The Ordovician of Scandinavia: a revised regional stage classification

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Abstract: The Ordovician of Scandinavia (i.e. Denmark, Norway and Sweden) has been investigated for over two centuries and, through time, various chronostratigraphic schemes have been introduced, facilitating regional correlation. However, a modern chronostratigraphy has never been proposed. Here, we delineate ten regional stages for the Ordovician of Scandinavia, comprising, in ascending order, the Slemmestadian, Ottenbyan, Billingenian, Volkhovian, Kundan, Segerstadian, Dalbyan, Moldåan, Jerrestadian and Tommarpian. We propose to discontinue the use of the term Hunnebergian Regional Stage despite its Scandinavian origin; this interval is included in the new Ottenbyan Stage. The base of each stage, as (re)defined here, is selected to coincide with the appearance of a characteristic fossil taxon and delimited at the top by the base of the overlying stage. The stage boundaries generally coincide with or approximate to significant changes in the depositional environment that are recognizable across Scandinavia from the carbonate platform to the foreland basin. Local efficacy has been the primary criterion for the recognition of Scandinavian stage boundaries rather than approximating to the global or East Baltic stage boundaries. It is proposed to abolish the Baltoscandian regional series and subseries, as correlation with the global series is sufficiently precise to make these higher rank regional schemes redundant.

Ordovician sedimentary rocks deposited in an extensive epeiric sea originally covered all of Scandinavia and adjacent countries, but are today preserved across most of Sweden and Finland only in scattered outliers and impact craters, as well as in the subsurface of the Bothnian Sea (Fig. 1). The Ordovician strata deposited along the western margin of Baltica were telescoped into the Caledonian Mountain chain during the Caledonian Orogeny in the Silurian and Devonian (e.g. Bruton and Harper 1988; Gee *et al.* 2008; Gee 2015). These successions are strongly overprinted by tectonism and associated metamorphism, but the original sedimentary sequence can usually be reconstructed, at least for the Parautochthonous foreland deposits of the Oslo Region, Norway, as well as for the Lower Allochthon in southern Norway and western Sweden (e.g. Bruton *et al.* 1989; Owen *et al.* 1990; Karis 1998). A more continuous package of Ordovician strata that is relatively undisturbed by tectonism is preserved in the Baltic Sea area, dipping southeastwards from the Swedish islands of Öland–Gotland and below Lithuania–Latvia–southern Estonia and Poland (Fig. 1). Exposures are restricted to Öland and Estonia–western Russia. Deeply buried Ordovician strata are also preserved in the Danish area and below the Baltic Sea north of Germany but they have been encountered only in a few deep wells (Michelsen and Nielsen 1991; Nielsen and Japsen 1991; Vejbæk *et al.* 1994; Maletz 1997*a*; Stouge 2001;

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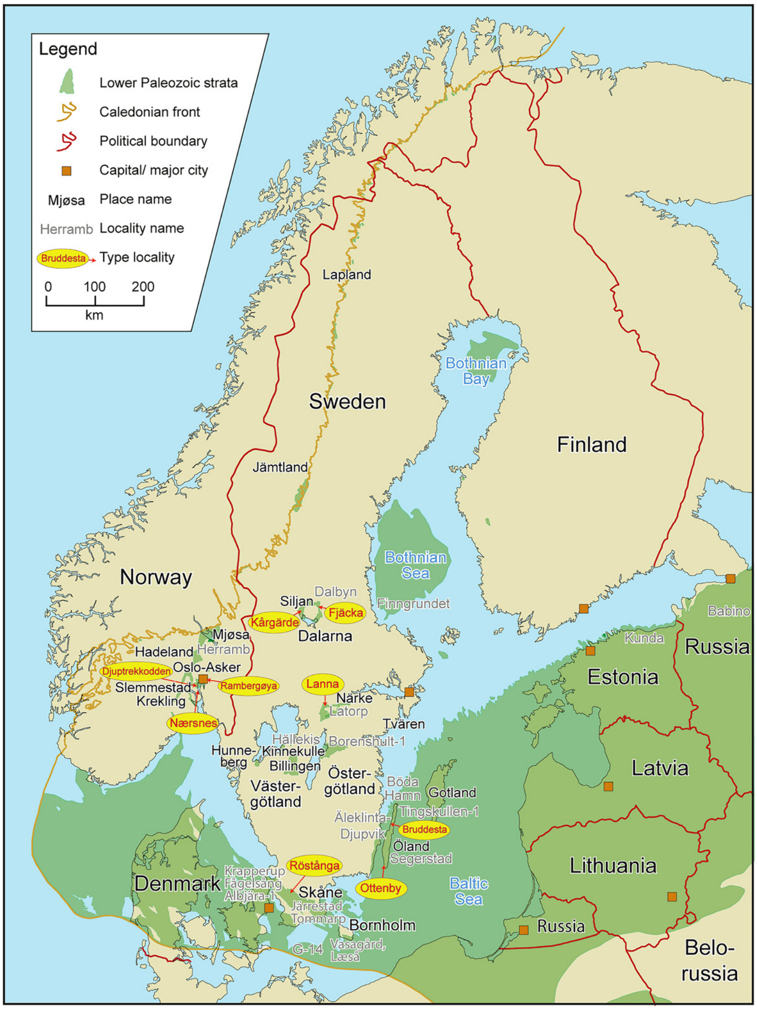

Fig. 1. Present-day distribution of Ordovician strata in Baltoscandia. Location of provinces, districts and localities mentioned in the text are also shown. Source: base map modified from Nielsen and Schovsbo (2011).

Schovsbo *et al.* 2016). Exposures in that area are limited to Skåne–Bornholm. The names of the Scandinavian districts with preserved Ordovician strata are shown in Figure 1.

The Ordovician rocks of Scandinavia and their fossil content have been studied for more than 200 years and they are described in countless publications. Over time, various chronostratigraphic classifications have also been advanced; a brief historical review is given below. However, a modern stage system applicable specifically to the Scandinavian successions has never been introduced and it is clear that the schemes currently used are lacking in stratigraphical precision, clear definitions and recognizability. Proposing regional Ordovician stages for Scandinavia is therefore the primary aim of the present paper. Moreover, in contextualizing these stages, we provide an overview of the Ordovician of Scandinavia.

Construction of a chronostratigraphy is not an easy task. Scandinavian successions include highly condensed limestones with shelly faunas deposited on a carbonate shelf that west- and southwestwards grade into offshore graptolitic mudstones and shales, and which further westwards are replaced by comparatively expanded Caledonian foreland deposits that often contain rather sparse macrofossils in commonly deformed successions. A workable regional stage system has to accommodate all of these settings and this is the main reason why modern regional stages have never been adopted and utilized. Instead, reference has been made looking west to the British and east to the East Baltic stages but the schemes developed for these regions were originally defined in quite different geological settings and are only partly applicable in Scandinavia.

Why regional Scandinavian stages?

Within Baltoscandia, a formal chronostratigraphic classification has been established for the Ordovician only in Estonia. It comprises three series, seven subseries and 18 (or 19) stages, of which some are further subdivided into substages. For reviews of this scheme, see Männil and Meidla (1994), Raukas and Teedumäe (1997) and Meidla *et al.* (2014, 2022). Only two of the stages, the Lower Ordovician Hunnebergian and Billingenian, are based on Scandinavian sections (Tjernvik 1956). In addition to these two stages, the Middle Ordovician Volkhovian and Kundan stages, originally based on sections in Estonia and Russia, have been widely used also for the shelly facies in Scandinavia (e.g. Jaanusson 1960*b*, 1982*a*; Nielsen 1995; Lindskog *et al.* 2014, 2018). All other East Baltic stages, including the upper Cambrian–Lower Ordovician Pakerort Stage and in particular the very elaborate stage classification for the upper Middle to Upper Ordovician above the Kundan, have never successfully been adopted for the thicker and stratigraphically more complete successions in Scandinavia (e.g. Jaanusson 1982*a*, 1995). Instead, the British standard scheme has commonly been used, notably in Norway by British workers (e.g. Bruton and Owen 1982; Owen *et al.* 1990), but to some extent also in Sweden (e.g. Tjernvik 1956; Kielan 1960; J. Bergström 1968; Lindström 1971*b*; Karis 1998). The difficulties of correlating the thin/short East Baltic stages/ages outside of the type area hamper interregional as well as intercontinental correlation with implications for palaeogeographical reconstructions, compilation of biodiversity data and correlation of sea-level changes (see e.g. various compilations in Webby *et al.* 2004). The lack of a workable regional stage classification for the whole of Baltoscandia was noted by Nielsen *et al.* (2004), but the issue has never been subsequently addressed (however, see Nõlvak *et al.* 2006).

Seven global Ordovician stages have been established during the last couple of decades and it is obviously relevant to question whether there is any value in recognizing regional stages or whether such a scheme just complicates communication. However, despite the much-improved global correlation in recent years, the majority of the global stage boundaries can be precisely identified only in the offshore graptolitic successions of Scandinavia. Recognizing the global stage boundaries in the expanded foreland deposits of the Oslo Region, dominated by nodular limestones interbedded with mudstones that commonly are relatively low in fossil content, and, in particular, in the highly fossiliferous carbonate-dominated successions, deposited in shallower water across the greater part of Sweden, is in most cases less clear-cut. Hence, correlation is usually subject to some degree of interpretation. For this reason, we maintain that there is a *raison d'être* for regional stages, as they can be correlated with a higher degree of precision within Scandinavia than the global stages.

Here we introduce a regional stage classification for the Ordovician of Scandinavia including both new units as well as formal (re)definitions of previously proposed stages. These regional units are more straightforward to use for local geological studies than the East Baltic and the global stages. Regional series and subseries that duplicate global series and stages are not defined and it is proposed to abolish the Oelandian/Ölandian, Viruan and Harjuan series as well as the local subdivisions thereof (for a summary of the Baltoscandian series and subseries, see Männil and Meidla 1994). Notably, the boundaries originally defined for these regional series and subseries (Luha 1940; Rõõmusoks 1956; Jaanusson 1960*a*, *b*; Männil 1990) do not match those of the current global Lower, Middle and Upper Ordovician. The introduction of regional series for Baltoscandia was based on the fact that the tripartite subdivision of the Ordovician in practice had different meanings around the world (Jaanusson 1960*b*, pp. 293–297; for an illustration of the problem, see Bergström 1986, fig. 1). However, as this is no longer the case, regional series and subseries appear redundant.

If a need arises for defining substages for Scandinavia, the existing East Baltic stages may be considered as potential candidates, but there is currently no incentive or clear motivation to apply dual terms for the same intervals (substages/chronozones). Several of the East Baltic stages actually represent shorter time intervals than chronozones and these stages are commonly difficult to recognize precisely in Scandinavian sections. This is in part due to faunal differentiation, but also because the Scandinavian successions generally are more expanded and stratigraphically more complete than those in Estonia and western Russia. So-called stage slices (~ substages) have been defined for the global stages (Bergström *et al.* 2009), but they are individually of quite dissimilar stratigraphic ranges. No effort has been made to match these boundaries when defining the regional stage boundaries.

Several readily identified major faunal changes and turnovers – many with apparent links to sea-level changes – can be recognized across most Ordovician facies. These are selected here as markers for defining regional stage boundaries in Scandinavia. We have contemplated whether these stadial boundaries should approximate to international boundaries, which obviously would ease intercontinental correlation, but local efficacy and correlative robustness are the primary criteria. Local and practical utility is also the basic rationale behind operating with regional stages in the first place as local correlation inevitably is more precise than comparison with global chronostratigraphic units. Two Global Stratotype Sections and Points (GSSPs), both correlated by graptolites, are located in Sweden, namely the bases of the Floian and Sandbian stages; the latter coincides with the base of the Upper Ordovician Series (Bergström *et al.* 2000). However, somewhat paradoxically, neither of these boundaries can easily be correlated with the shallower-water carbonate domains of Sweden and further eastwards, and they do not coincide with the regional stage boundaries defined herein.

Geological setting

The Scandinavian Ordovician strata east of the Caledonides are highly condensed (Lindström 1971*a*), with a maximum thickness of little more than 200 m, recorded in NW Skåne (Scania) (Fig. 1; see Jaanusson 1973, 1982*a*; Nielsen 1995, fig. 41 and references therein). In the gently folded foreland basin of the Oslo Region, the thickness is close to 500 m in the Oslo–Asker district (Owen *et al.* 1990). Further westwards, the thickness increases but is difficult to reconstruct precisely due to overprinting by the Caledonian tectonics; a magnitude of 1 km was indicated by Bruton *et al.* (2010). The western and southern parts of Scandinavia are dominated by graptolitic shales, deposited on the outer shelf, whereas stratigraphically condensed carbonate successions, deposited in shallower water, characterize most of mainland Sweden. It has, however, remained a long-standing issue how deep ‘shallower water’ is. One school infers deposition in quite shallow water (e.g. Thorslund 1940; Hadding 1958; Jaanusson 1960*a*, 1973; Holmer 1983; Nordlund 1986, 1989; Lindskog 2014, 2017; Lindskog and Eriksson 2017; Lindskog *et al.* 2018), whereas another school led by the late Professor Maurits Lindström argued for much greater depths of deposition even approaching kilometre-scale (e.g. Lindström 1963, 1979, 1984; Chen and Lindström 1991; Lindström *et al.* 1996, 2005; Shuvalov *et al.* 2005). Part of the controversy reflects the fact that these authors studied different sites on the platform and/or different parts of the stratigraphic column. It is evident that depth of deposition overall increased westwards across Sweden, but it also varied significantly during the Ordovician in association with sea-level changes (cf. Nielsen 2004; Dronov *et al.* 2011; Lindskog 2017). Further east, the Ordovician is dominated by marly limestones in Estonia and western Russia with only a few incursions of offshore mudstones and shales. The lithofacies distribution across Baltoscandia has traditionally been described in terms of ‘confacies belts’ as also the fossil faunas differ between the facies belts (Fig. 2; see Jaanusson 1976, 1995). For this reason, precise correlation between the facies is commonly difficult, at least based on macrofossils. The position of the facies belts varied over time in concert with sea-level changes (e.g. Männil 1966).

There is broad agreement that Baltica was positioned at high southerly latitudes during the early part of the Ordovician, moving into mid-latitudes in the Mid Ordovician and finally entering subtropical latitudes in the Late Ordovician (e.g. Perroud *et al.* 1992; Torsvik and Cocks 2017 and references therein). Foreland deposition relating to the ongoing Caledonian collision developed in Norway and parts of western Sweden early in the Mid Ordovician. From then on clastic supply to the Scandinavian epicontinental sea was predominantly from the incipient Caledonides to the west with only minor influx from cratonic Baltica itself (e.g. Jaanusson 1973); the latter supply dominated in the East Baltic area. Reef and carbonate mound build-ups occurred from the Late Ordovician (Kröger *et al.* 2016*a*, *b*).

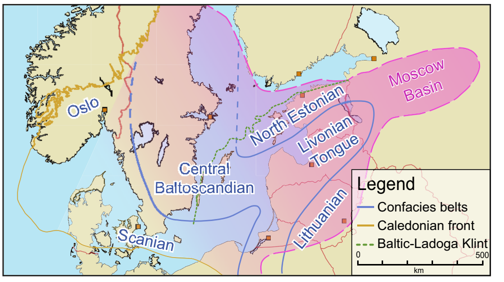

Fig. 2. Ordovician ‘confacies belts’ *sensu* Jaanusson (1995) in Baltoscandia. Source: modified from Jaanusson (1995), Nielsen (1995) and Hints and Harper (2003).

Previous work

A first chronostratigraphic division of the Ordovician of Sweden, based on fossils, was established by Angelin (1854). Törnquist (e.g. 1865, 1871, 1874, 1884) and Linnarsson (e.g. 1869, 1871, 1873, 1875*a*, *b*, 1876, 1879), among others, further refined the stratigraphic classification of the Ordovician in Sweden, based on a lithological-palaeontological approach. In the latter half of the nineteenth century, Ordovician carbonates of Sweden were commonly classified according to colour, i.e. Lower Red, Lower Grey, Upper Red, etc. (e.g. Törnquist 1874, 1884; Nathorst 1881), but this ‘colour index’ proved inconsistent for correlation between regions. Moberg (1890) introduced the long-standing Swedish division of the lower part of the 'orthoceratite limestone' (or 'Orthoceras Limestone') comprising the Planilimbata, Limbata and Asaphus limestones that in modern terminology would be referred to as stages. This approach of naming units after the dominant fossil content was extended upwards by later authors (e.g. Wiman 1906; Moberg 1910*b*; Thorslund 1936; Westergård 1939); see also Jaanusson (1960*a*, 1963*a*) for reviews of the Middle Ordovician. With various amendments, this terminology survived until around 1960 (e.g. Thorslund 1936; Jaanusson 1947, 1951*a*, *b*, 1954, 1956, 1957; Bohlin 1949; Jaanusson & Mutvei 1951, 1953; Tjernvik 1952, 1956). In a succession of papers, Jaanusson (1960*a*, *b*, 1963*a*, *b*, 1964, 1976, 1982*a*) introduced the East Baltic stage terminology for Sweden, although not without comment from Swedish and Danish researchers (e.g. Tjernvik 1972, 1980; Nielsen 1995, pp. 29–31). Despite Jaanusson's efforts, the application of most of the East Baltic stages defined for the upper half of the Ordovician never found consistent or widespread usage in Sweden, primarily because they are difficult to identify precisely due to faunal differences, besides being of very short duration. Hence, a reference to chronozones is more straightforward. During recent decades, no attempts have been made to establish Swedish or Scandinavian stages for the Ordovician. The changing Swedish terminology through time has been adopted also for the Ordovician exposed on Bornholm, Denmark (e.g. C. Poulsen 1936; V. Poulsen 1966).

In Norway, Kjerulf (1857, 1865) defined a so-called 'etage system' with a numbering of the stratigraphic units. This system was based on a mixture of lithological and faunal changes (for summary, see Henningsmoen 1982) but the overall approach is similar to a stage classification. Kjerulf's system was extensively emended by Brøgger (1882) and the resulting scheme was widely used with various minor amendments until Owen *et al.* (1990) established a modern lithostratigraphic classification for the Ordovician in the Oslo Region. The latter authors generally referred these units to the British stage system although East Baltic stages are also indicated on their correlation chart (Owen *et al.* 1990, pl. 1).

'Topostratigraphy'

The concept of topostratigraphy is a Baltoscandian approach that was formulated by Jaanusson (1960*a*, pp. 217–219). Topostratigraphical units are defined based on a mixture of lithological and palaeontological evidence, generally with one boundary placed at a level of an easily recognizable faunal shift, and the other at a conspicuous lithological change (Jaanusson 1976). Geographical names are used for these units, so they deceptively indicate a lithostratigraphic approach. Although purportedly of practical value (cf. Jaanusson 1960*a*), this hybrid practice has actually been a hindrance to the introduction of a conventional lithostratigraphic classification of the Ordovician in many districts of Sweden. The topostratigraphical approach has now been formally deemed obsolete and should be abolished (Kumpulainen 2017). Nonetheless, for historical reasons, many of these names linger on in Swedish stratigraphy and misidentifications of the various units abound in the literature. To signal that the units do not refer to lithostratigraphical formations in a strict sense despite their names, we herein refer to them within quotation marks.

Chronostratigraphic and geochronological frame

Correlation of the proposed Scandinavian stages is illustrated in Figure 3 using the graptolite-based CONOP time-scale of Goldman *et al.* (2020) as the base-line with only minor changes as specified below. The Volkhovian Stage appears unrealistically short and the CONOP composite ages developed for conodonts appear more reliable for that interval (cf. Goldman *et al.* 2020, fig. 20.17). However, for consistency, the graptolite-based dates have been retained as the reference. Changes relative to the zonal scheme published by Goldman *et al.* (2020) are specified below.

A few recent papers deal with Ordovician astrochronology in Scandinavia (Svensen *et al.* 2015; Ballo *et al.* 2019; Rasmussen *et al.* 2021) but the data are too limited as yet to establish an independent local time frame for the Ordovician. Potentially dateable bentonite beds occur regularly from the Kundan Stage (*Asaphus raniceps* trilobite Zone) and upwards in Scandinavia and are especially abundant in the lower part of the Upper Ordovician (e.g. Bergström and Nilsson 1974; Bergström 1989; Huff *et al.* 1992; Bergström *et al.* 2016; Huff 2016; Ballo *et al.* 2019; Liao *et al.* 2020; Rasmussen *et al.* 2021). However, up until now, no effort has been made to establish an independent Scandinavian radioisotopic age scale for the Ordovician based on systematic dating of these beds.

