into the depression west of it. Both units are dated by brachiopods as representing the lower Katian (Oandu to Rakvere RS).

The *Suboch Formation* is represented by bioclast-rich limestones separated by a hiatus from the underlying strata and distributed over a large area comprising the deep subsurface of the Lvov–Volyn Depression and the Pre-Carpathian Foredeep. It crops out in places within the Volyn–Podillya Platform and extends into subsurface of northern Moldova (being located at depths between 127 and 710 m – Bukachuk 1972). The reported thickness reaches 8.5 m. The rich ostracod assemblage (Abushik and Sarv 1983) together with *A. ordovicicus* and *Boreadorthis crassa* suggest a middle Katian age (Nabala to Vormsi RS).

Depositional history, climate evolution and sea-level changes

According to palaeomagnetic reconstructions, the palaeocontinent of Baltica migrated from high latitudes to subequatorial region during the Ordovician (e.g. Torsvik and Cocks 2017). This drift across several palaeoclimatic belts was thought to produce gradual change in marine deposition in the Baltoscandian palaeobasin and allowed to distinguish four complexes reflecting the succession of different depositional environments in the BPB: (1) cold water siliciclastic ramp (Tremadocian); (2) cold water carbonate ramp (Floian–Darriwilian); (3) temperate water carbonate ramp (Darriwilian–Sandbian); and (4) warm water (tropical) carbonate shelf (Katian–Silurian) (Nestor and Einasto 1997; Dronov and Rozhnov 2007). These changes are accompanied by upward increasing carbonate productivity and successive changes in benthic faunal communities and sedimentation (e.g. gradual appearance of micritic limestones, appearance of reefs). Several recent isotope-geochemical studies on Baltoscandian sections (Männik *et al.* 2021; Edward *et al.* 2022), however, do not support the idea of warming and show that global cooling described by Trotter *et al.* (2008) has been a prevailing trend also in Baltica, despite the continental drift towards the Equator.

The sea-level history of the Ordovician basin of Baltoscandia has been summarized in regional sea-level curves in several studies (Nestor and Einasto 1997; Nielsen 2004; Dronov *et al.* 2011) which differ in some stratigraphic levels but also in a level of detail. The reconstructed regional sea-level curve in Fig. 4 (modified from Dronov *et al.* 2011) is mainly based on sequence stratigraphic analysis and depositional changes in the relatively shallow-water Estonian part of the basin. The main regional unconformities reflect substantial sea-level drops of different magnitudes (forced regressions) and the main transgressions are marked by the widening of the area of deep water facies. The most prominent regressions marked by unconformities and extensive erosion coincide with the early Katian, the earliest Hirnantian and middle Hirnantian ages; the most prominent transgressions occurred during Dapingian–early Darriwilian, middle Katian and latest Katian times (Dronov *et al.* 2011). Comparing the regional sea-level curves, Dronov (2017) concluded that the curve of Baltica generally combines quite well with that from Gondwana but differs from the curves of the Siberian and the North American platforms, probably owing to different local tectonic histories.

Main biotic events and regional diversity curves

The Ordovician succession of the BPB is richly fossiliferous. The first stratigraphic frameworks were based mainly on macrofaunal changes, and the regional stages reflect this history until today. Since the mid-twentieth century, a lot of data became available also from the subsurface regions ensuring a fairly good understanding of the distribution and diversification of most fossil groups. Studies with a broader view are, however, sparse. Männil *et al.* (1966) and Männil (1966) were among the first to review the development of Ordovician faunas of BPB based on integrated data about brachiopods, bryozoans, trilobites and ostracods. They tied the peak of regional diversity to the early Sandbian, identified the main origination episodes in the early Darriwilian and Darriwilian–Sandbian transition and pronounced extinction events in the early Darriwilian, early Sandbian, early Katian and latest Katian–Hirnantian. The same events have been addressed by many subsequent authors, backed by various datasets on different fossil groups.