Graptolite zonation. Rhabdinopora praeparabola and *R. parabola* are now regarded as junior synonyms of *R. campanulatum* (see Wang *et al.* 2019, 2021; Maletz *et al.* in press) and the two eponymous zones are combined into one zone. The *Kiaerograptus kiaeri–Aorograptus victoriae* Zone spans the lower part of the Bjørkåsholmen Formation as well as the upper *c.* 2.1 m of the underlying Alum Shale Formation at Slemmestad, Oslo Region (Maletz *et al.* 2010), hence this zone is shown as a separate

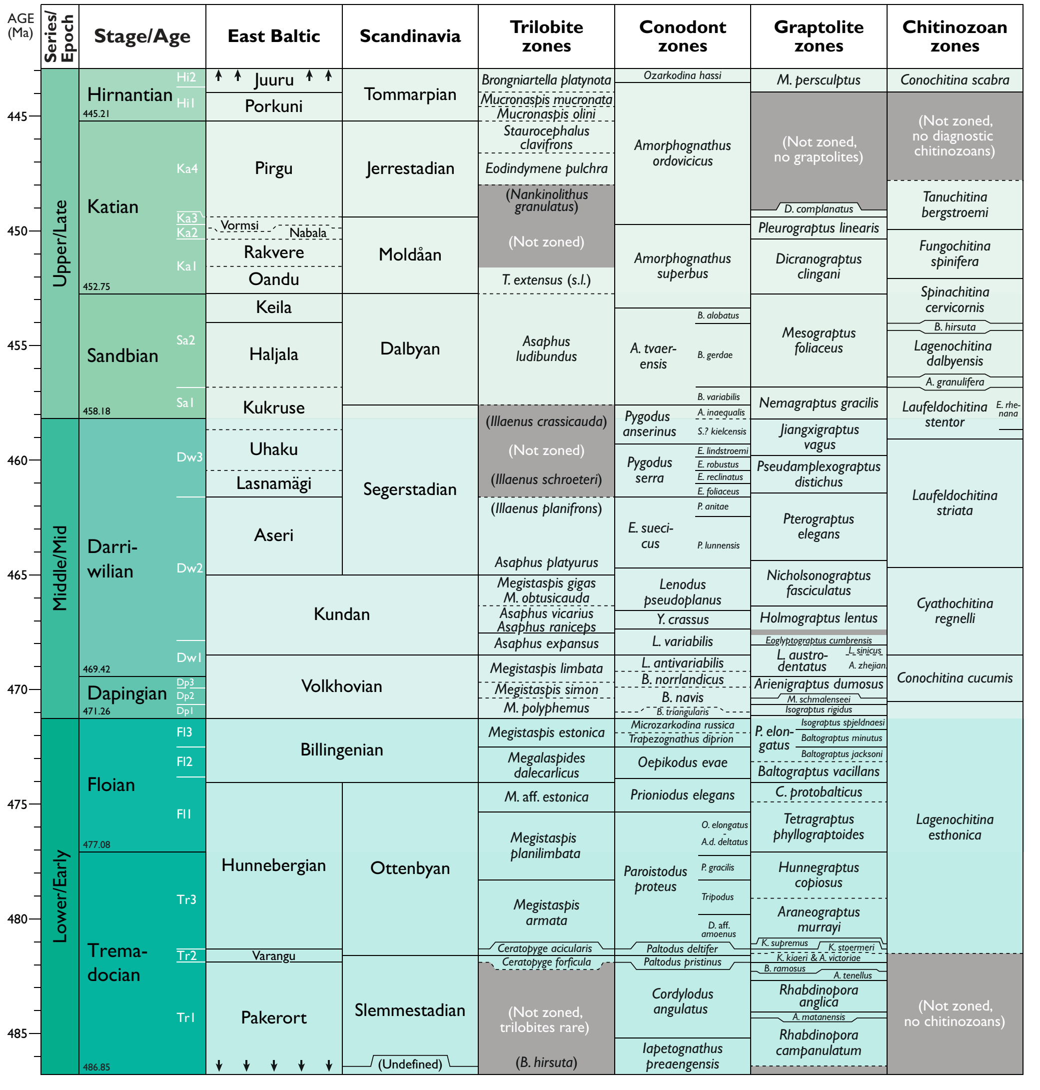

Fig. 3. Correlation of the Ordovician regional stages defined herein for Scandinavia. The graptolite-based CONOP time-scale of Goldman *et al.* (2020) is used as the base-line for the chart. The stage slices defined by Bergström *et al.* (2009) are also shown (left-hand column). Calibration of the cross-zonal correlations have been made in the following order: (a) Graptolite zonation (base-line), (b) conodont zonation, (c) trilobite zonation and (d) chitinozoan zonation. Regarding changes relative to the zonal schemes published by Goldman *et al.* (2020), see section on chronostratigraphy and geochronology.

entity. These authors also indicated that the *Kiaerograptus stoermeri* Zone comprises the upper part of the Bjørkåsholmen Formation and that the *Kiaerograptus supremus* Zone starts immediately above, so these thin zones are also recognized on the chart. The zonation above this level and into the middle part of the Volkhovian is based on Maletz and Ahlberg (2011*a*); for correlation with older schemes, see Maletz and Ahlberg (2018). The *Levisograptus austrodentatus* Zone was subdivided into the *Arienigraptus zhejiangensis* and *Levisograptus sinicus* subzones by Maletz and Ahlberg (2021*a*) and the overlying zone was named *Eoglyptograptus cumbrensis*. Then follows a short graptolite-barren interval in Scandinavia, separating the *E. cumbrensis* and the *Holmograptus lentus* zones. This interval is a presumed correlative of the 'Täljsten/Sphaeronites bed' at the *Asaphus expansus*–*A. raniceps* trilobite zonal boundary, as this level marks a major sea-level lowstand. This horizon was dated by zircons at *c.* 467.5 Ma (Lindskog *et al.* 2017; see also Liao *et al.* 2020 and Rasmussen *et al.* 2021) and the age of the *E. cumbrensis*–*H. lentus* zonal boundary is adjusted slightly relative to the time-scale in Goldman *et al.* (2020). The graptolite zonation from the middle Kundan *H. lentus* Zone through to the top of the Ordovician is adopted without changes from Goldman *et al.* (2020).

Conodont zonation. The *Iapetognathus fluctivagus* Zone is now replaced by the *Iapetognathus preaengensis* Zone (Wang *et al.* 2019, 2021 and references therein) and this designation is used also here in preference of the *Cordylodus lindstromi* Zone (e.g. Kaljo *et al.* 1986; Löfgren and Viira 2007), as there are taxonomic issues with the latter taxon (e.g. Nicoll 1990). The *Paltodus deltifer* Zone was subdivided into the *Paltodus pristinus* and *P. deltifer* subzones by Löfgren (1997), which here are elevated to zonal rank. The *Paroistodus proteus* Zone is subdivided into four subzones following Löfgren (1993, 1994). The upper part of the *Oepikodus evae* Zone *sensu* Lindström (1971*b*) was assigned to the *Trapezognathus diprion* and *Microzarkodina* sp. A zones by Bagnoli and Stouge (1997) and the latter taxon was subsequently renamed as *Microzarkodina russica* by Löfgren and Tolmacheva (2008). We here follow Stouge *et al.* (2020) in regarding the *Paroistodus originalis* Zone as an acme zone reflecting palaeoecological preferences and this mid Volkhovian interval is here included in the *Baltoniodus navis* Zone. We also use the *Baltoniodus norlandicus* Zone rather than the older designation *Microzarkodina parva* Zone (see Stouge 1989; Löfgren 2000). The zonation above this level follows Goldman *et al.* (2020, figs 20.2 and 20.3). The base of the *Eoplacognathus suecicus* Zone correlates with a level slightly above the base of the *Asaphus platyurus* trilobite Zone (see remarks on the Segerstadian Stage below). The subzones of the *E. suecicus* Zone were established by Zhang (1998*a*), whereas the subzones of the *Pygodus serra*, *Pygodus anserinus* and *Amorphognathus tvaerensis* zones were established by Bergström (1971). For the subsequent renaming of the *P. anserinus* subzones, see Bergström (1983). The *Baltoniodus variabilis*–*B. gerdae* subzonal boundary approximates to the *Nemagraptus gracilis*/*M. foliaceus* graptolite zonal boundary (Bergström 1971, 1986). The base of the *Amorphognathus superbus* conodont Zone correlates with a level within the *Mesograptus foliaceus* graptolite Zone (Bergström *et al.* 1967).

Trilobite zonation. Trilobites are rare in most of the Ordovician Alum Shale and no regional zonation is established for the greater part of the Slemmestadian Stage. The ‘Ceratopyge shale’ at the top is now assigned to the *Ceratopyge forficula* Zone, whereas the basal Ottenbyan Bjørkåsholmen Formation and equivalent levels are assigned to the *Ceratopyge acicularis* Zone (Ebbestad 1999; Frisk and Ebbestad 2008; Pärnaste *et al.* 2013; Pärnaste and Bergström 2013). The zonation of the Ottenbyan, Billingenian and Volkhovian is well established (e.g. Tjernvik and Johansson 1980; Nielsen 1995 and references therein). The middle Kundan zonation was revised by Stein and Bergström (2010), but otherwise the Kundan zonation follows the long-established scheme. Above this level, the trilobite faunas (and zonation) are generally in need of revision with precise documentation of biostratigraphic significance and definition of zonal boundaries. Traditionally the lower part of the Jerrestadian is assigned to the *Eodindymene pulchra* Zone (e.g. Kielan 1960), but where ranges are documented, this species does not appear at the base of the stage (Nilsson 1977; Pålsson 1996). The cross-zonal correlation of the trilobite zones is based mostly on comparison with the conodont scheme.

Chitinozoan zonation. The Tremadocian *Lagenochitina destombesi* Zone has not been recognized in Scandinavia, where the oldest chitinozoans known so far were recovered from the very top of the Bjørkåsholmen Formation at Slemmestad in the Oslo Region (Grahn and Nõlvak 2007*b*). They represent the long-ranging *Lagenochitina esthonica* Zone (cf. Grahn and Nõlvak 2010), a designation preferred instead of the *Euconochitina primitiva* Zone (cf. Goldman *et al.* 2020). *Lagenochitina esthonica* was also listed from the Tremadocian? of Skåne by Grahn (1980). The *Conochitina cucumis* Zone was shown by Goldman *et al.* (2020, fig. 20.3) with a short range in the upper Volkhovian–lowermost Kundan, but in Estonia the eponymous taxon ranges from the upper part of the Saka Member, i.e. through most of the Volkhovian Regional Stage (Nõlvak *et al.* 2019). The zone is defined by the total range of the eponymous species (Nõlvak and Grahn 1993). To our knowledge, *Conochitina cucumis* has not been recorded from Scandinavia. Higher up, the boundary between the *Laufeldochitina striata* and the *Laufeldochitina stentor* zones is adjusted to a level within the lower part of the *Pygodus anserinus* conodont Zone, as demonstrated by the presence of *L. striata* in the lower part of the ‘Ryd Limestone’ in Västergötland (Grahn 1981; Grahn and Nõlvak 2010, fig. 4) and which represents the *P. anserinus* conodont Zone (Zhang 1998*a*). The *Eisenackitina rhenana* Subzone comprises the greater upper part of the *Laufeldochitina stentor* Zone (Nõlvak and Grahn 1993; Vandenbroucke 2004). The base of this subzone is taken to mark the lower boundary of the East Baltic Kukruse Stage following Stouge *et al.* (2016). The report of *Lagenochitina dalbyensis* from the *Nemagraptus gracilis* graptolite Zone at

Fågelsång, Skåne (Vandenbroucke 2004), is disregarded here (see discussion below on the new Dalbyan Stage); it would entail moving the lower boundary of that chitinozoan zone significantly downwards. In Scandinavia, the *Angochitina curvata* Zone is not recognized (Nõlvak *et al.* 1999; Grahn and Nõlvak 2010) and the *Armoricochitina granulifera* Zone is extremely thin (Nõlvak *et al.* 1999; Grahn and Nõlvak 2007*a*). However, the record of a single specimen at the very base of the *Mesograptus foliaceus* graptolite Zone in the Koängen core (Grahn and Nõlvak 2007*a*, fig. 4) appears to slightly predate the occurrence within the *Baltoniodus gerdae* conodont Subzone in the 'Dalby Limestone' of the Siljan district (cf. Nõlvak *et al.* 1999). The *Belonechitina hirsuta* Zone was reported from the upper part of the 'Dalby Limestone' of the Siljan district by Laufeld (1967) and Nõlvak *et al.* (1999); this zone has not been recognized in other Swedish districts whereas the eponymous species has a rather long range in the Oslo Region from the upper part of the Vollen Formation into the Solvang Formation (Grahn *et al.* 1994). It is unclear whether the First Appearance Datum (FAD) of that species has any correlative value. The *Spinachitina cervicornis* Zone is known from the 'Skagen Limestone' of the Siljan district (Laufeld 1967; Nõlvak and Grahn 1993) and from the subsurface of Gotland (Grahn 1982; Männik *et al.* 2015); to our knowledge, the eponymous species has not been found *in situ* in other Scandinavian sections. The index species of the *Fungochitina spinifera* Zone is not reported from Scandinavia and neither can the *Tanuchitina anticostiensis, Belonechitina gamachiana* and *Spinachitina taugourdeaui* zones be differentiated in Scandinavia (Grahn and Nõlvak 2010). *Conochitina scabra* was reported as *Conochitina robusta* from Skåne by Grahn (1978).

Scandinavian stages

Slemmestadian (Erdtmann 1994, 1995; emended)

Derivation of name: After the township of Slemmestad SW of Oslo, where Cambrian and Ordovician strata are exposed in numerous outcrops. The name was introduced without formal description by Erdtmann (1994, 1995).

Basal stratotype (designated here): The Nærsnes section south of Slemmestad, Oslo–Asker district, described by Bruton *et al.* (1982, 1988, 2008), is designated as the basal stratotype (for location, see Fig. 1). The lower boundary of the Slemmestadian Regional Stage is marked by the FAD of rhabdinoporid graptolites at 3.4 m in the section immediately above the limestone concretion labelled no. 2 (cf. Bruton *et al.* 1988, fig. 2). The oldest graptolites were originally assigned to *Dictyonema praeparabola* but this taxon is now synonymized with *Rhabdinopora campanulatum* (see Wang *et al.* 2019, 2021; Maletz *et al.* in press). The lowest occurrences of the trilobite *Boeckaspis hirsuta* and the conodont taxa *Cordylodus* [now *Iapetognathus*] *preaengensis* and *C. lindstromi* were recorded in limestone concretion no. 2 below the boundary; the centre of this concretion is 30 cm below the FAD of the graptolites (Bruton *et al.* 1988, fig. 2). These conodonts are important for a broader-scale correlation of the boundary interval (cf. Terfelt *et al.* 2012; Wang *et al.* 2019, 2021).

Remarks: Erdtmann (1995) and later Ebbestad (1999, fig. 5) used the names Slemmestad and Nærsnes stages as Scandinavian equivalents of the East Baltic Pakerort and Varangu stages, but these designations were not discussed any further, nor have they been formally defined or referred to in newer literature. Hence, we consider it permissible to retain the name but redefine the concept of the Slemmestadian Regional Stage. The designated stratotype at Nærsnes was originally considered as a potential candidate for a global stratotype section for the base of the Ordovician (Bruton *et al.* 1982, 1988).

This Scandinavian stage overlaps with the upper part of the East Baltic Pakerort Stage (e.g. Kaljo *et al.* 1986; Männil and Meidla 1994; Meidla *et al.* 2014). The base of that stage is marked by the incoming of the conodont *Cordylodus andresi* (e.g. Heinsalu and Viira 1997) which is well below the Cambrian–Ordovician boundary. The FAD of *C. andresi* thus correlates with a level in the *Parabolina lobata* trilobite Zone in Scandinavia (see Bagnoli and Stouge 2014) and, hence, the uppermost Furongian *Acerocarina* trilobite Superzone correlates in its entirety with the lower part of the Pakerort Stage. The lower boundary of the East Baltic stage predates the Cambrian–Ordovician boundary by some 3 Myr (cf. Zhao *et al.* 2022*a*, *b*).

The base of the Slemmestadian corresponds to the base of the Ordovician as traditionally recognized in Scandinavia, marked by the appearance of rhabdinoporid graptolites. This level approximates closely to the global base of the Ordovician System, coinciding with the FAD of the conodont *Iapetognathus preaengensis* [=*I. fluctivagus* of Cooper *et al.* 2001; see Wang *et al.* 2019, 2021; see also Terfelt *et al.* 2012 v. Miller *et al.* 2014]. However, in detail, the GSSP in the Green Point section, western Newfoundland, Canada, correlates with a marginally lower level in Scandinavia that cannot be precisely pinpointed using fossils in the shaly succession. Chemostratigraphy based on $\delta^{13}C$ isotopes indicates an offset between the Scandinavian boundary and the GSSP level corresponding to *c.* 30 cm of Alum

Shale in the Albjära-1 core in Skåne (Zhao *et al.* 2022*a*). This figure corresponds well with the occurrence of conodonts of Ordovician aspect (notably *I. preaengensis*) in limestone concretion no. 2 immediately below the Slemmestadian in the Nærsnes section (cf. Bruton *et al.* 1988). The 30 cm of Alum Shale in the Albjära-1 core corresponds to approximately 60 000 years, assuming that the depositional rate was around 5 mm ka^{-1} in the Cambrian–Ordovician boundary interval as calculated by Zhao *et al.* (2022*b*, in their Supplementary Table 1). In Scandinavia, the most complete Cambrian–Ordovician boundary sections are described from Skåne and the Oslo Region, where the incoming of rhabdinoporid graptolites in the lithologically monotonous Alum Shale Formation traditionally has been taken as the local marker for the base of the Ordovician (Westergård 1909; Bulman 1954; Tjernvik 1958; Bruton *et al.* 1982, 1988; Spjeldnæs 1985; Erdtmann 1988; Terfelt *et al.* 2012, 2014; Hammer and Svensen 2017; Zhao *et al.* 2022*a*).

Zonation: Only a few trilobites have been described from the lowermost Ordovician of Scandinavia (e.g. Henningsmoen 1957; Terfelt *et al.* 2012) and no regional trilobite zonation has been established for the lower part of the Slemmestadian (see Pärnaste *et al.* 2013 and Nielsen *et al.* 2020 for remarks). In the Oslo Region, the *Boeckaspis hirsuta* Zone has been used, but the eponymous trilobite is rare and unknown outside that area. Sparse representatives of *Hysterolenus* have been reported from Skåne (Moberg 1898; Moberg and Segerberg 1906; Westergård 1909). The upper part of the Ordovician Alum Shale contains *Ceratopyge* and various other trilobites (e.g. Brøgger 1882; Størmer 1920; Tjernvik 1956; Pärnaste *et al.* 2013; Pärnaste and Bergström 2013) and has been loosely referred to as the 'Shumardia' zone or the *Shumardia pusilla* Zone (Tjernvik 1956; Ebbestad 1999). This stratigraphic level is now assigned to the *Ceratopyge forficula* Zone (Fig. 3). The conodont zonation comprises in ascending order the *Iapetognathus preaengensis*, *Cordylodus angulatus* and *Paltodus pristinus* zones (Fig. 3; Lindström 1955*a*, 1971*b*; van Wamel 1974; Szaniawski 1980; Bruton *et al.* 1988; Löfgren 1996; Stouge 2004; Löfgren and Viira 2007; Stouge *et al.* 2020). However, limestone intercalations are rare in the Ordovician Alum Shale and this zonation is difficult to apply in practice. The most important fossil group for zonation of this stage is graptolites and several zones have been established (Fig. 3; Bulman 1954; Tjernvik 1958; Erdtmann 1982, 1988; Cooper *et al.* 1998; Cooper 1999). The rhabdinoporid graptolites are, however, bedevilled by a complicated taxonomy and the zonation has been repeatedly revised (see Wang *et al.* 2019, 2021 and Maletz *et al.* in press and references therein).

Lithology: The Slemmestadian Regional Stage comprises the Ordovician part of the Alum Shale Formation (Figs 4 & 5). In Västergötland its distribution is patchy (e.g. Tjernvik 1956; Jaanusson 1982*c*; Löfgren 1996) and in the Siljan district the Slemmestadian Stage is represented only by the locally developed Djupgrav conglomerate, which is *c.* 3 m thick (Bergström 1988; Ebbestad and Högström 2007). A thin shale in the highest parts of this conglomerate yielded rhabdinoporid graptolites (Thorslund 1960). The best exposures of Ordovician Alum Shale are in the Oslo Region, but coeval shales are known also from northern Västerbotten, Östergötland, Öland, Skåne (drillings mainly) and Bornholm (Westergård 1942, 1944; Hede 1951; Tjernvik 1956, 1958; Nielsen *et al.* 2018; Ahlberg *et al.* 2021; Streng *et al.* 2022). The Ordovician Alum Shale extends into Estonia and western Russia, where the unit locally is referred to as the Türisalu Formation (e.g. Heinsalu and Viira 1997). The Ordovician Alum Shale is less than 16.5 m thick and generally only a few metres or even less. Notably on Öland, but also locally in Västergötland (Thorslund 1937; Tjernvik 1956), the upper part of the Slemmestadian is highly glauconitic and has previously been referred to as the 'Ceratopyge shale' (now referred to as the Djupvik Formation on Öland, see van Wamel 1974; Stouge 2004; Ahlberg *et al.* 2021). This upper part of the Alum Shale Formation is less than 3 m thick on Öland; it may be envisaged as a western equivalent of the Estonian Varangu Formation (see e.g. Heinsalu and Viira 1997). The glauconitic 'Ceratopyge shale' is seen locally also in Västergötland (Thorslund 1937), including as fill in the peculiar sink holes in the Furongian Alum Shale described from Brattefors, Västergötland, with a thickness exceeding 10 m (Teves and Lindström 1988; Löfgren 1997). An up to 2 m thick quartz sandstone, the Skåningstorp Sandstone Bed, is developed at the base of the Ordovician Alum Shale in Östergötland (Nielsen and Schovsbo 2007 and references therein).

Global correlation: The Slemmestadian essentially corresponds to the Tr1 stage slice *sensu* Bergström *et al.* (2009), i.e. the lower part of the Tremadocian Global Stage (Fig. 3). However, as discussed above, the lower boundaries of these units do not match precisely and the upper part of the Slemmestadian overlaps with stage slice Tr2 (Fig. 3). The Slemmestadian is equivalent to the upper part of the East Baltic Pakerort Stage and the lower part of the Varangu Stage (characterized by the conodont *Paltodus pristinus*, see Mägi *et al.* 1989).

Ottenbyan (new)

Derivation of name: After Ottenby, a small village on the southern part of the island of Öland that has also given its name to a nature reserve comprising

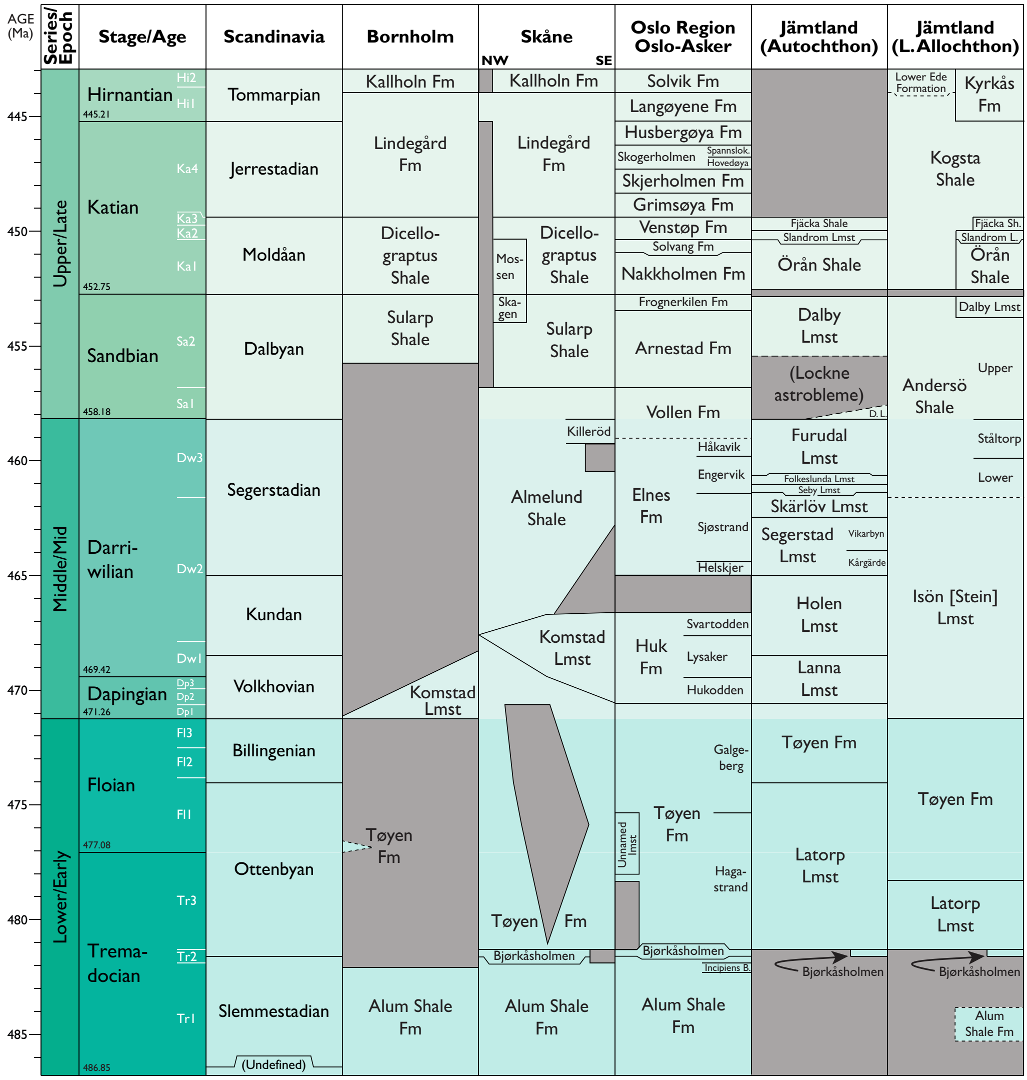

Fig. 4. Correlation chart of Ordovician strata in the various districts of Scandinavia; the zonation is shown in Figure 3. See also Figure 5. The chart is based on – **Bornholm**: Hadding (1915); Funkquist (1919); Poulsen (1966); von Jansson (1979); Nielsen (1995); Koren' and Bjerreskov (1997); Bruvo and Nielsen (2004); Nielsen *et al.* (2018). **Skåne**: Moberg and Segerberg (1906); Hede (1951); Tjernvik (1958, 1960); J. Bergström (1973); Nilsson (1977; unpublished data on the Lovisefred core); Grahn (1978); Lindholm (1991*a*); Nielsen (1995); Pålsson (1996, 2001, 2002); Bergström *et al.* (2002, 2014); Maletz (2005); Maletz and Ahlberg (2018, 2020); Maletz *et al.* (2020). **Oslo-Asker**: Størmer (1920); Henningsmoen (1960); Erdtmann (1965); Wandås (1983); Harper *et al.* (1984); Bruton *et al.* (1988); Owen *et al.* (1990); Rasmussen (1991); Nielsen (1995); Maletz (1997*b*); Ebbestad (1999); Hoel (1999*a*, *b*); Nielsen and Schovsbo (2007); Maletz *et al.* (2007); Hansen (2009); Candela and Hansen (2010); Rasmussen *et al.* (2013); Bockelie *et al.* (2017). **Jämtland autochthon**: Tjernvik (1956); Löfgren (1978); Sturkell (1991); Karis (1998); Wickström *et al.* (2007); Wu *et al.* (2015). **Jämtland allochthon**: Hadding (1912); Tjernvik (1956); Löfgren (1978); Karis (1998); Rasmussen (2001); Pålsson *et al.* (2002); Dahlqvist (2004); Dahlqvist and Bergström (2005).

the entire southern cape of Öland. The stratotype section is located within this protected area.

Basal stratotype (designated here): The low cliff section of Lower Ordovician strata on the west coast of Öland near Ottenby, described by Tjernvik (1956, pp. 145–149, figs 16–18), is designated as the basal stratotype for the Ottenbyan Regional Stage; for references to older publications on this

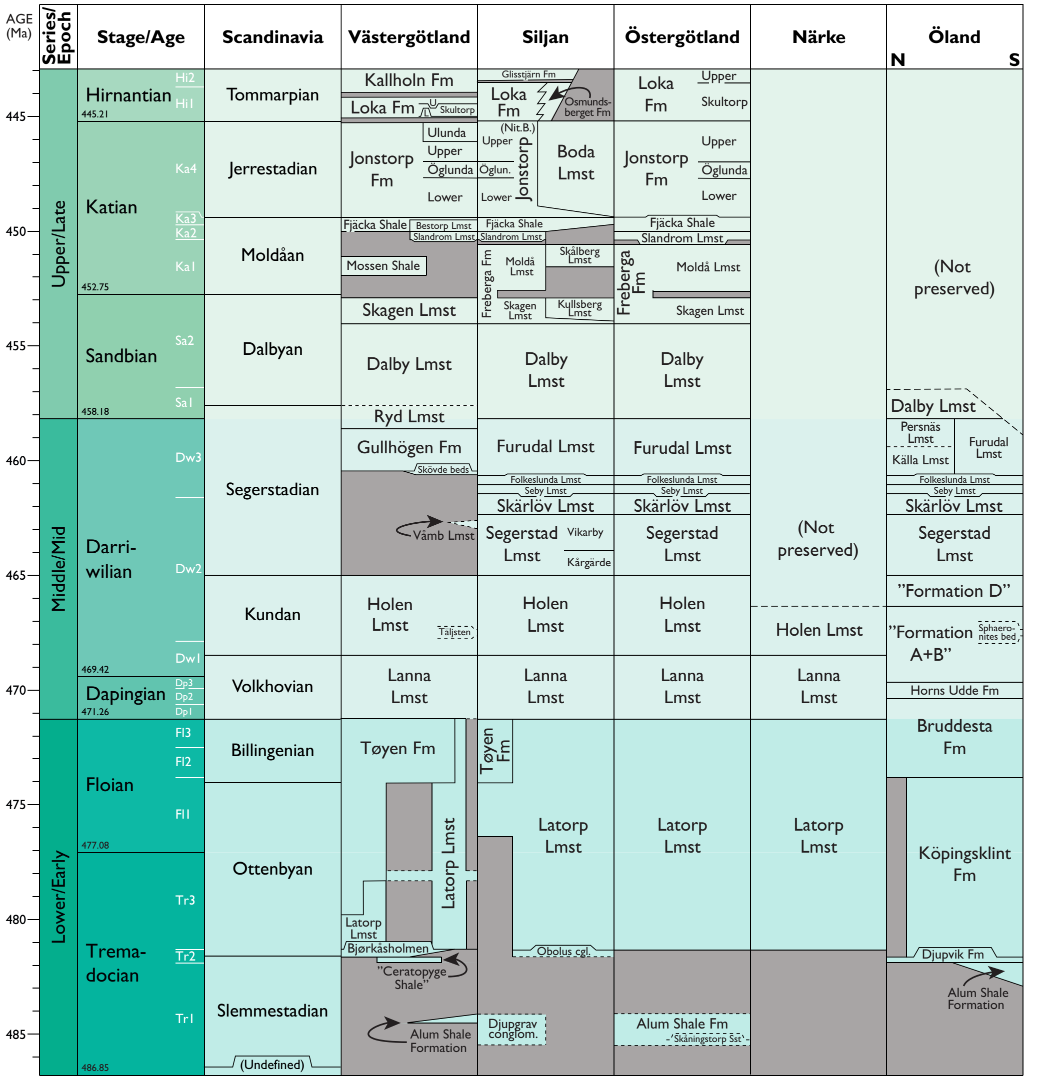

Fig. 5. Correlation chart of Ordovician strata in the various districts of Scandinavia; the zonation is shown in Figure 3. See also Figure 4. The chart is based on – **Västergötland**: Thorslund (1937); Johansson *et al.* (1943); Wærn *et al.* (1948); Tjernvik (1956); Jaanusson and Skoglund (1963); Skoglund (1963); Jaanusson (1963*b*, 1964, 1982*c*); Fåhræus (1966); Grahn (1981); Holmer (1986); Teves and Lindström (1988); Löfgren (1996, 1997); Bergström and Löfgren (2009); Bergström *et al.* (2014); Lindskog *et al.* (2014, 2019); Ahlberg *et al.* (2016). Regarding correlation of the 'Våmb Limestone', see remarks on the conodont zonation of the Segerstadian. **Östergötland**: Westergård (1940); Tjernvik (1956); Jaanusson (1962, 1963*b*); Fromm and Kjellström (1976); Bruun and Dahlman (1980); Bergström and Bergström (1996); Nielsen and Schovsbo (2007); Bergström *et al.* (2011*a*). **Närke**: Tjernvik (1956); Karis and Magnusson (1972); Lindskog *et al.* (2018). **Siljan**: Holm (1882); Thorslund (1960); Tjernvik (1956); Jaanusson (1963*a*); Bergström (1988); Holmer (1993); Nõlvak *et al.* (1999); Ebbestad and Högström (2007); Bergström (2007*a*); Suzuki *et al.* (2009); Ebbestad *et al.* (2015); Kröger *et al.* (2015, 2016*a*, *b*). **Öland**: Westergård (1947); Bohlin (1949); Tjernvik (1956); Jaanusson (1960*a*, 1982*a*); van Wamel (1974); Grahn (1981); Bagnoli and Stouge (1997, 2014); Stouge (2004); Frisk and Ebbestad (2008); Wu *et al.* (2017).

exposure, see that paper. The appearance of the trilobite *Ceratopyge acicularis* (*C. forficula* in the terminology of Tjernvik 1956) at the base of the Köpingsklint Formation marks the base of the stage. Outside Öland, this trilobite appears at the base of the Bjørkåsholmen Formation. The stage boundary is located at *c.* 0.4 m in the section illustrated by Tjernvik (1956, fig. 17). Detailed data on trilobite occurrences through the section were published by Frisk and Ebbestad (2008, fig. 2); the lower boundary of the Ottenbyan Stage is located at the base of their bed II. Lingulate brachiopods from Ottenby were described by Popov and Holmer (1994) and a study on the conodont zonation is in preparation by Stouge and co-authors.

Remarks: Tjernvik (1956, p. 117) introduced the 'Hunneberg group' which subsequently has been treated as a stage or substage and applied in both Scandinavia and the East Baltic area. Jaanusson (1960*b*, p. 299) defined a Latorpian Stage comprising the Hunnebergian and Billingenian substages and this terminology has been used occasionally (e.g. Männil 1966; Tjernvik and Johansson 1980; Männil and Meidla 1994). From Jaanusson (1982*a*) and onwards, the Hunnebergian and Billingenian have generally been ranked as separate stages in Scandinavia. Here we discontinue using the designation Hunneberg Stage and include the unit in the more readily recognizable Ottenbyan Stage. For the sake of nomenclatural stability, we considered maintaining the use of Hunnebergian, due to the fact that it is one of the few stages that has been widely applied in both Scandinavia and the East Baltic area. However, ease of recognition of the stage boundaries across Scandinavia is the fundamental goal for this revision and therefore we propose the abandonment of the Hunnebergian Stage notably because the lower boundary cannot be identified precisely in graptolitic facies.

The 'Hunneberg group' *sensu* Tjernvik (1956) originally comprised the *Megistaspis armata* and *M. planilimbata* trilobite zones. Subsequently, the upper part of the latter zone was separated as the *Megistaspis* aff. *estonica* Zone and allocated to the Billingenian Stage (Tjernvik and Johansson 1980). The lower boundary of the *Megistaspis armata* trilobite Zone coincides with the base of the *Paroistodus proteus* conodont Zone (e.g. Löfgren 1993, 1994) and the base of the former Hunneberg Stage is thus readily identifiable in carbonate-dominated facies, whereas it is difficult (and usually impossible) to pinpoint in shale facies. The fact that the Hunnebergian part of the Tøyen Formation commonly contains rather few graptolites in both the Oslo Region and most parts of Skåne (e.g. Tjernvik 1960; Erdtmann 1965) does little to help recognize the Hunnebergian and aid its correlation. In reality, even the Floian Global Stage boundary, based on graptolites, is impossible to identify precisely in these areas.

The lower boundary of the new Ottenbyan Regional Stage is recognizable throughout Scandinavia from the Lower Allochthon to the inboard sections on Öland and the accompanying shift from deposition of shale to limestone heralded the depositional pattern that eventually characterized much of the Ordovician in Sweden. The traditional Hunnebergian may be treated as a substage of the Ottenbyan Regional Stage; this solution would protect the identity and utility of a unit that has wide applicability in East Baltic chronostratigraphy.

The Diabasbrottet outcrop on Mt Hunneberg, Västergötland, is the GSSP section for the Floian Global Stage (Bergström *et al.* 2004; Egenhoff and Maletz 2007; Ahlberg *et al.* 2013*b*). The global stage is characterized by the appearance of the graptolite *Tetragraptus approximatus*. Graptolites are essentially restricted to the western facies belt in Scandinavia and identification of the global stage boundary in carbonate facies remains tentative, as it is located somewhere within the *Megistaspis* (*P.*) *planilimbata* trilobite Zone and the *Paroistodus proteus* conodont Zone (Bergström *et al.* 2004; Fig. 3). For this reason, the base of the Floian is not a convenient boundary for the Swedish carbonate-dominated sections. Within Scandinavia, this boundary can be precisely identified only in a few shale-dominated sections on Mt Hunneberg and in NW Skåne (cf. Lindholm 1991*a*, *b*; Maletz and Ahlberg 2011*a*).

Originally, the Hunnebergian was considered to span an interval between the classical Tremadoc and Arenig series in the UK (cf. Tjernvik 1956) as it contains several trilobites of Tremadocian aspect (see Tjernvik 1956, p. 179). Thus, for palaeontological reasons, a new stage combining the Hunnebergian interval with the 'Tremadocian' fauna described from the Bjørkåsholmen Formation presents a logical and pragmatic solution.

Zonation: Trilobites are common in the Ottenbyan carbonates and the *Ceratopyge acicularis*, *Megistaspis armata*, *M. planilimbata* and *Megistaspis* aff. *estonica* zones are recognized (Fig. 3; see Tjernvik 1956; Tjernvik and Johansson 1980; Ebbestad 1999). *Ceratopyge acicularis* corresponds in part to *Ceratopyge forficula* of older literature, see Ebbestad (1999), Frisk and Ebbestad (2008) and Pärnaste *et al.* (2013). The *C. acicularis* Zone is present throughout the Oslo Region (see Ebbestad 1999 for review) and is described also from many districts in Sweden (in older literature under the name of *Apatokephalus serratus* Zone, see e.g. Moberg and Segerberg 1906 and Tjernvik 1956). The *C. acicularis* Zone is absent in parts of Västergötland, most of Jämtland and all of Närke, Östergötland and the Siljan district. The *M. armata* Zone is commonly very condensed or even missing in the carbonate-dominated districts of south-central Sweden, whereas the overlying *M. planilimbata* Zone is thicker and laterally more continuous. Note that the *Megistaspis* aff. *estonica* Zone in most cases is difficult to separate from the *M. planilimbata* Zone based on the existing descriptions of sections; the geographically most widespread macrofossil indicator of this zone seems to be *Pricyclopyge gallica*. For this reason, we revert to the original definition of the Billingenian Stage (see below) and, in consequence, assign the so-called 'Transition Beds' (see Tjernvik and Johansson 1980) to the Ottenbyan Stage.

The Ottenbyan carbonates are usually rich in conodonts, and three zones have been established, namely the *Paltodus deltifer*, *Paroistodus proteus* and *Prioniodus elegans* zones (e.g. Lindström 1955*a*, 1971*b*; van Wamel 1974; Löfgren 1978, 1985, 1993, 1994, 1997; Bergström 1988; Bagnoli *et al.* 1989; Lindholm 1991*a*, *b*). Löfgren (1993, 1994) subdivided the *P. proteus* Zone into four subzones (Fig. 3), of which the upper *Oelandodus elongatus–Acodus deltatus deltatus* Subzone offers a tie to Cow Head, western Newfoundland (Stouge and Bagnoli 1988), where *O. elongatus* co-occurs with *T. approximatus*. Hence, this upper conodont subzone seems to approximate the lowermost part of the Floian Global Stage. Note, however, that *O. elongatus* appears slightly below the FAD of *T. approximatus* on Mt Hunneberg (Löfgren 1993; Bergström *et al.* 2004). The 'Transition Beds' *sensu* Tjernvik and Johansson (1980) in the upper part of the Ottenbyan Stage represent the *Prioniodus elegans* conodont Zone (Lindström 1957, 1971*b*; S. M. Bergström 1968, 1988). However, this assemblage is often reworked into the overlying *O. evae* conodont Zone.

The Bjørkåsholmen Formation is succeeded by the mudstone and shale-dominated Tøyen Formation in western and southernmost Scandinavia. The Ottenbyan part of this unit has been divided into five graptolite zones (Fig. 3). However, the precise correlation of the zonal boundaries with the coeval trilobite and conodont zonations remains uncertain, although the mixed facies at Mt Hunneberg offers some prospect for correlation with both basinal and platform successions (e.g. Tjernvik 1956; Lindholm 1991*b*; Bergström *et al.* 2004). The Ottenbyan part of the Tøyen Formation is overall less graptolitic than the younger shales in the western facies belt and the richest graptolite faunas are described from Skåne, although there are hiatuses locally (Lindholm 1991*a*; Maletz and Ahlberg 2011*a*, 2018), and in Hunneberg (Törnquist 1901, 1904; Lindholm 1991*b*; Maletz *et al.* 1996; Egenhoff and Maletz 2007). In the Oslo Region, the Hagastrand Member of the Tøyen Formation contains only sporadic graptolites (Erdtmann 1965).

Lithology: The Bjørkåsholmen Formation (referred to as the Ceratopyge Limestone in older literature), forming the lowest part of the Ottenbyan, is a thin limestone unit (≤ 1.5 m thick), commonly with interbeds of mudstone, that is developed in the Oslo Region, the south Bothnian district, Skåne and parts of Västergötland, Jämtland and southern Lapland (Figs 4 & 5) (see Thorslund 1937; Tjernvik 1956; Owen *et al.* 1990; Wu *et al.* 2015; see Ebbestad 1997, 1999 and Egenhoff *et al.* 2010 for reviews). In the Siljan district, the Obolus Conglomerate (containing the brachiopod *Lamanskya splendens*, see Holmer 1993) and the overlying glauconitic limestone bed (yielding the conodont *Paltodus deltifer*, see Löfgren 1994) apparently represents this level. The Bjørkåsholmen Formation is also recorded in the offshore well G-14 north of Rügen (Stouge 2001). On Öland, the equivalent interval is assigned as the lower part of the Köpingsklint Formation (van Wamel 1974). The Bjørkåsholmen limestone is overlain directly by the 'Latorp Limestone' also in parts of Västergötland and a distinction largely relies on palaeontological evidence. A corresponding development is seen in the Krekling area of the Oslo Region where the basal part of the Tøyen Formation is locally developed as a thin limestone unit, up to 1.2 m thick (Owen *et al.* 1990; Hoel 1991*a*, *b*; see also Ebbestad 1999). It is possible that the Bjørkåsholmen Formation and the overlying limestone in such cases should be combined into one formation as has been done on Öland. The sedimentology of the Bjørkåsholmen Formation in sections across Scandinavia is treated by Egenhoff *et al.* (2010, 2018).

The Bjørkåsholmen Formation is overlain by the Tøyen Formation (mudstone/shale) in the western facies belts and by the 'Latorp Limestone' in the eastern facies belts. This pattern heralded the general broad-scale facies distribution seen in the Ordovician of Scandinavia with a western mudstone/shale-dominated facies usually containing graptolites, and an eastern facies belt dominated by condensed, commonly glauconitic carbonate deposits containing a shelly fauna dominated by trilobites and brachiopods as well as conodonts (Fig. 2). Generally, the Ottenbyan part of the Tøyen Formation is lean in organic matter and graptolites are rather sparsely occurring in most districts; in the Oslo Region this lower part of the formation is separated as the Hagastrand Member, which is less than 11 m thick (Owen *et al.* 1990). The Tøyen Formation is developed in the Oslo Region, Jämtland (both in the Autochthon and Lower Allochthon), Skåne and parts of Västergötland (Tjernvik 1960; Jaanusson 1982*a*, *c*; Owen *et al.* 1990; Karis 1998; Maletz and Ahlberg 2011*a*, 2018; Egenhoff and Maletz 2012). The greatest thicknesses are seen in NW Skåne, where the Ottenbyan shale interval exceeds 63 m (Lindholm 1981; see also Maletz and Ahlberg 2011*a*). A very thin extension of the Tøyen Formation, 0.2 m thick, was recently described from one drill-core on Bornholm (Nielsen *et al.* 2018).

The 'Latorp Limestone' predominantly consists of very fine-grained carbonates (e.g. Lindström 1963; Jaanusson 1982*a*, *b*, *c*; Lindskog *et al.*

2018). The Ottenbyan part of this unit is less than 1.2 m thick (e.g. Tjernvik 1956; Karis 1998). A formal lithostratigraphic classification of the 'Latorp Limestone' has never been established, except on Öland (Köpingsklint Formation; van Wamel 1974; Stouge 2004); see also the results and discussion in Lindskog *et al.* (2018, p. 145).