The first extensive high-resolution regional database covering multiple fossil groups in the Ordovician of Baltoscandia was built by Hammer (2003). Roughly half of that dataset represented the eastern Baltic region and the data for brachiopods, bryozoans, molluscs and ostracods were mainly coming from this area. Regardless of the biases and limitations of that dataset, it showed similar patterns as demonstrated by the previous authors, with the highest species diversity in the Sandbian; however, individual fossil groups differed from each other significantly (Hammer 2003).

The Palaeobiology Database is the primary tool in many palaeobiodiversity studies and holds ca 650 Ordovician genera and 870 species from the Baltic countries at present (The Paleobiology Database 2022). The distribution of these taxa shows the main diversification in the Darriwilian, the highest number of taxa in the Sandbian and Katian, and a decline in the Hirnantian and Rhuddanian. Including Scandinavian data changes the patterns, especially for the Early Ordovician, and this might point at uneven data coverage. Moreover, considering that Männil *et al.* (1966) counted more than 1100 Ordovician species of four groups from Estonia alone, the eastern Baltic data are obviously rather incomplete in the Palaeobiology Database at present.

The best temporal resolution in reconstructing biodiversity dynamics is achieved using a quantitative stratigraphic approach with CONOP (Sadler 2012). The respective time scales and species richness curves of eastern Baltic are available for conodonts and chitinozoans (Goldman *et al.* 2014; Hints *et al.* 2018*b*), providing standing diversity estimates that are independent of time binning. These high-resolution approaches, together with previous compilations and recent summaries on brachiopods (Hints and Harper 2003; Hints *et al.* 2018*a*), trilobites (Pärnaste and Bergström 2013), acritarchs (Hints *et al.* 2010*b*), rugose corals (Kaljo 2003), chitinozoans (Nõlvak *et al.* 2019), conodonts (Männik and Viira 2012), scolecodonts (Hints 2000) and ostracods (Tinn *et al.* 2006; Truuver *et al.* 2021), allow discussion of diversity curves and bioevents of eastern Baltic (Fig. 4).

The Early Ordovician Late Tremadocian Event is expressed as a rearrangement mainly among linguliformean brachiopods (Popov 1993), acritarchs (Erdtmann and Paalits 1994), graptolites (Kaljo and Kivimägi 1976) and conodonts (Männik and Viira 2012; Goldman *et al.* 2014).

A rapid diversity rise in the Dapingian and/or early Darriwilian (Volkhov to Kunda RSs) is characteristic of most fossil groups in the eastern Baltic region. Brachiopods diversified in early Kunda Age in the eastern Baltic region (Hints and Harper 2003; Rasmussen *et al.* 2016; Hints *et al.* 2018*a*) and this has been interpreted as an expression of the Great Ordovician Biodiversification Event, like also the Dapingian diversification of asaphid trilobites (Pärnaste and Bergström 2013), and can be considered pivotal also for chitinozoans (Hints *et al.* 2018*b*; Nõlvak *et al.* 2019) and ostracods (Hammer 2003). Collectively the Dapingian–early Darriwilian interval can be viewed as the 'Baltic Great Ordovician Biodiversification Event' and is mostly ascribed to the drift of Baltica to lower latitudes, sea-level changes and evolutionary innovations in different groups of organisms. Jawed polychaetes, however, show important innovations in the Dapingian, but their main diversification occurs only in Mid-Darriwilian in this area (Hints 2000; Hints *et al.* 2010*b*).

The boundary of Aseri RS marks a turnover in shelly faunas, notably bryozoans and trilobites (Männil 1966) and brachiopods (Hints *et al.* 2018*a*), but also conodonts (Männik and Viira 2012). This level (Öland Turnover, Fig. 4) coincides with the start of the prolonged MDICE carbon isotopic event that is thought to be linked to climate change and biodiversification that influenced the carbon cycle (Rasmussen *et al.* 2016), although the forcing mechanisms behind the MDICE still need further validation (Ainsaar *et al.* 2020).