Global correlation: The Ottenbyan Regional Stage is equivalent to the upper part of the Tremadocian Global Stage (upper half of the Tr2 and the entire Tr3 stage slice *sensu* Bergström *et al.* 2009) and the lower part of the Floian Global Stage (stage slice Fl1). It corresponds to the upper part of the Varangu Stage (characterized by the conodont *Paltodus deltifer,* see Mägi *et al.* 1989) and the entire Hunneberg Stage in the East Baltic scheme and may also include the lower part of the Billingenian Stage, depending on whether or not our redefinition of that stage, excluding the *Megistaspis* aff. *estonica* Zone, is adopted also for that area (see below).

Billingenian (Tjernvik 1956; emended)

Derivation of name: After Mt Billingen, an outlier of Lower Paleozoic strata, adjacent to the town of Skövde, Västergötland.

Basal stratotype (designated here): The abandoned Stora Brottet ['The Large Quarry'] locality at Lanna in the Närke district is here designated as the basal stratotype for the Billingenian Regional Stage. The trilobite biostratigraphy in this section was documented in detail by Tjernvik (1952, 1956, pp. 134–137, text-fig. 12). The base of the Billingenian Stage is marked by the appearance of the trilobite *Megalaspides dalecarlicus* at *c.* 1 m above the Cambrian–Ordovician boundary in the section (start of bed interval D, Tjernvik 1956, text-fig. 12); regarding the chosen level, see remarks below. The conodont zonation of this section was investigated by Lindström (1955*a*, see 1955*b* for corrections); the base of the Billingenian coincides with the lower boundary of the *Oepikodus evae* conodont zone in this section (see also Bergström 1988; Löfgren 1995). The carbonate-sedimentology of the Stora Brottet section ('Lanna C') was documented by Lindskog *et al.* (2018); their definition of the Hunnebergian–Billingenian boundary corresponds to the one proposed herein. An integrated bio- and chemostratigraphic study of the section is in preparation (Lindskog and co-authors).

Remarks: The name Billingen group was introduced by Tjernvik (1956), but since then the unit has been treated as a stage or substage (see remarks on the Ottenbyan above). The introduction of the Billingen group was not particularly formal by modern standards and a type section was not designated. The unit was first mentioned in connection with a description of the Stenbrottet (Orreholmen) locality at Ålleberg, Västergötland, and further elaborated in the section on the Stora Stolan exposure on northern Billingen, which was the only section described from Mt Billingen (cf. Tjernvik 1956). However, the latter locality is not an obvious candidate for a type section, as shelly fossils occur rather sporadically due to the predominant shale lithology in the lower part of the Billingenian (see Tjernvik 1956, text-fig. 7). No sections at Mt Billingen have been described in sufficient detail to serve as a stratotype and, besides, the lower boundary of the Billingenian Stage is here partly obscured by facies changes from carbonate to mudstone. Instead, we designate the carbonate-dominated Lanna section in Närke as stratotype.

Originally, the 'Billingen group' comprised only the *Megalaspides dalecarlicus* and *Megistaspis estonica* trilobite zones, but subsequently the underlying so-called 'Transition Beds' were also included (see Tjernvik and Johansson 1980, pp. 185–187). As the name implies, these beds contain faunal elements of both 'Hunnebergian' and Billingenian aspect and the interval was referred to as the *Megistaspis* aff. *estonica* Zone (Tjernvik and Johansson 1980). The trilobite fauna of this zone, however, is comparatively poorly known and the characterizing trilobite species is treated under open nomenclature. In effect, the zone is in most cases difficult or impossible to recognize in the sections across Sweden documented by Tjernvik (1956). By contrast, the originally defined lower boundary of the Billingenian is accompanied by a conspicuous faunal turnover that is readily recognized in essentially all the sections described from this interval. Overall, the lithological properties and fossil assemblages change significantly at this level (see below). Hence, we propose to revert to the original definition of the Billingenian with a lower boundary marked by the appearance of the trilobite *Megalaspides dalecarlicus*. This boundary appears far superior and much more straightforward to recognize than the revised boundary introduced by Tjernvik and Johansson (1980).

In shale facies, the lower boundary of the Billingenian Stage is correlated with the base of the *Baltograptus vacillans* graptolite Zone (previously: *Phyllograptus densus* Zone). Mixed facies in Västergötland (Tjernvik 1956; Lindström 1957; Lindholm 1981), the Siljan district (Törnquist 1879; Holm 1882; S. M. Bergström 1968, 1988) and Jämtland (Tjernvik 1956; Löfgren 1978; Bergström 1988) facilitate comparison of the trilobite, conodont and graptolite zonations. The Talubäcken section in the Siljan district demonstrates an apparent coincidence between the lower boundaries of the *Baltograptus vacillans* graptolite Zone and the *M. dalecarlicus* trilobite Zone, whereas the *P. elegans–Oepikodus evae* conodont zonal boundary apparently is located

0.4–0.5 m higher in the section (Bergström 1988); for further remarks on this correlation, see below.

The Billingenian Regional Stage is recognized also in the East Baltic area, sometimes as a substage of the Latorp Regional Stage (e.g. Männil and Meidla 1994). Note that it includes the lower part of what initially was called the Volkhov Stage by Balashova and Balashov (1959) and Orviku (1960) (see remarks on the Volkhovian below). The adjustment of the Billingenian Stage proposed herein, reverting to the original definition, allocates most of the *Prioniodus elegans* conodont Zone and the *M.* aff. *estonica* trilobite Zone to the Ottenbyan Stage. For the East Baltic area, this has the consequence that the upper part of the Leetse Formation, representing the *P. elegans* conodont Zone (see e.g. Viira *et al.* 2006), should be reassigned to the Hunnebergian as it is untenable to have different definitions of the Billingenian in Scandinavia and Estonia. Within Scandinavia, the interval corresponding to the 'Transition Beds' is commonly represented by a condensed interval or a hiatus (e.g. Tjernvik 1956; Lindström 1971*b*; Tjernvik and Johansson 1980; Löfgren 1985; Bergström 1988).

Zonation: The Billingenian, as redefined herein, comprises the *Megalaspides dalecarlicus* and *Megistaspis estonica* zones described by Tjernvik (1956) and summarized by Tjernvik and Johansson (1980). The condensed carbonate succession in Sweden is commonly extremely rich in conodonts. The *Prioniodus elegans* conodont Zone ranges into the lowermost part of the *M. dalecarlicus* trilobite Zone at Talubäcken in the Siljan district (Bergström 1988), but at other sites in Sweden the *O. evae* conodont Zone apparently starts in the uppermost part of the *M.* aff. *estonica* Zone (Lindström 1957, pp. 165–166; Löfgren 1985, pp. 118–119). This discrepancy may be due to undetected local reworking of the uppermost part of the Ottenbyan; the *P. elegans* fauna is commonly recognized as a ghost fauna at the base of the *O. evae* conodont Zone in Sweden (Lindström 1971*b*). The *Oepikodus evae, Trapezognathus diprion* and *Microzarkodina russica* conodont zones have been established for the stage (Lindström 1955*a*, 1971*b*; Stouge 1989; Bagnoli and Stouge 1997; Stouge *et al.* 2020). *Oepikodus evae* is widely distributed within and outwith Baltica (e.g. Lindström 1971*b*; van Wamel 1974; Löfgren 1978; Bergström 1988; Bagnoli and Stouge 1997; Rasmussen 2001); note that it locally ranges into the Volkhovian (e.g. Kohut 1972; Rasmussen 2001; Bergström and Löfgren 2009). The Billingenian is subdivided into the *Baltograptus jacksoni* and *Phyllograptus elongatus* graptolite zones, the latter with several subzones (Fig. 3; see Tjernvik 1956 and Maletz and Ahlberg 2018).

Lithology: The sea-level rose substantially during the Billingenian and strata of this age show a more consistent lateral continuity than the underlying Ottenbyan. Graptolitic shales (upper part of the Tøyen Formation) spread eastwards in Sweden, encroaching into Västergötland and the Autochthon of Jämtland (e.g. Jaanusson 1982*a*, *c*; Karis 1998), see Figures 4 and 5. The Billingenian part of this shale unit is rich in organic matter and graptolites in Skåne, and may be up to *c.* 20 m thick with a maximum thickness attained in NW Skåne (Tjernvik 1960; Lindholm 1981; Maletz and Ahlberg 2011*a*, 2018). The Oslo Region was also characterized by deposition of graptolitic shales, mostly up to *c.* 12 m thick (Galgeberg Member of the Tøyen Formation; Owen *et al.* 1990). Further east, condensed carbonate deposits, in places intensely red coloured, dominate in mainland Sweden and on Öland. The thickness is usually only a few metres (Tjernvik 1956). Thin mudstone beds (essentially incursions of Tøyen Formation) are common in the upper 'Latorp Limestone' in Sweden (e.g. Tjernvik 1956; Karis 1998; Lindskog *et al.* 2018). In most districts of Sweden, the Billingenian carbonates comprise the upper part of the 'Latorp Limestone'; on Öland they have been included in the Bruddesta Formation (van Wamel 1974; Stouge and Bagnoli 1990; Bagnoli and Stouge 1997; Stouge 2004).

Global correlation: The Billingenian Regional Stage is equivalent to the upper part of the Floian Global Stage (stage slices Fl2 and Fl3 *sensu* Bergström *et al.* 2009). The stage is recognized in both Scandinavia and the East Baltic area.

Volkhovian (Raymond 1916; emended)

Derivation of name: After the Volkhov River some 100 km SE of St Petersburg, Russia, known for its outcrops of Ordovician strata.

Auxiliary Scandinavian stratotype (designated here): The coastal cliff section at Bruddesta between Äleklinta and Djupvik, northern Öland, is here designated as the Scandinavian auxiliary type section for the Volkhovian. The easily accessible section was measured in detail by van Wamel (1974, chart III) and the characteristic 'Blommiga Bladet' hardground (see below) is located at 3.45 m in the section. The base of the Volkhovian is marked by the first appearance of the conodont *Baltoniodus triangularis* [=*Prioniodus navis* in van Wamel's terminology; see Bagnoli and Stouge 1997] immediately above the hardground.

The stage boundary is underlain by the upper Billingenian *Microzarkodina russica* conodont Zone and the *Megistaspis* (*Paramegistaspis*) *estonica* trilobite Zone, both having their base *c.* 40 cm below 'Blommiga Bladet'. The first occurrence of *B. triangularis* is associated with *Megistaspis* (*Megistaspis*) sp. [= *Megistaspis* aff. *limbata* in Tjernvik 1956, p. 153]; this trilobite genus includes a number of species characteristic of the Volkhovian Stage. *Microzarkodina flabellum* is another conodont species characteristic of the Volkhovian Stage; its FAD is in the *B. triangularis* Zone (van Wamel 1974; Bagnoli and Stouge 1997; Löfgren and Tolmacheva 2008; Bergström and Löfgren 2009).

Remarks: Raymond (1916) is usually credited for introducing the term Walchow [Volkhov] formation, although his original unit was of a very different scope and spanned the Ottenbyan, Billingenian and Volkhovian stages as recognized here, even including the lower part of the Kundan. The term Volkhovian was (re)introduced in the Russian stratigraphic classification in the 1950s (see Balashova and Balashov 1959 for review) and in Estonia by Orviku (1960). These authors included the Päite Beds of Estonia and Russia in the Volkhovian. The current use of the Volkhov Stage was established by Jaanusson (1960*b*) as a replacement for the 'Limbata Limestone', a long-standing designation originally introduced by Moberg (1890) for southern Öland and afterwards used throughout Sweden and Denmark (see Tjernvik 1972). The 'Limbata Limestone' was characterized by a suite of trilobite taxa that in modern taxonomy are assigned to *Megistaspis* (*Megistaspis*). The Estonian/Russian classification of the Billingenian–Volkhovian boundary interval was thereafter modified according to Swedish usage, assigning the Päite Beds, containing *Megistaspis* (*Paramegistaspis*) *estonica*, to the Billingenian (e.g. Männil 1966; Kaljo and Nestor 1990). In the East Baltic classification scheme, the Volkhovian Stage is subdivided into three substages, namely the Saka, Vääna and Langevojan, listed in ascending order. These have never found wider application in Scandinavia, although Jaanusson (e.g. 1960*b*) proposed to apply the Langevojan Substage on northern Öland (see also Jaanusson and Mutvei 1982).

Männil and Meidla (1994) referred to the Volkhov River as the type section for Raymond's (1916) Walchow formation but no specific outcrop or levels were detailed. However, Raymond (1916) noted that the sections at Lava River are better than those at the Volkhov River, so the Lava River is thus a preferable primary type section. The Billingenian–Volkhovian boundary interval at the Lava River was described in detail by Tolmacheva and Fedorov (2001) and it is one of the few places in the East Baltic area where the *Baltoniodus triangularis* conodont Zone is recorded.

The Babino limestone quarry, located *c.* 2 km east of the Volkhov River, was designated as the auxiliary stratotype for the Volkhov Formation by Dmitrovskaya (1991) according to Ivantsov (2003). However, this lithostratigraphic unit includes the Billingenian Päite Beds and thus cannot be a type section for the Volkhovian Stage. Somewhat confusingly, the Russian Volkhov Formation (=Toila Formation in Estonia) does not correspond entirely to the Volkhov 'Horizon' [= Stage], see, for example, Ivantsov (2003).

The base of the Volkhovian Stage is in many places marked by a highly characteristic disconformity, known as 'Steklo' in Russia, 'Püstakkiht' in Estonia and 'Blommiga Bladet' on Öland, Sweden. For a description of 'Blommiga Bladet', see Bohlin (1949), Lindström (1979) and Ekdale and Bromley (2001). Hence, a depositional gap is clearly present at the base of the classical Volkhovian and the auxiliary type section ought to be designated further west in Scandinavia, where the succession is more complete. However, a boundary in graptolitic shales is impossible to correlate precisely into the carbonate successions. A potential section is exposed at Herramb, Mjøsa area, Norway, where the lower boundary is well constrained by conodonts, but here trilobites are infrequent and poorly preserved in the Volkhovian (ATN and SS unpublished data, but see Skjeseth 1952). For this reason, we decided to designate the coastal cliff section at Bruddesta on northern Öland as the Scandinavian auxiliary type section for the Volkhovian. The primary indicator, *Baltoniodus triangularis,* is widely used as a marker for the base of the Volkhovian in Baltoscandia (e.g. Lindström 1971*b*; Löfgren 1985; Tolmacheva and Fedorov 2001; Bergström and Löfgren 2009). A suite of *Megistapis* (*Megistaspis*) trilobite species is also characteristic of the Volkhovian Stage, see Tjernvik (1972), Tjernvik and Johansson (1980) and Nielsen (1995). The Billingenian–Volkhovian transition is documented from several localities in Sweden, for example Lanna and Latorp in Närke, Hällekis on Kinnekulle in Västergötland, Ottenby on Öland, and the Finngrundet core in the Bothnian Sea (Tjernvik 1952, 1956; Tjernvik and Johansson 1980; Löfgren 1995; Bergström and Löfgren 2009; Lindskog and Eriksson 2017). For correlations based on conodonts, see Bergström and Löfgren (2009). Those authors indicated an offset between the trilobite and conodont zonal boundaries at the base of the Volkhovian at a few localities (see also Löfgren 1994). Further investigations are required to unravel whether this observation relies on biofacies differences, sample density, etc., or whether the appearance of *Megistaspis* (*M.*) *polyphemus* truly predates the FAD of *B. triangularis*.

Zonation: The Volkhovian of Scandinavia is subdivided into three trilobite zones, referred to as the *Megistaspis polyphemus*, *M. simon* and *M. limbata* zones (Tjernvik and Johansson 1980; Nielsen 1995). On northern Öland and in the Oslo Region, the *Asaphus lepidurus* trilobite Zone is equivalent to the upper part of the *M. limbata* Zone (cf. Bohlin 1949; Tjernvik 1972; Nielsen 1995; Stein and Bergström 2010). However, the trilobite stratigraphy of mainland Sweden remains to be documented in detail (cf. Tjernvik and Johansson 1980). Conodonts are abundant in the Volkhovian carbonates and detailed investigations of numerous sections have established a stratigraphy that currently comprises the *Baltoniodus triangularis*, *Baltoniodus navis*, *Baltoniodus norrlandicus* and *Lenodus antivariabilis* zones (Löfgren 1985, 1995, 2000; Stouge *et al.* 2020 and references therein). Stouge *et al.* (2020) did not recognize the *Paroistodus originalis* Zone (which is an acme zone) and included that interval in the *B. navis* Zone. In the relatively expanded Stein Limestone, located in the western shale-dominated facies belt, a modified zonation was introduced by Rasmussen (2001) and slightly revised by Rasmussen *et al.* (2021).

The Volkhovian shale facies in western and southwestern Scandinavia spans, in ascending order, the *Isograptus rigidus* through the *Isograptus mobergi–Meandrograptus schmalenseei*, *Arienigraptus dumosus* type–*Pseudisograptus manubriatus* and the lower *Levisograptus austrodentatus* (*Arienigraptus zhejiangensis* Subzone) graptolite zones (Maletz and Ahlberg 2021*a*, *b*). Graptolitic shales of middle to late Volkhovian age are known only from cored wells in NW and west-central Skåne (e.g. Lindholm 1981; Maletz 2005; Maletz and Ahlberg 2011*a*, *b*, 2018, 2021*a*, *b*). The early Volkhovian *Isograptus rigidus* and *Isograptus mobergi–Meandrograptus schmalenseei* graptolite zones are developed also in the Oslo Region and SE Skåne in the upper part of the Tøyen Formation (Tjernvik 1960; Erdtmann 1965; Maletz and Ahlberg 2018).

Very few chitinozoan species have been found in the Volkhovian of Scandinavia and Grahn and Nõlvak (2010) assigned most of the stage to the *L. esthonica* Zone with a thin *C. cucumis* Zone at the very top. However, the latter taxon ranges through most of the Volkhovian in Estonia (Nõlvak *et al.* 2019), so it should be used for correlation with caution.

Lithology: The Volkhovian of Sweden is dominated by stratigraphically condensed carbonates, generally assigned to the 'Lanna Limestone' (Fig. 4). This unit varies geographically in terms of visible characteristics, from light grey to reddish brown, but it is generally composed of relatively fine-grained carbonates with distinctly cyclical bedding (e.g. De Geer 1941; Jaanusson 1982*a*; Lindskog and Eriksson 2017; Lindskog *et al.* 2018). The total thickness of the Volkhovian is commonly around 10 m or a little less in carbonate settings in Scandinavia, but reaches 15 m in Västergötland and nearly 20 m in the Finngrundet drill-core in the Bothnian Sea (e.g. Tjernvik and Johansson 1980; Jaanusson and Mutvei 1982; Jaanusson 1982*b*, *c*; Lindskog and Eriksson 2017; Lindskog *et al.* 2018, 2019). On northern Öland, proper lithostratigraphic units were established by van Wamel (1974) and Stouge (2004), and the Volkhovian here comprises the upper part of the Bruddesta Formation, the Horns Udde Formation and the lower part of 'Formation A + B'. The strata on southern Öland differ somewhat and are generally quite similar to the 'Lanna Limestone' of mainland Sweden (e.g. Jaanusson and Mutvei 1982; Lindskog *et al.* 2018). Limestone facies spread westwards in Skåne and the Oslo Region during the Volkhovian (Fig. 5) and carbonate units in the western facies belt are referred to the Komstad Limestone (Skåne–Bornholm), Huk Formation (southern Oslo Region) and Stein Limestone (Lower Allochthon in northern Oslo Region and parts of Jämtland) (e.g. Owen *et al.* 1990; Rasmussen and Bruton 1994; Nielsen 1995; Rasmussen 2001; Wu *et al.* 2018). The Volkhovian part of the Komstad and Huk formations is *c.* 4 m on Bornholm and at Slemmestad in the Oslo Region and *c.* 10 m in SE Skåne (Nielsen 1995). In the Stein Limestone, the Volkhovian interval is *c.* 25 m thick (Rasmussen 2001). These limestone units are underlain by Volkhovian graptolitic shales assigned to the Tøyen Formation (e.g. Tjernvik 1960; Erdtmann 1965). The Volkhovian Stage is developed in its entirety as mudstone and shale only in NW Skåne; it comprises a *c.* 23 m thick interval in the Lovisefred core (Lindholm 1981; Maletz 2005; Maletz and Ahlberg 2021*a*, *b*).

Global correlation: The Volkhovian Regional Stage is applied both in the East Baltic area and in Scandinavia. *Baltoniodus triangularis*, marking the base of the Volkhovian, is also indicative of the base of the Dapingian Global Stage, coinciding with the base of the global Middle Ordovician Series (Bergström *et al.* 2009; Wang *et al.* 2009; Cooper and Sadler 2012). The Volkhovian Regional Stage is equivalent to the entire Dapingian Global Stage and the lowermost part of the Darriwilian Global Stage (stage slice Dw1 of Bergström *et al.* 2009). A Dw1 age of the upper part of the Volkhovian (not shown in the recent publication by Goldman *et al.* 2020, fig. 20.12) is indicated by the graptolite fauna intercalated in the Komstad Limestone at locality E22, Fågelsång, see Cooper and Lindholm (1985) and Maletz and Ahlberg (2018). The latter authors correlated this level with the Darriwilian *Levisograptus sinicus* Zone. The limestone at locality E22 was correlated with the *Lenodus antivariabilis* conodont Zone by Stouge and Nielsen (2003). Compare also with the graptolite zonation of the Tøyen Formation below the Komstad Limestone and equivalent levels in the Krapperup, Albjära and Lovisefred cores, Skåne (Maletz 2005; Maletz and Ahlberg 2021*a*, *b*), where graptolites indicative of stage slices Dw1 and Dw2 are recorded. Chitinozoans from the lower part of the Lysaker Member, Huk Formation, at Slemmestad in the Oslo Region also indicate a Darriwilian age according to Grahn and Nõlvak (2007*b*).

Kundan (Raymond 1916; emended)

Derivation of name: After Kunda, a small town in northern Estonia *c.* 100 km east of Tallinn.

Auxiliary Scandinavian stratotype (designated here): Raymond (1916) listed Kunda, in northern Estonia, as the type section. The exposures emphasized by Raymond (1916) in and adjacent to the then newly opened cement factory a few miles south of Port Kunda may be taken as the stratotype section. This disused quarry is now filled with water, but another larger and still active quarry is located *c.* 1 km further south. However, any section in northern Estonia is ill suited as a basal stratotype because the lower part of the Kundan Stage is strongly condensed or even missing there (e.g. Raukas and Teedumäe 1997; Rasmussen and Harper 2008; Rasmussen *et al.* 2009; ATN unpublished trilobite data). Originally Raymond (1916) assigned the BIIIα zone *sensu* Lamansky (1905) [≈ *Asaphus expansus* trilobite Zone] to the Walchow [Volkhov] formation, but Lamansky had already grouped this zone with the overlying strata and this has been the practice in Baltoscandia ever since.

The *A. expansus* Zone is well developed in Scandinavia and we designate the section at Djuptrekkodden, Slemmestad, Oslo Region, as an auxiliary Scandinavian basal stratotype (for description, see Nielsen 1995; Rasmussen *et al.* 2013). There, the appearance of *Asaphus expansus* in bed 29 at 2.5 m above the base of the Lysaker Member (Huk Formation) marks the base of the Kundan Stage (see Nielsen 1995, fig. 36). The conodont zonation of the section is detailed by Rasmussen (1991), see also Rasmussen *et al.* (2013, fig. 73); note that *Lenodus antivariabilis* and *L. variabilis* are difficult to separate as the conodont platform elements are fragmentary in the interval, and the shown lower boundary of the *L. variabilis* Zone is arguably positioned too low in the section.

Remarks: The Kundan Stage is applied both in the East Baltic area and in Scandinavia and there is general agreement about its concept. The stage is characterized by a distinct turnover in the shelly fauna although the preceding *Asaphus lepidurus* Zone (upper Volkhovian) to some extent heralds this change (e.g. Lindström 1971*a*; Jaanusson and Mutvei 1982; Jaanusson 1982*b*; Nielsen 1995; Rasmussen *et al.* 2016).

Due to the generally low sea-level during deposition of the lower part of the Kundan, the sections in the East Baltic area are strongly condensed and stratigraphically incomplete (e.g. Lamansky 1905; Ivantsov 2003; Rasmussen *et al.* 2009). Three Kundan substages, the Hunderumian, Valastean and Aluojan, are recognized in the East Baltic area (e.g. Männil and Meidla 1994), but they have rarely been referred to in studies dealing with Scandinavian sections, despite the fact that the Hunderumian Substage is based on a section on northern Öland (Jaanusson 1960*b*; Jaanusson and Mutvei 1982). There is no need for a substage classification to entirely duplicate the trilobite chronozones, as is the case here.

In mainland Sweden, the Kundan is particularly well documented from the Kinnekulle area, where the stage is well exposed and relatively thick (e.g. Zhang 1998*a*; Villumsen *et al.* 2001; Eriksson *et al.* 2012; Kröger and Rasmussen 2014; Lindskog *et al.* 2014, 2019; Lindskog and Eriksson 2017).

Zonation: The Kundan Regional Stage comprises three trilobite zones in Scandinavia, in ascending order, the *Asaphus expansus*, *A. raniceps–A. vicarius* and *Megistaspis obtusicauda–M. gigas* zones (e.g. Bohlin 1955; Jaanusson 1982*a*; Nielsen 1995; Stein and Bergström 2010). The conodont zonation comprises the *Lenodus variabilis, Yangtzeplacognathus crassus* and *Lenodus* [or *Eoplacognathus*] *pseudoplanus* zones (e.g. Lindström 1971*b*; Löfgren 1978, 2003, 2004; Stouge 1989; Stouge and Bagnoli 1990; Zhang 1998*a*; Stouge *et al.* 2020). Graptolitic mudstones and shales of this age are reported only from Skåne and they have been assigned to the upper *Levisograptus austrodentatus* (*Levisograptus sinicus* Subzone) through the *Eoglyptograptus cumbrensis*, *Holmograptus lentus* and *Nicholsonograptus fasciculatus* zones (Maletz and Ahlberg 2021*a*, *b*). The large smooth orthoconic cephalopod *Proterovaginoceras incognitum* is abundant in the Kundan across Baltoscandia (Kröger 2012; Kröger and Rasmussen 2014). Grahn and Nõlvak (2010) assigned the entire Kundan Stage to the *Cyathochitina regnelli* chitinozoan Zone, which also ranges into the Segerstadian Stage.

Lithology: The Kundan Stage in Sweden, characterized by widespread deposition of limestone, is mainly assigned to the 'Holen Limestone' (Fig. 4). Although it is topostratigraphically defined (Jaanusson 1982*a*), this unit is commonly distinguished from the underlying 'Lanna Limestone' by generally coarser carbonate textures and more abundant macrofossils (e.g. Bohlin 1949; Jaanusson 1982*b*; Karis 1998; Lindskog and Eriksson 2017; Lindskog *et al.* 2018). Iron ooids are occasionally common (e.g. Hessland 1949; Sturesson 2003). Beds crowded with cystoid echinoderms, *Sphaeronites*, form a characteristic grey-green coloured horizon, the so-called 'Täljsten', in the lower part of the 'Holen Limestone' of Västergötland (lowermost *Asaphus raniceps* Zone) (Holm and Munthe 1901; Regnéll 1945; Paul and Bockelie 1983). The equivalent horizon on southern Öland is referred to as the '*Sphaeronites* bed'. The superficial characteristics of the 'Holen Limestone' vary geographically, but it commonly comprises a lower greyish and an upper reddish part, differing in relative thickness (e.g. Hessland 1949; Jaanusson 1982*b*; Karis 1998; Lindskog and Eriksson 2017). The 'Holen Limestone' is up to *c.* 7 m thick in the Siljan district (Ebbestad and Högström 2007), *c.* 14 m in Västergötland (Lindskog and Eriksson 2017), and up to around 20 m or even more in Jämtland (Löfgren 1978; Karis 1998; Wu *et al.* 2015). The equivalent strata on northern Öland, provisionally referred to as formations A–D (upper part of A only), are up to *c.* 14 m thick (Wu *et al.* 2017). The preserved part of the 'Holen Limestone' is 20 m thick in the Finngrundet core in the Bothnian Sea, but the succession is truncated in the *A. raniceps* trilobite Zone (*L. pseudoplanus* conodont Zone) (Tjernvik and Johansson 1980; Löfgren 1985).

The upper part of the Huk and Stein formations in the Oslo Region, as well as the upper part of the Komstad Limestone in Skåne–Bornholm, correlate with the Kundan Stage (Fig. 5) (Owen *et al.* 1990; Rasmussen 1991; Nielsen 1995; Stouge and Nielsen 2003). The Kundan upper part of the Lysaker Member, Huk Formation, is 1.9 m thick at Slemmestad (Nielsen 1995), the overlying Svartodden Member is up to 2.7 m thick in the Oslo–Asker district (Owen *et al.* 1990), the Kundan part of the Stein Limestone is *c.* 25 m and the Kundan part of the Komstad Limestone is probably 7–8 m thick in SE Skåne (Nielsen 1995). Associated with a sea-level rise from the middle Kundan onwards, graptolitic shales spread eastwards and overlie the Komstad Limestone in central Skåne (Ekström 1937; Hede 1951; Bergström *et al.* 2018; Maletz and Ahlberg 2018); these shales are assigned to the Almelund Shale (Bergström *et al.* 2002). The Kundan part of this unit is probably 10 to maybe 15 m thick in the Fågelsång area, but the Kundan–Segerstadian boundary cannot be identified within the *N. fasciculatus* graptolite Zone (cf. Maletz and Ahlberg 2020). The Almelund Shale thins southeastwards in Skåne where the top of the Komstad Limestone is truncated by a major unconformity that extends further southeastwards onto Bornholm, where the hiatus spans most of the Kundan, all of the Segerstadian and the main part of the Dalbyan (cf. Poulsen 1966; Nielsen 1995; see also below). A hiatus also spans the upper part of the Kundan in the Oslo Region; for details, see remarks on the Segerstadian Stage below. The Kundan is developed in its entirety as mudstone and shale only in NW Skåne (Maletz and Ahlberg 2021*a*, *b*), with a total thickness around 45–50 m (Maletz and Ahlberg 2020). A non-graptolitic, carbonate-rich interval between the *E. cumbrensis* and the *H. lentus* graptolite zones in the Krapperup drill core probably correlates with the Komstad Limestone.

Global correlation: The Kundan Regional Stage is recognized in both Scandinavia and the East Baltic area. It corresponds to the middle part of the Darriwilian Global Stage (upper Dw1 through the lower half of the Dw2 stage slices *sensu* Bergström *et al.* 2009).

Segerstadian (new)

Derivation of name: After Segerstad Parish on southern Öland, defined as the type area for the topostratigraphic 'Segerstad Limestone' (Jaanusson 1960*a*). This unit forms the lower part of the new stage in many districts of Sweden and it also extends into southern Estonia.

Basal stratotype (designated here): The small and discontinuous exposures on the east coast of Öland near Segerstad and on the nearby 'Alvar' stone plain are poorly suited as type section(s) for the stage. A shallow cored drilling through the Lower Paleozoic succession was made at Segerstad Lighthouse in 1969, but detailed information about the penetrated Ordovician strata has not been published (cf. Erlström 2016). Besides, an outcrop is preferable as type section. We therefore designate the well described Kårgärde section in the Siljan district as the basal stratotype. Here the entire Segerstadian (*c.* 25 m) is exposed in a continuous succession (cf. Jaanusson and Mutvei 1953; Jaanusson 1982*b*; Holmer 1989; Shaikh *et al.* 1989, fig. 27). The lower boundary of the stage is defined within a predominantly red-coloured limestone interval by the appearance of the trilobite *Asaphus* (*Neoasaphus*) *platyurus* at 16 m above the basal contact to the bedrock porphyry (see Jaanusson and Mutvei 1953; Jaanusson 1982*b*). This level is located at *c.* 7.1 m above the distinct iron-stained hardground complex that marks the base of the 'Holen Limestone' (see Jaanusson 1982*b*, p. 41). The underlying limestone beds contain abundant *Megistaspis* (*Megistaspidella*) *gigas*. The conodont biostratigraphy of the section was treated by Bergström (2007*a*) (see also Löfgren 2004) and, according to him, the Kundan–Segerstadian boundary coincides with the base of the *Eoplacognathus suecicus* Zone. There are, however, different approaches how to define the lower boundary of that zone due to taxonomic difficulties with the identification of *E. suecicus* (cf. Zhang and Sturkell 1998; Zhang 1999). Here we follow the latter authors and suspect that the lower boundary of the *E. suecicus* Zone is located at *c.* 1.5 m above the base of the 'Segerstad Limestone' in the Kårgärde section, based on the FAD of *Pygodus lunnensis* (see further remarks below). The phosphatic brachiopod fauna in the section also exhibits a distinct faunal shift at the Kundan–Segerstadian boundary (Holmer 1989). $\delta^{13}C_{carb}$ curves from the Kårgärde succession, showing a well expressed Middle Darriwilian Isotopic Carbon Excursion

(MDICE), were published by Ainsaar *et al.* (2010*a*, *b*, fig. 3).

Remarks: The faunal changeover between the *Megistaspis* (*M.*) *gigas* and *Asaphus* (*N.*) *platyurus* trilobite zones is 'extraordinarily distinct in all districts of Sweden, where these zones can be distinguished' (Jaanusson 1960*a*, p. 217). Indeed, this faunal shift is so conspicuous that it commonly can be recognized in the field even by non-specialists, but despite being so abrupt, the faunal discontinuity is not accompanied by obvious lithological changes in Sweden (e.g. Jaanusson 1960*a*), where the shift commonly occurs within a distinctly reddish limestone interval. In detail, the 'Segerstad Limestone' contains slightly more argillaceous material than the underlying 'Holen Limestone'.

Jaanusson and Mutvei (1953) referred the lower part of the Segerstadian Stage as defined herein to the Platyurus Stage.

The Kårgärde section is the reference locality also for the *Pygodus serra* conodont Zone (Bergström 1971), the 'Holen Limestone' and the 'Kårgärde Limestone' (a subdivision of the 'Segerstad Limestone') (Jaanusson 1963*a*, 1982*b*; Ebbestad and Högström 2007). Due to its geological importance, the locality has been designated as a nature reserve ('Naturminne'), which ensures that it is protected from infrastructural development and encroachment.

Exposures of the Kundan–Segerstadian boundary interval are described also from Öland (e.g. Jaanusson 1960*a*; Jaanusson and Mutvei 1982), Jämtland (e.g. Larsson 1973; Löfgren 1978; Karis 1998; Zhang and Sturkell 1998) and the Oslo Region (see below). The Segerstadian and bounding strata have also been documented in several drill cores. Among these, the Böda Hamn core from northern Öland is of special interest as it has a detailed trilobite biozonation (Bohlin 1955; Jaanusson 1960*a*). Detailed conodont and isotope data for the interval, outlining the MDICE, are published for the nearby Tingskullen core (Wu *et al.* 2017). The base of the Segerstadian Regional Stage is located at *c.* 18 m in this core.

In the Oslo Region, the Helskjer Member at the base of the Elnes Formation contains a fairly diverse trilobite fauna, including rare specimens of *Asaphus* (*N.*) *platyurus* (Wandås 1983; Hansen 2009). Thus, the Kundan–Segerstadian boundary appears to coincide with the base of the Elnes Formation. Based on a study of conodonts, Rasmussen (1991) inferred that a hiatus encompassing the upper part of the Kundan is present between the Huk and the Elnes formations (see also Rasmussen *et al.* 2013, fig. 73). It is in this context relevant to point out that the trilobite *Megalaspis* [now *Megistaspis*] *gigas*, reported from the uppermost part of the Huk Formation (Brøgger 1882; Størmer 1953), does not represent that species (Bohlin 1955, p. 136). Many parts of the Elnes Formation are graptolitic and the formation spans the *Nicholsonograptus fasciculatus* Zone (probably only the upper part) as well as the *Pterograptus elegans, Pseudamplexograptus distichus* and *Jiangxigraptus vagus* zones (Maletz 1997*b*; Maletz *et al.* 2007). The diverse trilobite fauna of the Elnes Formation above the Helskjer Member is of limited biostratigraphic significance (Hansen 2009), although the presence of *Pseudomegalaspis patagiata,* ranging from the middle part of the formation and into the overlying Vollen Formation, is known also from the Segerstadian in various districts of Sweden (see summary in Hansen 2009). The Segerstadian–Dalbyan stage boundary is located somewhere in the upper part of the Vollen Formation, but the precise level cannot be pinpointed. Sparse conodont data suggest that the lower and middle parts of the Vollen Formation represent the *Pygodus anserinus* conodont Zone (Bergström 1971, p. 104), i.e. are of Segerstadian age (for further remarks, see discussion on the Dalbyan Stage below).

The Segerstadian is associated with significant stratigraphic gaps in some areas of mainland Sweden. In Västergötland, the lower part of the Segerstadian is thus missing or very condensed. Strata corresponding to the *A. platyurus* trilobite Zone are missing altogether on Kinnekulle and (where present) only comprise a thin bed in the nearby Billingen–Falbygden area (e.g. Jaanusson 1964, 1982*c*; Holmer 1983; Lindskog and Eriksson 2017). Stable deposition did not recommence in Västergötland until the late *Pygodus serra* conodont Chron (Zhang 1998*b*). The Segerstadian is also absent on the island of Bornholm (cf. Poulsen 1966 and references therein).

Zonation: Trilobites indicative of the *Asaphus* (*Neoasaphus*) *platyurus* Zone are typically abundant in the lower part of the Segerstadian Regional Stage, where developed in carbonate facies. Above this level, the Scandinavian trilobite fauna is not documented in detail and regional zones have not been established (cf. Jaanusson 1982*a*). In the 'Segerstad Limestone' of the Siljan district, a basal *Angelinoceras latum* cephalopod-based zone ('Kårgärde Limestone') followed by an *Illaenus planifrons* trilobite zone ('Vikarby Limestone') were recognized by Jaanusson and Mutvei (1953) and Jaanusson (1963*a*). In older literature, the strata above the 'Segerstad Limestone' (= Platyurus Limestone) in the Siljan district were referred to as the Schroeteri and Crassicauda limestones, named after common trilobites in what now are termed the ~'Skärlöv' + 'Folkeslunda' (*Illaenus chiron*) and ~'Furudal' (*Illaenus crassicauda*) limestones, respectively (Jaanusson 1960*a*, 1962, 1963*a*, *b*, 1964; and references therein).

The Segerstadian Stage encompasses the uppermost part of the *Lenodus* [*Eoplacognathus*] *pseudoplanus* conodont Zone, the *Eoplacognathus suecicus* and *Pygodus serra* zones and the lower part of the *Pygodus anserinus* Zone, with several subzones (Fig. 3; e.g. Bergström 1971, 2007*a*; Löfgren 1978, 2004; Zhang and Sturkell 1998; Rasmussen 2001; see also Dzik 1994). Distinction of the key species *L. pseudoplanus* and *E. suecicus* relies on details in the P elements and these species have occasionally been mixed (see Zhang and Sturkell 1998, pp. 77–78). As a result, the base of the *E. suecicus* Zone has commonly been considered coinciding with the Kundan–Aseri boundary [here Kundan–Segerstadian boundary]. However, we agree with Zhang and Sturkell (1998) that the FAD of *E. suecicus sensu stricto* slightly postdates the appearance of *Asaphus platyurus*.

The thin 'Våmb Limestone' (in older literature assigned to the 'Vikarby Limestone'), is developed only on Billingen, Västergötland. It contains rare *Eoplacognathus foliaceus* (see Fåhræus 1966; Bergström 1971), suggesting a correlation with the basal subzone of the *P. serra* conodont Zone (cf. Zhang and Sturkell 1998; Bergström 2007*a*, *b*). This is peculiar, however, as the thin bed also has yielded common and well-preserved *Asaphus platyurus* and therefore was correlated with the Aseri Stage by Jaanusson (1964). No shelly elements suggest a younger age. This discrepancy is puzzling and calls for further investigations; for the time being we correlate the 'Våmb Limestone' with the *Asaphus platyurus* trilobite Zone (Fig. 5), but maybe different parts of the condensed limestone, containing several discontinuity surfaces (see Holmer 1983), are of different ages. The infilling of the V-shaped desiccation crack-like structures in the upper part of the bed, described by Holmer (1989, p. 8), may also be significantly younger than the main bed. Studies on the Kårgärde section, Dalarna, demonstrated that there is no overlap between the *A. platyurus* trilobite Zone and the *P. serra* conodont Zone (Jaanusson and Mutvei 1953; Bergström 2007*a*, *b*).

The Segerstadian is equivalent to the upper part of the *Nicholsonograptus fasciculatus* graptolite Zone as well as the *Pterograptus elegans*, *Pseudamplexograptus distichus* and *Jiangxigraptus vagus* graptolite zones (e.g. Maletz 1997*b*; Maletz *et al.* 2007). The stage also includes the lower part of the *Nemagraptus gracilis* graptolite Zone (see discussion on the Dalbyan Stage below). According to chitinozoan data, the Segerstadian spans the uppermost part of the *Cyathochitina regnelli* Zone, the entire *Laufeldochitina striata* Zone and the lower part of the *Laufeldochitina stentor* Zone (Fig. 3), see Grahn and Nõlvak (2010).

The MDICE $\delta^{13}C$ isotope excursion peaks in the lower part of the Segerstadian and is a useful marker for regional and global correlations (e.g. Kaljo *et al.* 2007; Ainsaar *et al.* 2010*a*, *b*, 2020; Bauert *et al.* 2014; Wu *et al.* 2017; Bergström *et al.* 2018; Lindskog *et al.* 2019).

Lithology: The sea-level rose during the late part of the Kundan and into the early Segerstadian, but still the greater part of Sweden was characterized by deposition of limestones with varying texture and colour; some intervals are distinctly marly/nodular and commonly red-coloured (e.g. Jaanusson 1960*a*, 1962, 1963*a*, 1964, 1973, 1982*a*; Larsson 1973; Jaanusson and Mutvei 1982; Karis 1998). The interval corresponding to the Segerstadian is assigned to the 'Segerstad', 'Skärlöv', 'Seby', 'Folkeslunda', 'Furudal', 'Källa' and 'Persnäs' topoformations, of which the last two are local for northern Öland (Fig. 4). The Segerstadian is *c.* 21 m thick on northern Öland (cf. Jaanusson 1960*a*) and about 25 m in Östergötland and the Siljan district including the lower 5 m of the 'Dalby Limestone' (cf. Jaanusson 1962, 1982*b*; Ebbestad and Högström 2007; Bergström *et al.* 2011*a*). In Västergötland, the 'Våmb Limestone', 'Skövde Limestone', Gullhögen Formation and 'Ryd Limestone' have been distinguished (e.g. Jaanusson 1964, 1982*c*) above the basal Segerstadian hiatus (Fig. 4); these strata are altogether *c.* 21 m thick on Kinnekulle. The Gullhögen Formation, which is rich in mudstone and shale intercalations, deviates significantly from the 'typical' rocks of mainland Sweden and may be envisaged as a wedge of the Norwegian Elnes Formation. These units also share the trilobites *Ogygiocaris sarsi* and *Pseudomegalaspis patagiata.* The basal Segerstadian and several levels within the stage contain stromatolite-like features and iron ooids are locally common (Jaanusson 1960*a*, 1962, 1963*a*, 1964, 1982*b*; Larsson 1973; Holmer 1983; Sturesson 1989, 2003; Karis 1998).

In the Oslo Region, a foreland basin with increased subsidence developed and the clastic supply increased from the incipient Caledonides to the present-day west. The resulting expanded shale-dominated section is assigned to the Elnes Formation (see Owen *et al.* 1990), which reaches thicknesses of nearly 100 m in the central Oslo Region (Hansen 2009). It is overlain by the limestone-dominated Vollen Formation (exact thickness unknown but exceeds 40 m), consisting of rhythmically alternating limestone beds intercalated by mudstone; only the lower and middle part of this unit is of Segerstadian age (Fig. 4; see remarks on zonation above).

In Skåne, the Segerstadian is represented by the upper part of the Almelund Shale. However, the Kundan–Segerstadian boundary, located somewhere in the *N. fasciculatus* graptolite Zone, cannot be pinpointed. The Almelund Shale is close to 30 m thick in total in the Fågelsång area, but only the upper ~half is of Segerstadian age. The formation thins southeastwards, and the Killeröd Formation occurs in its upper part in SE Skåne (e.g. S. M. Bergström

1973; Nielsen 1995; Bergström *et al.* 2002). The graptolitic Andersö Shale in Jämtland is an equivalent of the upper part of the Almelund Shale; for description with references to older publications, see Pålsson *et al.* (2002).