A regionally significant turnover event at the Darriwilian-Sandbian transition (the Basal Sandbian Event, Uhaku–Kukruse RS) identified among brachiopods, bryozoans, trilobites, brachiopods and others was suggested by Hammer (2003), but the new data show a different pattern with no peaks in the basal Sandbian but somewhat later (Hints *et al.* 2018*a*). Conodont data still reveal a higher extinction rate and a diversity loss near the basal Sandbian (Mid-Sandbian Event or basal Caradoc event of Männik and Viira 2012). High-resolution chitinozoan data also show pronounced turnover rates near the basal Sandbian, whereas the estimated standing species diversity changes by about 15% near the lower and upper boundaries of the Kukruse RS (Hints *et al.* 2018*b*). The middle and late Sandbian (Haljala and Keila RS) environments provided seemingly optimal conditions for acritarchs (Hints *et al.* 2010*b*) and chitinozoans (Hints *et al.* 2018*a*) while conodonts, again, show a coeval decline (Männik and Viira 2012). The genus-level data on trace fossils (Toom *et al.* 2019), however, show the maximum ichnodiversity and ichnodisparity in the latest Darriwilian and Sandbian (Uhaku to Haljala RS) and in the lower Katian (Oandu RS).

A significant change in the basin development and faunas occurred near the base of Katian (Keila–Oandu RS). The Mid-Caradoc Event or Middle Caradoc Facies and Faunal Turnover is linked to the GICE carbon isotope excursion and influenced many organisms, especially in shallow shelf settings, representing a turning point for many groups (Meidla *et al.* 1999; Ainsaar *et al.* 2004). The driving factors may include sea-level perturbations, increased facies differentiation (Männil 1966), the appearance of tropical carbonate sediments and reefs (Kröger *et al.* 2014), faunal immigrations and changes in the global climate system, geochemical cycling and ocean circulation.

Kaljo *et al.* (2011) coined the term ‘Katian prelude’ for the prolonged diversity decline and fluctuations following the Middle Caradoc event and preceding the Hirnantian extinction. While acritarchs and chitinozoans showed a protracted crisis, brachiopods, conodonts, ostracods and jawed polychaetes thrived during the late Katian in the eastern Baltic. This may partly be related to the Boda Event of Fortey and Cocks (2005), an episode of unusual facies (development of reefs and mud mounds), faunas of high diversity and the rise of endemism in the region. The subsequent Hirnantian extinction, associated with rapid climate change and perturbations in ocean circulation patterns and chemistry (Harper *et al.* 2014), is reflected in the increased extinction rates among majority of groups in the latest Katian (Kaljo *et al.* 2011) and in the appearance of new faunal elements, including representatives of the global *Hirnantia* fauna (e.g. Kaljo *et al.* 2008; Hints *et al.* 2010*a*; Harper and Hints 2016). For example, an almost complete renovation of ostracod faunas near the Katian–Hirnantian transition (Pirgu–Porkuni boundary; Meidla 1996; Meidla *et al.* 2020; Truuver *et al.* 2021) was followed by another extinction within the Hirnantian and the appearance of a low diversity ‘Silurian-type fauna’ in the latest Hirnantian (basal Juuru RS; Meidla *et al.* 2020). At the same time, rugose corals, jawed polychaetes and cryptospores suffered considerably less from the mass extinction (Kaljo *et al.* 2011; Vecoli *et al.* 2011; Eriksson *et al.* 2013).

In conclusion, the Ordovician biodiversity dynamics in the BPB is complex and different fossil groups may show different diversity changes and responses to environmental perturbations. Significant spatial differences within the eastern Baltic area and between this area and Scandinavia are most likely due to uneven data coverage.

Concluding remarks

The long study history, highly detail stratigraphic framework, huge datasets on different fossil groups and rapidly increasing studies on geochemistry and isotopic geochemistry have made BPB one of the key regions of Ordovician research of the World. The area represents an excellent platform for experimental research, hypothesis testing and the development and validation of new theoretical concepts and approaches, capable of advancing the Paleozoic studies and representing a key to better understanding of today’s and future environmental changes.

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