Global correlation: The Segerstadian Stage corresponds to the East Baltic Aseri, Lasnamägi and Uhaku stages as well as the lowermost part of the Kukruse Stage (Fig. 3; e.g. Kaljo *et al.* 2007; Bauert *et al.* 2014; Bergström *et al.* 2020*a*, *b*). The base of the Segerstadian coincides with the base of the Aseri Stage whereas the upper boundary cannot be precisely correlated to the East Baltic scheme for the time being. The Segerstadian Regional Stage corresponds to the upper half of the Darriwilian Global Stage (upper part of stage slice Dw2 plus Dw3 *sensu* Bergström *et al.* 2009) and the basal part of the Sandbian Global Stage (lower part of Sa1). However, the exact correlation of the upper boundary of the Segerstadian with the global stage system is uncertain (see further discussion below on the Dalbyan Stage).

Dalbyan (new)

Derivation of name: Refers to the village of Dalbyn in the Siljan district, which also gave its name to the 'Dalby Limestone' (Jaanusson 1960*a*; Ebbestad and Högström 2007).

Basal stratotype (designated here): The well-documented Fjäcka main section in the Siljan district is designated as the basal stratotype for the Dalbyan Regional Stage. This section is discussed by Jaanusson and Martna (1948), Martna (1955), Jaanusson (1963*a*, 1976), Laufeld (1967), Bergström (1971, 2007*a*), Nõlvak *et al.* (1999) and Ebbestad and Högström (2007). The lower boundary of the new stage is marked by the appearance of the conodont *Amorphognathus* (which is in all probability *A. tvaerensis* according to Bergström 2007*a*) at 5.25 m above the base of the 'Dalby Limestone' and which was taken to indicate the base of the *A. tvaerensis* conodont Zone by Bergström (2007*a*). A secondary proxy for the boundary interval is *Eoplacognathus elongatus* but this species may appear slightly below *A. tvaerensis* (Bergström 1971, 2007*a*; Männik and Viira 2012). The stage boundary is located within the *Eisenackitina rhenana* Subzone of the *Laufeldochitina stentor* chitinozoan Zone, but the basal part of the 'Dalby Limestone' including the boundary interval, is barren of chitinozoans in the Fjäcka section (Nõlvak *et al.* 1999; see also Grahn and Nõlvak 2010). As a complementary stratigraphic marker, the *A. tvaerensis* Zone is characterized by a prominent decline and nadir in $\delta^{13}C$ (Kaljo *et al.* 2007; Bauert *et al.* 2014; Bergström *et al.* 2020*a*, *b*). This trend in the $\delta^{13}C$ curve has been termed the 'upper Kukruse low' and the Lower Sandbian Negative Isotopic Carbon Excursion (LSNICE).

Remarks: The 'Dalby' and 'Skagen' limestones are present in most Paleozoic districts of mainland Sweden, but the trilobite faunas of these units have received little attention in recent years and, hence, are at present of little use for biostratigraphic correlation. The upper part of the 'Dalby Limestone' was referred to as the Ludibundus Limestone in older literature, named after the trilobite *Asaphus ludibundus* (Jaanusson 1951*a*; Ebbestad and Högström 2007). In the Fjäcka type section, this taxon ranges through most of the 'Upper Member' of the 'Dalby Limestone' *sensu* Jaanusson (1982*b*, fig. 6), i.e. from *c.* 1 m above the base of the Dalbyan Stage as defined herein. It has a fairly long range and is known also from the 'Skagen Limestone' of mainland Sweden (e.g. Jaanusson 1982*c*) as well as from the Vollen, Arnestad and Frognerkilen formations in the Oslo Region (Henningsmoen 1960). The small trilobite *Panderia parvula* (for description and distribution, see Bruton 1968) is another potential marker for the new stage boundary; it ranges through most of the 'Dalby Limestone' and is widespread in Baltoscandia. In the Fjäcka stratotype section, the defined stage boundary is located *c.* 4 m above the FAD of *Panderia parvula*.

The Dalbyan Regional Stage is, broadly speaking, a Scandinavian equivalent of the Sandbian Global Stage. It appears desirable to adopt a lower boundary for the regional stage that as closely as possible aligns with the global stage boundary due to its coincidence with a series boundary – but at the same time this regional boundary must be operational in practice in Scandinavia. The lower boundary of the Sandbian Global Stage is based on the FAD of *Nemagraptus gracilis,* but graptolites are extremely rare in the carbonates of mainland Sweden and further east (cf. Regnéll 1948; Nõlvak and Goldman 2004, 2007). Correlation in carbonate facies therefore has to rely on other fossil groups but, as remarked above, the Scandinavian trilobites from the interval are in need of revision with accurate documentation of occurrences in measured sections before being useful for precise biostratigraphic correlation. Accordingly, correlation primarily hinges on conodonts or chitinozoans (e.g. Bergström 1971, 2007*b*; Bergström *et al.* 2000; Bergström and Ahlberg 2004; Vandenbroucke 2004; Grahn and Nõlvak 2007*a*, 2010).

The GSSP section for the Sandbian Global Stage is located at Fågelsång, Skåne (Bergström *et al.* 2000). A distinctive phosphorite bed, *c.* 15 cm thick, is located at 3 m above the base of the exposure (see Bergström *et al.* 2000, fig. 5; Calner *et al.* 2013, fig. 28); henceforth this bed is referred to as the PB. The PB is probably a 'maximum flooding surface' reflecting a major sea-level rise – potentially the '*Gracilis* transgression' of Fortey (1984) and others – associated with a transient cessation of sedimentation and concomitant precipitation of phosphorite; hence, a hiatus may be anticipated at this level. The PB is present in all the drill cores through this interval in the area (Hede 1951; Nilsson 1977; Bergström *et al.* 2018; Maletz and Ahlberg 2020) and is apparently recognizable also in the Röstånga-2 drill-core, retrieved some 30 km north of Fågelsång (Maletz *et al.* 2020; Bergström *et al.* 2020*a*, *b*).

Only one level with *N. gracilis* was indicated below the PB, at −1.4 m in the GSSP section, based on older collections (cf. Bergström *et al.* 2000, fig. 5). However, Maletz and Ahlberg (2020) were unable to locate that material in the Lund collections and they concluded that the *N. gracilis* Zone cannot be positively identified below the PB in the Fågelsång area. In the nearby Fågelsång-1 and Koängen drillings, described by Hede (1951) and Nilsson (1977), respectively, *N. gracilis* was reported only from above the PB. This pattern is also seen in the Röstånga-2 core, where *N. gracilis* is infrequent (Maletz *et al.* 2020). At Fågelsång, the succession up to the PB was, accordingly, assigned to the *Jiangxigraptus vagus* graptolite Zone by Maletz and Ahlberg (2020; see also Maletz *et al.* 2020). The chitinozoan zonation of the Fågelsång stratotype section has been described by Vandenbroucke (2004) and Grahn and Nõlvak (2007*a*), but their records are not in agreement except that the boundary level is within the *Laufeldochitina stentor* chitinozoan Zone. According to Vandenbroucke (2004), the *Eisenackitina rhenana* Subzone has its base at 0.3 m below the GSSP level.

We consider the report of *Lagenochitina dalbyensis* from immediately above the PB (Vandenbroucke 2004) as questionable (see also Grahn and Nõlvak 2007*a*, *b*); this occurrence is incompatible with the correlation of chitinozoan, conodont and graptolite zonations across the region as currently inferred (Fig. 3). If correct, it indicates a considerably longer downwards range of *L. dalbyensis* than previously documented from Baltoscandia.

The conodont zonation of the GSSP section was reviewed by Bergström (2007*b*). The GSSP level is located within the *P. anserinus* conodont Zone and the *A. tvaerensis* conodont Zone starts in the PB. Two subzones are defined within the *P. anserinus* conodont Zone (Dzik 1978; Bergström 1983), but the position of the GSSP in relation to these subzones cannot be resolved as the conodont record in the Fågelsång section is based primarily on occasional occurrences on bedding planes. This is significant, as the conodont subzone boundary commonly is taken as an indicator for the base of the Kukruse Stage and the base of the Upper Ordovician Series in the East Baltic area (e.g. Paiste *et al.* 2022) and a similar approach could be considered for defining the base of the Dalbyan Stage in Scandinavia. However, *Amorphognathus inaequalis*, the eponymous species of the upper subzone, is very rare in Baltoscandia and, hence, is not functional as a stratigraphical marker, and recognition of the upper subzone is in most cases based on the appearance of *Baltoniodus variabilis* (see Bergström 1971, 1983 and 2007*a* for details) or the Last Appearance Datum (LAD) of *Sagittodontina*? *kielcensis* (Paiste *et al.* 2022). Note in this context, the *B. variabilis* Subzone defined for the lower part of the *A. tvaerensis* conodont Zone is not based on the FAD of *B. variabilis* (see Bergström 1971, 1983 and 2007*a* for details). The evolution from *B. prevariabilis* to *B. variabilis* is through long-term gradual morphological changes that necessitate subjective assessment when identifying the species (see also remarks by Viira 2008, p. 33). Arguably, it is best to avoid this type of taxonomic uncertainty for the identification of chronostratigraphic boundaries. Due to the taxonomic ambiguity as well as the fact that the position of the conodont subzonal boundary in relation to the GSSP level is unknown, we are not promoting this boundary as marker for the base of the Dalbyan Regional Stage.

As none of the biozone boundaries based on conodonts or chitinozoans are known to coincide precisely with the lower boundary of the Sandbian Global Stage, it is impossible to unambiguously identify this level in the carbonate successions of mainland Sweden, irrespective of whether *N. gracilis* has its FAD at the defined GSSP or above the PB, as indicated by Maletz and Ahlberg (2020). For these reasons, the base of the *A. tvaerensis* conodont Zone is preferred as marker for the base of the Dalbyan Stage.

Lithology: The predominantly greyish 'Dalby Limestone' is developed throughout mainland Sweden and on Öland (Fig. 4); it is up to *c.* 20 m thick in the Siljan district (Ebbestad and Högström 2007) and *c.* 21 m in Västergötland (Jaanusson 1964). The 'Dalby Limestone' commonly comprises two lithological subunits, referred to as the Lower and Upper member (e.g. Jaanusson 1982*b*, *c*). Usually the lower part is compact, thick-bedded, and fine-grained, becoming more calcarenitic upwards whereas the upper part is composed mainly of bedded to nodular calcarenites with intercalations of mudstone. Abundant cystoid echinoderms (dominantly or maybe only *Echinosphaerites aurantium aurantium*) form a characteristic feature of the 'Dalby Limestone', in most cases allowing for easy identification of the unit (Regnéll 1948). In Östergötland, Västergötland and the Siljan district, the 'Dalby Limestone' is overlain by the 'Skagen Limestone', which is very fine-grained, grey and up to *c.* 6 m thick in the Siljan district and 4 m in Västergötland (Jaanusson 1964; Ebbestad and Högström 2007). This unit is now included as the lower part of the

Freberga Formation (e.g. Ebbestad and Högström 2007; Bergström *et al.* 2011*a*). Micritic limestone mounds, the Kullsberg Limestone, with thicknesses up to 35 m, are developed in the Siljan district. These mounds seem to be associated with the Frognerkilen sea-level lowstand (cf. Nielsen 2004). Biostratigraphically, the base of the Kullsberg Limestone is just above the base of the *Baltoniodus alobatus* conodont Subzone, whereas the youngest parts are within the *Amorphognathus superbus* conodont Zone (Bergström 1971, 2007*a*).

Graptolitic shales are known from western Skåne, where the uppermost part of the Almelund Formation, the entire Sularp Shale as well as the lower part of the Dicellograptus Shale represent the Dalbyan Stage (for lithostratigraphic nomenclature, see Bergström *et al.* 2002). The total thickness of the Dalbyan shales is *c.* 66 m in the Fågelsång area (cf. Nilsson 1977; Maletz and Ahlberg 2020). This stratigraphic interval is essentially absent in the Lovisefred core, NW Skåne (R. Nilsson, unpublished), and on Bornholm, the Almelund Formation is also absent (Fig. 5). Here, the Sularp Shale (*c.* 2 m thick, cf. Funkquist 1919) has traditionally been included in the Dicellograptus Shale (e.g. Poulsen 1966). In Röstånga, western Skåne, a limestone unit, 0.8 m thick, above the Sularp Shale has been referred to as the Skagen Limestone (e.g. Bergström *et al.* 1999; Pålsson 2002; Badawy *et al.* 2014); it is now assigned to the Freberga Formation (Bergström *et al.* 2016). It is overlain by a black limestone, 0.6 m thick, assigned to the Mossen Formation (Pålsson 2002).

The Autochthon of Jämtland is disturbed by the Lockne astrobleme (e.g. Lindström 2007). The 'Dalby Limestone' was deposited in the aftermath of the impact and is unusually thick in some parts of the area, up to 88 m (Lindström *et al.* 2005). The same phenomenon is seen in the coeval Tvären crater near Stockholm, where the post-impact 'Dalby Limestone' is nearly 70 m thick (Frisk and Harper 2011). In the Lower Allochthon of Jämtland, the uppermost part of the 'Upper Member' of the Andersö Shale is of Dalbyan age (see Karis 1998). This shale is commonly terminated upwards by a limestone, up to *c.* 3.5 m thick, referred to as 'Dalby Limestone' equivalent (Karis 1998), but it appears to be younger than the 'Dalby Limestone' of south-central Sweden (Fig. 5).

In the Oslo Region, the scattered occurrence of conodonts in the Vollen Formation, reported by Hamar (1964, 1966) and revised by Bergström (1971, p. 104), indicates that the lower to middle part of the unit represents the *Pygodus anserinus* Zone. This suggests that the base of the Dalbyan Stage is located somewhere in the upper part of this unit (the total thickness of the Vollen Formation is unknown, but exceeds 40 m). However, a precise identification of the base of the Dalbyan Regional Stage – or the Sandbian Global Stage – is not currently possible in the foreland succession of the Oslo Region, and no details are known from the Vollen Formation that permit identification of specific sea-level changes during deposition. The Vollen Formation, comprising nodular limestone intercalated in mudstone, also contains a sparse but fairly diverse trilobite fauna as well as other shelly fossils, but the correlation potential of the assemblage is untapped as yet. Note, however, that *Asaphus* (*N.*) *ludibundus*, known from the Swedish 'Dalby Limestone', has been recorded (Jaanusson 1953, 1964; Henningsmoen 1960), but its distribution within the Vollen Formation is unknown. It ranges into the overlying Arnestad Formation, which again is in accordance with the long range of this taxon known from Sweden (see Jaanusson 1953). The chitinozoan *Belonechitina hirsuta* was reported from the upper part of the Vollen Formation by Grahn *et al.* (1994). The Vollen Formation is overlain by the Arnestad and Frognerkilen formations that both are of presumed Dalbyan age, but detailed correlation is not possible as they contain no biostratigraphically significant graptolites and conodonts are essentially undescribed; for a review of biostratigraphic indicators, see Owen *et al.* (1990). Chitinozoans suggest a correlation with the East Baltic Haljala and Keila stages (Grahn *et al.* 1994).

Zonation: The Scandinavian trilobite faunas from this stage are in need of revision, see remarks above, but the *A. ludibundus* Zone may span most of the Dalbyan Stage. In the Fjäcka and Tvären areas, the 'Dalby Limestone' contains a rich macrofauna (Ebbestad and Högström 2007); the brachiopod fauna from the latter area has been documented in terms of ecological associations, associated with the Tvären crater (Frisk and Harper 2011, 2013). The entire Dalbyan Regional Stage is assigned to the *Amorphognathus tvaerensis* conodont Zone (cf. Bergström 1971) but it most probably also includes the very base of the *Amorphognathus superbus* conodont Zone, recorded from the upper part of the 'Skagen Limestone' (Bergström 1971, 1986); see remarks on the Moldåan Stage below. The *A. tvaerensis* Zone is subdivided into the *Baltoniodus variabilis, Baltoniodus gerdae* and *Baltoniodus alobatus* subzones (Bergström 1971; Fig. 3). A detailed chitinozoan zonation has been established for the interval, comprising the upper half of the *Laufeldochitina stentor* Zone and five overlying zones (Nõlvak and Grahn 1993; Nõlvak *et al.* 1999), see Figure 3. A continuous succession of graptolitic shales is described only from Skåne, where the Dalbyan Stage spans the *N. gracilis* and the *Mesograptus foliaceus* zones (e.g. Nilsson 1977). The latter zone is recognized in more sections across Scandinavia than the former, suggestive of a higher sea-level in the late Dalbyan. Graptolitic shales, the Andersö Shale, are known also from the Lower Allochthon of Jämtland (e.g. Hadding 1912, 1913; Karis 1998) (Fig. 4).

The Guttenberg Isotopic Carbon Excursion (GICE) correlates with the Frognerkilen lowstand (cf. Bergström *et al.* 2010; 2011*b*, fig. 4), but the maximum peak in $\delta^{13}C$ is unrecorded in most Swedish districts due to a hiatus.

Global correlation: The Scandinavian Dalbyan Regional Stage is equivalent to most of the Kukruse Stage as well as the Haljala and Keila stages in the East Baltic area. It approximates to most of the Sandbian Global Stage, but as discussed above, the lower boundary correlates with a level slightly above the base of the global stage.

Moldåan (new)

Derivation of name: Moldån is an older name for the Fjäckån rivulet in the Siljan district which gave its name to the now abandoned 'Moldå Limestone' (first used by Jaanusson 1973, fig. 3). The lower boundary of the new stage coincides with the base of this limestone.

Basal stratotype (designated here): The main Fjäcka section in the Siljan district, illustrated by Jaanusson (1976, fig. 9), is here designated as the basal stratotype for the Moldåan Stage. See Jaanusson and Martna (1948) for a general lithological description of the section; faunal logs have been published by Jaanusson (1976, fig. 9; 1982*b*, fig. 7). The lower boundary of the Moldåan Regional Stage is marked by the appearance of the trilobite *Toxochasmops extensus* (*s.l.*) at the boundary between the 'Skagen' and 'Moldå' limestones (now united into the Freberga Formation, see Ebbestad and Högström 2007), corresponding to level 6.3 m in the section shown by Bergström (2007*a*, fig. 8). The lower boundary of the *Amorphognathus superbus* conodont Zone was identified a few metres above the base of the stage in the type section by Bergström (2007*a*, fig. 8), but in fact, the stage and zonal boundaries probably coincide (see remarks on correlation of the conodont zone below).

Remarks: Jaanusson (1963*b*) established the Vasagaard Stage based on the exposure of Dicellograptus Shale at Vasagård, Læså, Bornholm, described by Hadding (1915). The stage comprised only the *Pleurograptus linearis* graptolite Zone. However, as (i) this stage has been little used by subsequent authors, (ii) it is notoriously difficult to precisely correlate boundaries based on graptolites into the carbonate successions and (iii) the Vasagaardian is short, spanning only one graptolite zone, we propose to abolish this stage.

Macrofossils are generally sparse in the Scandinavian carbonate successions representing this interval, but the trilobite *Toxochasmops extensus* is reported from several districts in Sweden and southern Norway and it may occur also in Estonia and England. The taxonomy is debated, however (e.g. Størmer 1940, 1953; Rõõmusoks 1953, 1998; Haller 1973; McNamara 1980 and references therein), and for this reason we prefer to treat the taxon as *T. extensus* (*s.l.*); it may possibly be envisaged as a group of closely related species. *Phacops macrourus* Angelin, 1851, the eponymous species of the now-abandoned 'Macrourus limestone' of Öland and the Siljan district, is a junior synonym (McNamara 1980). Another trilobite with biostratigraphic potential in this interval is *Tretaspis ceriodes.* Various subspecies are known from the 'Mossen Formation' in Västergötland and Skåne and from the Solvang and lowermost Venstøp formations in the Oslo Region (Thorslund 1948; Owen 1987; Pålsson 1996). Thorslund (1940) also recorded it from Jämtland (as *T. cerioides* [*sic*]). A couple of subspecies are described from the uppermost Caradoc in the UK (Owen 1987).

In most districts of Sweden, the former 'Skagen' and 'Moldå' topoformations are separated by a hiatus, but no obvious lithological indications of a sedimentary break have been described from the Fjäcka type section (cf. Jaanusson and Martna 1948). Nonetheless, it is believed that a break actually is present there as well, but has remained unnoticed, maybe due to the somewhat complicated tectonic setting of the section (see further discussion on correlation of the conodont and graptolite zonations below). A conglomerate marks this break in the Borenshult core described from Östergötland (Bergström *et al.* 2012). In Västergötland, the break is even more extensive. On Billingen, the 'Slandrom Limestone' and/or the 'Bestorp Limestone' thus rests directly on the 'Skagen Limestone' (e.g. Skoglund 1963; Jaanusson 1982*c*), whereas on Kinnekulle, the Fjäcka Shale rests unconformably on the Mossen Formation (Skoglund 1963; Holmer 1986; Bergström *et al.* 2011*b*, fig. 7). A conglomerate is even developed in the offshore Dicellograptus Shale succession at Vasagård, Bornholm, between the *M. foliaceus* and *D. clingani* graptolite zones, highlighting the magnitude of this interruption of deposition (cf. Funkquist 1919, p. 30, his bed 4).

Bergström (1986) summarized the biostratigraphic ties between the Ordovician conodont and graptolite zonations. He pointed out that the Fjäcka Shale, which contains graptolites diagnostic of the *Pleurograptus linearis* Zone (Thorslund 1935; Skoglund 1963; Jaanusson 1963*a*, 1964), also has yielded conodonts characteristic of the *Amorphognathus ordovicicus* Zone (Bergström 1971). Since then, an isolated limestone nodule has been found near the base of the *P. linearis* graptolite Zone on Bornholm and it contained a conodont assemblage characteristic of the *A. superbus* conodont Zone (Stouge and Rasmussen 1996). Hence, the boundary between the *A. superbus* and *A. ordovicicus* conodont zones must be located somewhere within the *P. linearis* graptolite Zone as also indicated by Goldman *et al.* (2020, fig. 20.2). It appears that the Fjäcka Shale of south-central Sweden only represents the upper part of the *P. linearis* graptolite Zone, as the very top of the underlying 'Slandrom Limestone' represents the *A. ordovicicus* conodont Zone (Bergström 2007*a*). A putative palaeokarst horizon is developed in the 'Slandrom Limestone' just below the Fjäcka Shale according to Calner *et al.* (2010*b*).

Bergström (1986) placed the base of the *A. superbus* conodont Zone within the *Diplograptus multidens* graptolite Zone [now: *Mesograptus foliaceus* Zone] based on a conodont assemblage extracted from limestone intercalated in graptolitic shales in western Skåne (Bergström *et al.* 1967). This correlation is in accordance with findings of *A. superbus* in the upper part of the 'Skagen Limestone' in some districts of Sweden (Bergström 1971) and it demonstrates that the *A. tvaerensis*–*A. superbus* zonal boundary does not correlate with a level in the lower part of the Katian Global Stage as indicated by Goldman *et al.* (2020, fig. 20.2). A location of the *A. tvaerensis*–*A. superbus* conodont zonal boundary within the *M. foliaceus* Zone further implies that the lower part of the Moldåan Stage in the stratotype section most likely represents the *A. superbus* conodont Zone, despite the lack of characteristic elements (there are many records of unidentified *Amorphognathus* sp. in that part of the section). We surmise that the basal part of the *A. superbus* conodont Zone has been excised in a cryptic unconformity between the 'Skagen' and 'Moldå' limestones.

The faunal turnover at the base of the Moldåan Stage is widely recognizable in Baltoscandia (Jaanusson 1995; Ainsaar *et al.* 2004), marking the boundary between the East Baltic Keila and Oandu stages, although very few taxa are shared between Scandinavia and Estonia. The abruptness of the faunal change is ascribed to a break in deposition below the Moldåan and Oandu stages associated with a sea-level lowstand (the Frognerkilen lowstand of Nielsen 2004).

Zonation: The *Toxochasmops extensus* Zone [regarding the spelling of the species name, see McNamara 1980] was the only regional trilobite zone indicated by Jaanusson (1982*a*, p. 9) for the Middle–Upper Ordovician of Scandinavia above the Segerstadian *Asaphus platyurus* Zone. For remarks on the regional distribution of this species, see above. No regional trilobite zones are defined for the upper part of the stage.

The Moldåan Stage spans the *Dicranograptus clingani* and the *Pleurograptus linearis* graptolite zones, but whether or not the base of the *D. clingani* Zone coincides precisely with the base of the stage remains uncertain. In a sequence-stratigraphical context, the Moldåan Stage represents deposition in the aftermath of a very significant sea-level lowstand that was associated with a depositional break across mainland Sweden, apparently even affecting the offshore shale facies (see remarks above on the Vasagård section on Bornholm). In the foreland basin, the lowstand was associated with deposition of the limestone-dominated Frognerkilen Formation in the Oslo–Asker district; it contains no graptolites and correlation with the graptolite zonation is uncertain. Neither has the Arnestad Formation, deposited prior to the Frognerkilen lowstand, yielded biostratigraphically significant graptolites (Hansen and Harper 2006) but the trilobite fauna from the uppermost 5 m of the formation suggests a correlation with the 'Skagen Limestone' of Sweden, which is generally assumed to correlate with the *M. foliaceus* Zone (e.g. J. Bergström *et al.* 1967; S. M. Bergström 1971; Nilsson 1977). The Nakkholmen Formation overlying the Frognerkilen Formation contains a sparse graptolite fauna indicative of the *Dicranograptus clingani* Zone together with a low-diversity, deep-water brachiopod fauna and some scolecodonts (Harper *et al.* 1984). The same sea-level rise led to deposition of the Mossen Formation in the mainland of Sweden, and which also represents the *D. clingani* Zone (e.g. Thorslund 1948; Skoglund 1963). Hence, we infer that the base of the Moldåan Stage approximates (and probably essentially coincides with) the base of the *D. clingani* graptolite Zone.

The chitinozoans recovered from the Fjäcka stratotype section are mainly undiagnostic, but *Spinachitina cervicornis* ranges into the Moldåan (Grahn and Nõlvak 2010, fig. 12). According to the data published on the Vasagård section on Bornholm (Vandenbroucke *et al.* 2013), the *D. clingani* and *P. linearis* graptolite zones span the *Fungochitina spinifera* chitinozoan Zone and the lower part of the *Tanuchitina bergstroemi* chitinozoan Zone and maybe also the top part of the *Spinachitina cervicornis* Zone. In terms of the conodont biozonation, the Moldåan Stage spans the *A. superbus* and the lower part of the *A. ordovicicus* zones (cf. Bergström 1971, 2007*a*). It may also include the very top of the *Amorphognathus tvaerensis* Zone (see Bergström 2007*a*, fig. 8), but as discussed above, we have reason to presume that also the lower part of the Moldåan Stage is within the *A. superbus* conodont Zone and that the boundary between the 'Moldå' and 'Skagen' limestones in the stratotype section is an unconformity like in all other districts of Sweden.

The Kope $\delta^{13}C$ isotope excursion correlates with the Solvang lowstand *sensu* Nielsen (2004) in the very top of the *D. clingani* graptolite Zone (cf. Bergström *et al.* 2011*b*, fig. 4). Conodonts from the

Solvang Formation suggest a correlation with the upper part of the *A. superbus* conodont Zone (Bergström 1971 based on Hamar 1966). The conglomeratic Skålberg Limestone in the Siljan district is suggested to reflect the same sea-level lowstand (for description, see Ebbestad and Högström 2007; Calner *et al.* 2010*a*).

Lithology: The sea-level rose significantly in the aftermath of the Frognerkilen lowstand (Nielsen 2004) and remained high during most of the Moldåan. However, another prominent sea-level fall, the Solvang lowstand of Nielsen (2004), characterized the latest *D. clingani* Chron. The generally high sea-level was associated with incursions of mudstone-dominated facies, the Mossen and Fjäcka formations, into south-central Sweden, even reaching as far east as southern Estonia (e.g. Wærn *et al.* 1948; Jaanusson 1963*b*, 1982*c*; Raukas and Teedumäe 1997). These units can be envisaged as extensions of the Dicellograptus Shale of SE Skåne and Bornholm (cf. Figs 4 & 5). This shale is a proper lithostratigraphic unit, but with a name based on a fossil taxon and obviously a new term is required. There has lately been a move towards introducing the Mossen and Fjäcka formations as replacement names for the Dicellograptus Shale, but in SE Skåne–Bornholm these units cannot be lithologically differentiated, rather they are separated based on their faunal content: the Mossen Formation belongs to the *D. clingani* Zone and the Fjäcka Shale to the *P. linearis* Zone. In that area, these units are thus, strictly speaking, topostratigraphic units which should be avoided. The Dicellograptus Shale at Vasagård (excluding the Sularp Shale, which traditionally has been included in this unit) is *c.* 10 m thick and consists of dark grey to black organic-rich laminated shales (cf. Hadding 1915). In western Skåne, the Dicellograptus Shale is strongly condensed and partly replaced by limestone-dominated units assigned to the 'Skagen' and Mossen formations (e.g. Pålsson 1996).

Within the mainland of Sweden, the Moldåan interval is characterized by condensed, usually very fine-grained limestones assigned to the upper part of the Freberga, Mossen, 'Bestorp', 'Slandrom' and Örån formations together with the Fjäcka Shale (e.g. Jaanusson 1963*b*, 1982*b*, *c*; Karis 1998; Bergström *et al.* 2011*a*; Calner *et al.* 2013). The 'Moldå Limestone' (now upper part of the Freberga Formation) is 9.5 m thick in Östergötland and 6 m in the Siljan district (Ebbestad and Högström 2007; Bergström *et al.* 2012); the Mossen Formation is up to 1.6 m thick in Västergötland (Skoglund 1963) and absent elsewhere in south-central Sweden; the 'Slandrom Limestone' is a little more than 8 m thick in the Siljan district, 7 m in the autochthon of Jämtland, only 1 m in Östergötland and *c.* 0.8 m in Billingen, Västergötland (Holmer 1986; Karis 1998; Ebbestad and Högström 2007; Bergström *et al.* 2012) and the Fjäcka Shale is 6–6.5 m in the Siljan district and Västergötland and only *c.* 1 m in Östergötland (Jaanusson 1982*c*; Ebbestad and Högström 2007; Bergström *et al.* 2012). The 'Bestorp Limestone', up to 4.5 m thick, occurs only in the Billingen area, Västergötland, and may be considered a local limy equivalent of the Fjäcka Shale; it rests on the 'Slandrom Limestone' (Holmer 1986; see also Skoglund 1963). The very top of the 'Slandrom Limestone' ranges into the *A. ordovicicus* conodont Zone, but the unit mainly represents the *A. superbus* conodont Zone (Bergström 1971, 2007*a*). The Skålberg Limestone in the Siljan district occurs on the flanks of the Dalbyan Kullsberg Limestone mounds and its deposition was possibly related to the Solvang sea-level lowstand *sensu* Nielsen (2004). In the Lower Allochthon of Jämtland, the lower part of the Kogsta Shale represents the Moldåan Stage; it ranges through the Jerrestadian and the very top contains fossils of Tommarpian aspect (cf. Karis 1998). The thickness of the Kogsta Shale is unknown due to tectonic overprinting but exceeds some tens of metres (cf. Karis 1998). In the Oslo–Asker district, the Moldåan Stage comprises intercalated shales and limestone of the Nakkholmen (≤ 22 m thick), Solvang (≤ 22 m), and Venstøp (≤11 m) formations (Owen *et al.* 1990; Bruton *et al.* 2010). Brachiopod associations occurring across the Oslo Region display a clear onshore–offshore gradient from the more marginal areas in the north and SW to the deeper-water basinal facies in central Oslo (Harper 1986). It is possible that the upper part of the Frognerkilen Formation also belongs to the Moldåan Stage but the sparse fossil fauna reported from that unit is biostratigraphically undiagnostic (cf. Owen *et al.* 1990). We assume that most of the unit represents the Dalbyan Stage.

Global correlation: The lower boundaries of the Moldåan Regional Stage and the Katian Global Stage are believed to coincide, but exact correlation remains uncertain as discussed above. The upper boundary corresponds to the Ka3–Ka4 boundary *sensu* Bergström *et al.* (2009). The Moldåan Regional Stage of Scandinavia corresponds to the Oandu, Rakvere, Nabala and Vormsi stages in the East Baltic chronostratigraphical scheme.

Jerrestadian (Jaanusson 1963b; emended)

Derivation of name: The name refers to the Järrestad village in SE Skåne, known for its outcrops of Ordovician strata along the Tommarpsån rivulet, initially described by Olin (1906) and Moberg (1910*a*). Formerly this stretch of Tommarpsån was occasionally referred to as the Jerrestadsån. Jaanusson (1963*b*) defined the topostratigraphic 'Jerrestad Formation' and the Jerrestad Stage, referring to these exposures. In stratigraphic nomenclature the original spelling Jerrestad is maintained.

Auxiliary stratotype (designated here): Jaanusson (1963*b*, p. 128) designated the exposure in Tommarpsån near Järrestad between localities nos 15 and 16 *sensu* Olin (1906, p. 34) as the basal stratotype for the 'Jerrestad Formation' and stage. We have not had the opportunity to reinvestigate the exposure but at any rate the fossil fauna from the Lindegård Formation in that section remains poorly known (for a description of the underlying graptolitic strata at locality no. 15, see Pålsson 2001). For that reason, we designate the more extensively studied, richly fossiliferous exposures along the Kyrkbäcken rivulet at Röstånga, Skåne, as the auxiliary stratotype (see Olin 1906; Moberg 1910*a*; Pålsson 1996). Parts of this section tend, however, to get covered by slumped soil and rock material, but it can relatively easily be excavated. In this area, the underlying strata are comparatively condensed and referred to as the Mossen Formation and Fjäcka? Shale by Pålsson (1996; see also Bergström *et al.* 1999); the latter unit is here included in the Dicellograptus Shale. The base of the Jerrestadian Regional Stage is marked by the appearance of the trilobite *Nankinolithus granulatus* [*Tretaspis granulata* in older literature] at 11.5 m in the section (see Pålsson 1996). This boundary corresponds to the base of the Lindegård Formation. That unit corresponds to the combined 'Jerrestad' and 'Tommarp' topostratigraphic formations of Jaanusson (1963*b*), but the name Lindegård Mudstone had already been introduced as a conventional lithostratigraphic unit by Glimberg (1961) and is preferred here. Olin (1906, p. 24) noted that there is a pyrite-rich boundary layer at the base of the Lindegård Formation [in modern terminology]; a similar pyrite-rich conglomerate is developed also on Bornholm (see Gry 1948). The conglomerate probably reflects a break in deposition associated with the marked sea-level fall that took place in the boundary interval between the Moldåan and the Jerrestadian. How much time the hiatus spans remains a matter of speculation.

Remarks: The Jerrestadian is a key interval between the mainly graptolitic facies of the Moldåan Stage and the terminal Ordovician Tommarpian Stage and thus captures strata that are correlatives of the Ashgillian *Dicellograptus complanatus* and *D. anceps* biozones. The Jerrestadian marks a major sea-level fall and even the offshore facies in Skåne–Bornholm became remarkably non-graptolitic, hampering correlation out of Baltica of the uppermost Ordovician successions. Sporadic occurrences of *D. complanatus* have, however, been reported from Skåne–Bornholm (Olin 1906; Poulsen 1936 [see Skoglund 1963]; Glimberg 1961; Skoglund 1963; Nilsson 1977; Pålsson 1996), all from a thin horizon a few metres above the base of the Lindegård Formation. The same species has been recorded also from Västergötland (Skoglund 1963). Stratigraphically, the next occurrence of graptolites is much higher up in Scandinavian sections – in the upper part of the Tommarpian – representing the *Metabolograptus persculptus* Zone (Koren' *et al.* 2003; Maletz *et al.* 2014). The shallower depth of deposition during the Jerrestadian is evident everywhere in Scandinavia. In the Siljan district, the famous Boda Limestone mounds developed at this stage.

Zonation: The entire Jerrestadian Stage falls within the *Amorphognathus ordovicicus* conodont Zone, but generally conodonts occur sparingly, and they are thus of little practical value for correlation in most sections (e.g. Bergström 1971). Likewise, chitinozoans are commonly infrequent or absent in Scandinavian sections of this age and only one zone, the *Tanuchitina bergstroemi* Zone, spans the entire stage (e.g. Grahn *et al.* 1994). Due to the general scarcity of chitinozoans in Scandinavia, Grahn and Nõlvak (2010) even assigned the interval to an 'interzone'. The *T. bergstroemi* chitinozoan Zone, as well as the *A. ordovicicus* conodont Zone, range from the uppermost part of the Moldåan Stage. A few species of agnostoids are known from several districts in Scandinavia as well as other continents and offer a crude stage-level correlation (see Kielan 1960 and Ahlberg 1989 and references therein).

The trilobite fauna of the Jerrestadian part of the Lindegård Formation of Skåne–Bornholm and the Jonstorp Mudstone of Västergötland represents the *Eodindymene pulchra* and the *Staurocephalus clavifrons* zones, defined by Kielan (1960); see also J. Bergström (1973). Additional species are described by Kielan-Jaworowska *et al.* (1991). These trilobite zones can be correlated to Poland (Kielan 1960). The base of the Jerrestadian is marked by the FAD of *Nankinolithus granulatus*, a trinucleid trilobite species that is fairly widely distributed in Scandinavia (Skåne, Bornholm and Västergötland; Kielan 1960). *Eodindymene pulchra* appears higher in the succession (Nilsson 1977; Pålsson 1996) and for this reason no regional trilobite zone is indicated for the lower part of the Jerrestadian in Figure 3. The Lindegård Formation also contains brachiopods of the deep-water *Foliomena* fauna (Sheehan 1973). This fauna is now known to have a near cosmopolitan distribution in deeper-water facies with a range from the Darriwilian to the top of the Katian (e.g. Rong *et al.* 1999). As remarked above, the lower part of the Jerrestadian represents the *Dicellograptus complanatus* graptolite Zone whereas the upper part is non-graptolitic.

The foreland succession in the Oslo Region is overall rather sparsely fossiliferous, notably the Grimsøya, Skjerholmen and Skogerholmen formations (Owen *et al.* 1990). For a review of the trilobites found in the upper part of this succession, see Amberg *et al.* (2017, fig. 5). It is evident that the Grimsøya Formation represents a shallower depositional environment than the underlying Venstøp Formation, a distinct facies change comparable to the lithological shift seen in Skåne–Bornholm from Dicellograptus Shale to Lindegård Formation, but palaeontological evidence for correlation is sparse. The few trilobites known from the Grimsøya Formation do not permit a detailed biostratigraphic correlation (Owen 1980*a*, 1981). The uppermost Jerrestadian Husbergøya Formation contains a relatively diverse fauna comprising both trilobites and brachiopods even though the macrofossil abundance is low (Brenchley and Cocks 1982; Cocks 1982). These authors termed the fauna the '*Tretaspis* Association', which in the upper part of the Husbergøya Formation changes into a '*Tretaspis–Onniella* Association'. The trilobites were described by Owen (1980*a*, *b*, 1981, 1982) and they indicate a Rawtheyan age for the unit, i.e. late Jerrestadian.

Lithology: In Skåne–Bornholm, the Jerrestadian comprises the lower part of the Lindegård Formation, which is a bioturbated, generally non-laminated mudstone with low content of organic matter (Fig. 5). The Jerrestadian is up to 13 m thick in western Skåne (Sheehan 1973; Nilsson 1977); it thins considerably towards NW Skåne (R. Nilsson, unpublished notes). Its thickness in SE Skåne and on Bornholm is unknown due to the lack of detailed biostratigraphic studies. In Västergötland, the Jerrestadian corresponds to the Jonstorp Formation, which is up to some 29 m thick (Fig. 4; Jaanusson 1963*a*). It has incursions of the Öglunda Limestone (up to 3 m thick) in the middle and the Ulunda Formation (up to 10 m thick) at the top (Jaanusson 1982*c*). The latter unit consists of monotonous dark mudstones and shales with a few limestone interbeds. The Jonstorp Formation including the Öglunda Limestone is also developed in the Siljan district and Östergötland, but these units are mostly poorly (Siljan) or not (Östergötland) exposed; the total thickness is up to 15.5 m (Siljan) and 11 m (Östergötland) (Jaanusson 1963*a*; Ebbestad and Högström 2007). In these districts, the upper grey part of the Jonstorp Formation (up to 3 m) was previously referred to as the 'Nittsjö Formation' (Jaanusson 1963*b*); sometimes this level is now called the 'Nittsjö Bed' (Ebbestad and Högström 2007). This unit consists of grey limestones and marls. Better known are the intercalated, spectacular Boda Limestone mud mounds of the Siljan district that are extremely rich in various macrofossils (Ebbestad and Högström 2007). The mounds are up to 100–140 m thick (Jaanusson 1982*b*; Kröger *et al.* 2016*a*, *b*). Similar mounds have been documented in the subsurface of Gotland (Klasen mounds, Bergström *et al.* 2004; Sivhed *et al.* 2004). The Jerrestadian is absent in the Autochthon of Jämtland but in the Lower Allochthon, the stage is represented by the upper part of the Kogsta Siltstone; a possible equivalent of the Öglunda Limestone occurs in the middle part of the succession (Jaanusson and Karis 1982; Cherns and Karis 1995).

In the Oslo Region, the Jerrestadian corresponds to shallower-water, largely carbonate-dominated facies, which vary across the districts (see Owen *et al.* 1990). They succeed the dark shales of the Venstøp Formation (Moldåan Regional Stage) and precede the Tommarpian strata of the Langøyene Formation (Owen *et al.* 1990). The Jerrestadian is best known from the Oslo–Asker district (Brenchley and Cocks 1982; Cocks 1982; Owen *et al.* 1990; Calner *et al.* 2021) where sections through the stage are well exposed in and around the Oslo Fjord and comprises the Grimsøya (≤46 m thick), Skjerholmen (≤48 m thick), Skogerholmen (≤43 m thick) and Husbergøya (≤35 m thick) formations, listed in ascending order (thicknesses from Owen *et al.* 1990).

Global correlation: The Jerrestadian Regional Stage is comparatively short but denotes a major fall in sea-level that introduced significant changes in the depositional environment and, hence, also influenced the fauna. The Scandinavian Jerrestadian Stage corresponds to the East Baltic Pirgu Stage and it is equivalent to the upper part of the Katian Global Stage (stage slice Ka4 of Bergström *et al.* 2009).

Tommarpian (Jaanusson 1963b; emended)

Derivation of name: After Östra Tommarp, a small town in eastern Skåne, known for its geological localities described by Olin (1906), Moberg (1910*a*), Troedsson (1918), Funkquist (1919) and Grahn (1978). However, most of these localities no longer exist. The name Tommarp Stage was introduced by Jaanusson (1963*b*, p. 132). In the same publication, the term Tosterup Stage was used interchangeably for this unit, even in the abstract, but this appears to be an editorial error.

Neostratotype (defined here): When introducing the Tommarp Stage, Jaanusson (1963*b*, p. 132) listed the exposures at Östra Tommarp, Skåne, described by Troedsson (1918, locality No. T 9, g–w) as the type section, but these outcrops no longer exist. Instead, we propose to define a neostratotype for the Tommarpian in the Oslo Region, where spectacular outcrops of Upper Ordovician strata are described from the Oslo–Asker district (e.g. Brenchley and Cocks 1982; Calner *et al.* 2021). We select the section at Rambergøya as the type section (corresponding to Section 7 of Brenchley and Cocks 1982, see their text-fig. 4). The lower boundary of the Tommarpian is defined at 21.4 m in their section and is marked by the appearance of a *Hirnantia* brachiopod fauna. Concomitantly all representatives of the trilobite genus *Tretaspis* disappeared in the Oslo Region (Owen 1980*a*). The same pattern is seen at the Rawtheyan–Hirnantian boundary in the UK (Ingham and Wright 1970; Owen 1986).

Remarks: The lithology of the Lindegård Formation in Skåne–Bornholm, spanning the Jerrestadian as well as the Tommarpian stages, is monotonous. Systematic documentation of the fossil content is based largely on drill-cores (Sheehan 1973; Nilsson 1977, 1979) whereas outcrops have mostly been subjected to 'bag-sampling' of macrofossils without exact documentation of the sampled levels (e.g. Ravn 1899; Troedsson 1918; Poulsen 1936). An outcrop at Röstånga, Skåne, described by Troedsson (1918; his Va locality) and illustrated also by Bergström *et al.* (2014, fig. 2), could potentially serve as a neostratotype for the base of the Tommarpian. This outcrop is, however, largely inaccessible nowadays and not suitable as a stratotype.

In the Oslo–Asker district of the Oslo Region, the Husbergøya Formation contains a sparse but fairly diverse fossil macrofauna, referred to as the '*Tretaspis* Association', which in the upper part contains elements characteristic of the *Onniella* brachiopod association (see Brenchley and Cocks 1982, pp. 792–794). The upper part of the Husbergøya Formation has also yielded the trilobite *Mucronaspis mucronata kiaeri*, which ranges into the overlying Langøyene Formation (Owen 1982). This mixed association also characterizes a brownish, *c.* 2 m thick marker sandstone at the very top of the Husbergøya Formation (Brenchley and Cocks 1982). The *Tretaspis* trilobites found in the Husbergøya Formation suggest a correlation with the Rawtheyan of the UK (see Owen *et al.* 1990 and references therein). The lower 2 m of the overlying Langøyene Formation contains a *Hirnantia* brachiopod association (for details, see Brenchley and Cocks 1982, pp. 795–796).

The Norwegian fauna is directly comparable with the *Hirnantia* fauna of Britain and Ireland and elsewhere (Rong *et al.* 2020), including the lack of graptolites. The Langøyene Formation marks a transient small-scale depth increase in the depositional environment and is surmised to be coeval with the *Normalograptus extraordinarius* graptolite Zone. This conjecture is to some extent corroborated by chemostratigraphical correlation of the Hirnantian Isotopic Carbon Excursion (HICE), but it is difficult to ascertain what part of the curve correlates with the exact base of the Hirnantian (cf. Calner *et al.* 2021). In Scandinavia, $\delta^{13}C$ records have been published for Upper Ordovician sections in Skåne, Bornholm, Västergötland, the Siljan district, and the Oslo–Asker district (Schmitz and Bergström 2007; Bergström *et al.* 2014; Ebbestad *et al.* 2015; Hammarlund *et al.* 2019; Calner *et al.* 2021). In both Skåne and Bornholm, where the successions presumably are comparatively continuous, the onset of the $\delta^{13}C$ excursion is quite abrupt. The peak of the excursion slightly postdates the appearance of *Mucronaspis olini* in the Röstånga section (Bergström *et al.* 2014, fig. 2) whereas there are no biostratigraphic constraints on the $\delta^{13}C$ record from the Lindegård Formation on Bornholm. In other Scandinavian sections, the $\delta^{13}C$ values increase more gradually towards the peak of the HICE and then the problem arises how precisely the curve relates to the base of the Hirnantian. We note that $\delta^{13}C$ values are relatively high already in the uppermost metres of the pre-Hirnantian Boda Limestone mounds in the Siljan district (Ebbestad *et al.* 2015, fig. 9; see also Schmitz and Bergström 2007), suggesting that the lower boundary of the Hirnantian is located within the rising limb of the HICE rather than at the very onset. This is, for instance, relevant for chronostratigraphic correlation of the $\delta^{13}C$ curve published for the Oslo Region by Calner *et al.* (2021, fig. 19).

Amberg *et al.* (2017) recorded the chitinozoan species *Spinachitina* cf. *taugourdeaui* from the Skogerholmen Formation in the Oslo Region and this early occurrence is remarkable, as that species is characteristic of Porkuni strata in the East Baltic area, considered to represent the Hirnantian. A Hirnantian age of this low level in the Norwegian succession is not corroborated by the shelly fauna (e.g. Owen 1980*a*, 1981) or the $\delta^{13}C$ pattern (Amberg *et al.* 2017; Calner *et al.* 2021).

Zonation: In Skåne, the Tommarpian is subdivided into the *Mucronaspis olini* and *M. mucronata* trilobite zones (Kielan 1960), but it is unclear to which extent the distribution of these taxa reflects ecology/environment rather than temporal differences (see e.g. Temple 1952). Nilsson (1979) noted that *Dalmanitina* [now *Mucronaspis*] *mucronata* apparently occurs already in the *Staurocephalus clavifrons* Zone and should not serve as an index species for a zone. The occurrence in the Husbergøya Formation in the Oslo Region noted above confirms that representatives of the *Mucronaspis* group undoubtedly appear below the Tommarpian. This obviously introduces uncertainty regarding precise correlation between the trilobite-dominated offshore facies in Skåne–Bornholm and the shallower-water brachiopod-dominated facies in the Oslo Region. Nonetheless, for the time being we adhere to the traditional zonation (Fig. 3) as trilobites of the *Mucronaspis* group overall are widespread in the latest Ordovician of Baltoscandia and representatives are described also from Poland, UK, Czech Republic (Bohemia), Kazakhstan, eastern Russia (Siberia), South China and Canada (Laurentian Avalonia) (cf. Temple 1952; Kielan 1960; Owen 1982, 1986; Pärnaste 2009). However, the various taxa exhibit high morphological variability and the assignment to species and subspecies have repeatedly been discussed (cf. Troedsson 1918; Temple 1952; Kielan 1960; Ingham 1977; Owen 1981; Hints *et al.* 2012).

Upwards, graptolites representing the *Metabolograptus persculptus* Zone are introduced into the local succession in Skåne–Bornholm and the shelly fauna disappears (Koren' and Bjerreskov 1997; Koren' *et al.* 2003; Maletz *et al.* 2014). The *M. persculptus* graptolite Zone is known also from Jämtland (e.g. Dahlqvist 2004). No graptolites are reported from the lower part of the Tommarpian Regional Stage anywhere in Scandinavia.

The Tommarpian Stage spans the upper part of the long-ranging *Amorphognathus ordovicicus* conodont Zone as well as the *Ozarkodina hassi* Zone (Bergström 1971, 2007*a*; Bergström and Bergström 1996; Bergström *et al.* 2014). However, conodonts are generally scarce in the Tommarpian strata.

Two chitinozoan zones, the *Spinachitina taugourdeaui* Zone and the *Conichitina scabra* Zone, have been defined for the Porkuni interval in Estonia (e.g. Nõlvak 1999). In Goldman *et al.* (2020, fig. 20-2B), the upper part of the *B. gamachiana* Zone is also shown to range into Hirnantian levels in Baltoscandia, but this is not supported by published occurrence data from Baltica (see remarks by Nõlvak *et al.* 2006). Chitinozoans are uncommon and of low diversity in the Tommarpian strata investigated so far in Scandinavia (Grahn and Nõlvak 2010) and only the *Conichitina scabra* Zone has been documented present with certainty.

$\delta^{13}C$ chemostratigraphy has been widely used for regional as well as global correlation of the latest Ordovician, as the HICE is recognizable in many sections around the world including Baltoscandia. It is concluded above that the lower boundary of the Hirnantian Global Stage is closer to the peak of the isotope excursion than to the very onset.

Lithology: The sea-level was very low during the early part of the Tommarpian. Even Skåne–Bornholm, containing the deepest-water facies of this age known from Scandinavia, were characterized by deposition of non-graptolitic mudstone, the Lindegård Formation, low in TOC and with a shelly fauna dominated by brachiopods and trilobites (e.g. Kielan 1960; Nilsson 1979; Pålsson 1996). Rare intercalations of sand-mixed mudstone, in part conglomeratic, have been observed in this formation on Bornholm and in Skåne (Troedsson 1918, pp. 15, 26; ATN unpublished data on the Billegrav-2 core), attesting to the markedly low sea-level prevailing in the latest Ordovician. Upwards, the Lindegård Formation is abruptly overlain by black graptolitic shales originally considered Silurian and traditionally referred to as the 'Rastrites Shale'. These shales have more recently been assigned to the Kallholn Formation (Bergström and Bergström 1996), a name originally established for Silurian shales in the Siljan district (Törnquist 1874). It may be debated whether this is an appropriate name for the successions of Skåne–Bornholm, but for the time being it is retained (Fig. 5). The lower part of the Kallholn Formation in Skåne–Bornholm contains graptolites characteristic of the *Metabolograptus persculptus* Zone (e.g. Koren' and Bjerreskov 1997) and is, hence, of Ordovician age. The introduction of black graptolitic shale bears evidence of a fairly strong sea-level rise towards the end of the Tommarpian.

In the Siljan district, some confusion has prevailed concerning the age of the various lithological units; we here follow the terminology and correlations published by Suzuki *et al.* (2009), Ebbestad *et al.* (2015) and Kröger *et al.* (2015), see Figure 4. The Boda Limestone mounds are of Jerrestadian age as shown by the occurrence of *Holorhynchus giganteus* (see Jaanusson 1982*b*), which has been found even towards the top and in the flanks of the mounds; regarding the age of this brachiopod, see Rong and Harper (1988), Brenchley *et al.* (1997) and Rasmussen *et al.* (2010). It appears, however, that the so-called Upper Boda Member *sensu* Suzuki *et al.* (2009), renamed as the Osmundberget Formation by Kröger *et al.* (2016*a*, *b*), is of Tommarpian age. This unit, which is up to *c.* 14 m thick, was deposited on the flanks of the Boda mounds (Suzuki *et al.* 2009; Kröger *et al.* 2015) and consists of bedded limestone. Very rare *Mucronaspis mucronata* have been found in this limestone (Suzuki *et al.* 2009).

The Tommarpian intermound facies of the Siljan district is now assigned to the Loka Formation, which is only a couple of metres thick in this district (Ebbestad and Högström 2007). It is composed of calcareous sandstone or calcarenites with a limestone, previously called 'Klingkalk', at the base. The trilobite *M. mucronata* has also been found in the Loka Formation (Thorslund 1935; Temple 1952; Jaanusson 1982*b*). This unit is in turn overlain by mudstone, poor in macrofossils (but see Kröger *et al.* 2011), that is assigned to the Glisstjärn Formation and which is up to 13 m thick (Jaanusson 1982*b*; Ebbestad and Högström 2007). It was originally assumed to be of Silurian age but the conodont assemblage suggests a latest Ordovician age (Ebbestad and Högström 2007; Bergström 2007*a*; Bergström *et al.* 2012; Ebbestad *et al.* 2015). This is the youngest Ordovician unit in the area and it is unconformably overlain by Silurian shales assigned to the Kallholn Formation (Bergström *et al.* 2012). There is a considerable hiatus between the Ordovician and the Silurian in this district.

In Västergötland, the Tommarpian strata are also referred to the Loka Formation, which here is up to *c.* 3 m thick (see Bergström and Bergström 1996; Bergström *et al.* 2014). It is dominated by mudstones (e.g.

Wærn *et al.* 1948; Ahlberg *et al.* 2013*a*). The mudstone is interrupted in its middle part by a limestone unit, in places oolitic, crossbedded and conglomeratic (Stridsberg 1980), that contains relatively abundant corals and other fossils. The mudstones have yielded a typical *Hirnantia* brachiopod fauna that is diverse and well preserved (J. Bergström 1968). The lower part (*c.* 3.5 m on Mt Kinnekulle) of the overlying Kallholn Formation, comprising graptolitic shales, was also considered to be of Tommarpian age by Bergström *et al.* (2014).

The Loka Formation is also developed in Östergötland, where it is a little more than 2 m thick (Bergström and Bergström 1996). It contains a shelly fauna with taxa that are most similar to the Edgewood-Cathay fauna (cf. Rong *et al.* 2020), suggesting correlation with the upper part of the Tommarpian, but there seems to be a hiatus separating the Ordovician from the Silurian also in this district (cf. Bergström and Bergström 1996).

Tommarpian strata are not known from the Autochthon of Jämtland (Karis 1998). In the Lower Allochthon, the uppermost part of the Kogsta Siltstone contains faunal elements reminiscent of the *Hirnantia* fauna, including *Mucronaspis mucronata* (Karis 1998; Dahlqvist *et al.* 2010), but whether or not this interval represents the Jerrestadian or Tommarpian remains uncertain. The overlying sandstone-dominated Kyrkås Formation, which is 20–40 m thick, is of Tommarpian age, as demonstrated by the occurrence of, for example, the graptolite *Metabolograptus persculptus* (Karis 1998 and references therein; see also Dahlqvist *et al.* 2010). Westwards, the Ede Formation, also sandstone-dominated, replaces the Kyrkås Formation. It overlies the Kogsta Siltstone with a sharp boundary. The lower part, some 1.7 m thick, may be of Tommarpian age according to sequence stratigraphical interpretation (Dahlqvist and Calner 2004).

In the central part of the Oslo–Asker district in the Oslo Region, the Tommarpian strata are assigned to the sandstone-dominated Langøyene Formation, which is up to 60 m thick (Brenchley and Newall 1975; Owen *et al.* 1990). Five members were defined by Bockelie *et al.* (2017), see also Calner *et al.* (2021). According to Baarli (2014) and Bockelie *et al.* (2017), the lowermost part of the overlying Solvik Formation, consisting predominantly of nodular limestone with mudstone interbeds, is also of Tommarpian age.

Global correlation: The Scandinavian Tommarpian Regional Stage is equivalent to the Porkuni and lowermost part of the Juuru stages in the East Baltic scheme. We presume that the Tommarpian Regional Stage corresponds in extent to the Hirnantian Global Stage but there are no direct biostratigraphic ties with the graptolite-based lower boundary defined in Hubei, China. The graptolitic GSSP section is highly condensed (e.g. Chen *et al.* 2006) and not readily comparable with Scandinavian successions; correlation is based on $\delta^{13}C$ chemostratigraphy and assumptions about sea-level changes.

The Ordovician–Silurian boundary

No regional stage definitions have been introduced for the Silurian of Scandinavia and usually reference is made to the global stages (e.g. Bjerreskov 1975; Baarli 1995; Loydell *et al.* 2017), some of which are under revision (e.g. Rong *et al.* 2019; a recent update of progress is given by Štorch 2022). For a brief stratigraphic summary of the Silurian in western Baltica including Scandinavia, see Baarli *et al.* (2003). Traditionally the Ordovician–Silurian boundary was recognized at the base of the *Metabolograptus persculptus* Zone (e.g. Bjerreskov 1975; Nilsson 1979), where black graptolitic shales, currently assigned to the Kallholn Formation, reappear in southern Scandinavia (Skåne–Bornholm) associated with a marked sea-level rise. Nowadays the lower boundary of the Silurian is correlated with the base of the *Akidograptus ascensus* Zone with the GSSP defined at Dob's Linn, southern Scotland (see Melchin *et al.* 2020 and references therein). This zone is developed in the graptolite shale facies in Skåne–Bornholm (Koren' and Bjerreskov 1997; Koren' *et al.* 2003; Maletz *et al.* 2014; Loydell *et al.* 2017), although the horizon is occasionally assigned to the *Parakidograptus acuminatus* Zone (see summary in Loydell *et al.* 2017 for local details). Thus, there appears to have been continuous sedimentation across the Ordovician–Silurian boundary in Skåne–Bornholm and here the Ordovician–Silurian transition is closely comparable to that at the global stratotype section.

Across most of the foreland basin of the Oslo Region, the basal Silurian succession, assigned to the Sælabonn Formation, was deposited in shallower water than the Kallholn Formation of Skåne–Bornholm, and the Norwegian strata are characterized by a brachiopod-dominated shelly fauna (e.g. Baarli *et al.* 2003). In this area, the basal Silurian is usually absent and the Ordovician–Silurian boundary is represented by a hiatus, increasing in extent northwards (Baarli 1990). Graptolites are known from the lower part of the more shaly Solvik Formation deposited in the southeastern, deeper part of the foreland basin (Howe 1982). The latter author reported graptolites of early *P. acuminatus* or possibly late *M. persculptus* Zone age from Ormøya in the Oslo Fjord area near Oslo city centre, indicating the lower Silurian to be virtually complete without a hiatus. A basal Silurian conodont fauna, including *Ozarkodina oldhamensis,* has been reported from 8 m above the base of the Solvik Formation at Konglungen further west in the Oslo Fjord (Aldridge and Mohamed 1982; Worsley *et al.* 1983). For additional details on the Ordovician–Silurian boundary around the Oslo Fjord, see Calner *et al.* (2021).

In the western Lower Allochthon of Jämtland, the Ede Formation is overlain by the Berge Limestone (Karis 1998). The contact was described as gradual by Karis (1998). Based on a study of conodonts, Dahlqvist and Calner (2004) concluded that the Ede–Berge transition is of mid Aeronian age and that the Ordovician–Silurian boundary is located somewhere within the lower part of the Ede Formation or, less likely, in the upper part of the underlying Kogsta Shale. It is thus possible that the Ede Formation is of Silurian age in its entirety and that the unconformity at its base represents the Ordovician–Silurian boundary. If so, the correlation shown in Figure 4 should be adjusted. Further east, the Upper Ordovician Kyrkås Formation is bounded upwards by a major unconformity.

On Kinnekulle, Västergötland, the graptolitic Kallholn Formation rests unconformably on the Upper Ordovician Loka Formation according to Bergström *et al.* (2014). These authors inferred, based on comparison with the Röstånga-1 core in Skåne, that the unconformity represents parts of the *M. persculptus* Zone and that the basal interval of the Kallholn Formation on Kinnekulle is of latest Ordovician age with the Ordovician–Silurian boundary located a little more than 3 m above the base. However, neither *M. persculptus* nor *A. ascensus* have been recorded from the Kallholn Formation of the Kullatorp core (see Wærn 1948); *P. acuminatus* was registered at 6.27 m above its base (Wærn 1948). Thus, if Bergström *et al.* (2014) are correct, deposition in the area was seemingly continuous across the Ordovician–Silurian transition, following a short-lived depositional break in the latest Ordovician.

Elsewhere in Scandinavia, the Ordovician–Silurian boundary is associated with a rather extensive hiatus, as observed in Östergötland (e.g. Bergström *et al.* 2012), the Siljan district (e.g. Bergström *et al.* 2012 and references therein), the subsurface of Gotland (Grahn 1995), and the Autochthon and eastern Lower Allochthon of Jämtland (Karis 1998). The regional unconformity, developed at a time of eustatic sea-level rise in the early Silurian, is suggestive of widespread epeirogenic uplift, presumably in some way associated with the Caledonian Orogeny.

Conclusions

With few exceptions, neither the global stages nor the East Baltic regional stages introduced for the Ordovician can be recognized precisely in Scandinavia (for details, see discussion of the individual stages). In order to facilitate more accurate local correlation, a regional stage system is here proposed for the Ordovician of Scandinavia. This area, with many classical Ordovician sections, is located on the present-day western part of the Baltica palaeocontinent. Throughout the period, the entire region was, with few exceptions, continuously flooded by an epicontinental sea showing a general westwards deepening. However, associated with closure of the Iapetus Ocean, a foreland basin developed in westernmost Scandinavia from the Mid Ordovician onwards, leading to some uplift towards the western margin as well as significantly increased sedimentary supply from the west. Much of this foreland basin was subsequently telescoped into the Caledonian mountain chain. East of the foreland basin, the epicontinental sea was dominated by slow deposition of condensed carbonates. Graptolite shales, deposited in relatively deep water, are primarily known from southernmost Sweden (Skåne).

The stadial system proposed here comprises ten stages, in ascending order, the Slemmestadian (redefined and formalized), Ottenbyan (new), Billingenian (modified by reverting to the original definition), Volkhovian (unchanged), Kundan (unchanged), Segerstadian (new), Dalbyan (new), Moldåan (new), Jerrestadian (redefined) and Tommarpian (redefined). Although originally defined in Scandinavia, we propose to discontinue the use of the term Hunnebergian Regional Stage, notably because its lower boundary in general cannot be identified precisely in graptolitic facies. This interval is included in the new Ottenbyan Regional Stage, which is readily recognizable across all Scandinavian facies. It is also suggested to abandon the Balto-scandian regional series and subseries, as correlation with the global series now are sufficiently precise to make these higher rank regional units redundant. The global Lower–Middle Ordovician boundary can be recognized with great precision in the carbonate-dominated facies of Scandinavia and the East Baltic area. There appears, on the other hand, to be critical problems with the base for the Sandbian Stage (and, hence, the base of the Upper Ordovician), defined at Fågelsång, Skåne. The problems encountered affect the detailed correlation of this important boundary into the East Baltic area as well as across Scandinavia (see text for details). As currently defined (based on chitinozoans), the base of the East Baltic Kukruse Stage is located somewhat below the base of the Upper Ordovician Series whereas the base of the Scandinavian Dalbyan Stage (based on conodonts) is located above.

It is obviously not ideal to operate with two rather different regional stage schemes for the Ordovician in western Baltica, but it has proven impossible to apply most of the established East Baltic units to the

Scandinavian successions with sufficient precision. This condition reflects the reality that successions in Scandinavia were deposited in the deeper parts of the Ordovician epicontinental sea as well as in the Caledonian foreland basin and therefore are thicker, more variable in terms of facies, characterized by different faunas, and generally have fewer stratigraphic gaps. Future work may aim at establishing a combined regional stage classification operational throughout Scandinavia and the East Baltic area. In both areas, identification of the global stage boundaries, based mainly on graptolites, relies to some degree on non-biological criteria and secondary stratigraphic proxies except, generally, in the offshore shale facies of Scandinavia. In fact, the only global stage boundary that can be identified with confidence in the carbonate-dominated successions throughout western Baltica is the base of the Dapingian Global Stage (base of the Volkhovian Regional Stage).

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Author contributions **ATN**: conceptualization (lead), writing – original draft (lead), writing – review & editing (lead), visualization (lead); **PA**: writing – original draft (supporting), writing – review & editing (supporting); **JORE**: writing – review & editing (supporting); **ØH**: writing – review & editing (supporting); **DATH**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **AL**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting), visualization (supporting); **CMØR**: writing – review & editing (supporting), visualization (supporting); **SS**: writing – review & editing (supporting).

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