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Baltica from the late Precambrian to mid-Palaeozoic times: The gain and loss of a terrane's identity

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Abstract

The old terrane of Baltica occupies the mass of northern Europe eastwards to the Urals and lies mostly to the north of the Trans-European Suture Zone. The core, the East European Craton, is thick and formed of rocks dating back to well over 3 billion yr, and Protobaltica can be identified as forming part of the supercontinent of Rodinia at about 1 billion yr ago. Following Rodinia's break up at about 800 Ma, Protobaltica remained attached to Laurentia until it became the newly independent Baltica at between 570 and 550 Ma, with the inauguration of plate spreading to form the northern part of the Iapetus Ocean. To the south, during the Early Cambrian, Baltica was separated from Gondwana by the relatively narrow Ran Ocean. Baltica remained a separate terrane until its docking, firstly with Avalonia at the very end of the Ordovician (443 Ma), and then with Laurentia during the Silurian in the Scandian part of the Caledonide Orogeny. The terrane was much enlarged in the Vendian to include the areas such as Timan–Pechora now lying to the north as they became accreted to Baltica during the late Precambrian Timanide Orogeny. During the Cambrian and Ordovician, Baltica firstly rotated through more than 120° and then drifted northwards from high to low palaeolatitudes. New maps present Baltica's outline and progressive positioning, its late Precambrian and Lower Palaeozoic history, and the Cambrian, Ordovician and Silurian land, basins and biofacies belts within and around it. Some of the Lower Palaeozoic faunas are reviewed briefly: the oceans surrounding Baltica were so wide during the Early Ordovician that a substantial part of the benthic fauna of trilobites, brachiopods and other phyla were endemic. As those oceans narrowed, so the faunas of Baltica became progressively more similar to those of adjacent terranes. Some plankton distributions augment the palaeomagnetic data in latitudinal positioning.

Keywords: Baltica; Cambrian; Ordovician; Silurian; paleogeography; Avalonia; Iapetus Ocean

1. Introduction

All terranes have a finite geological life: they start either by division from an earlier entity or by accretion around a new oceanic island arc, and end by

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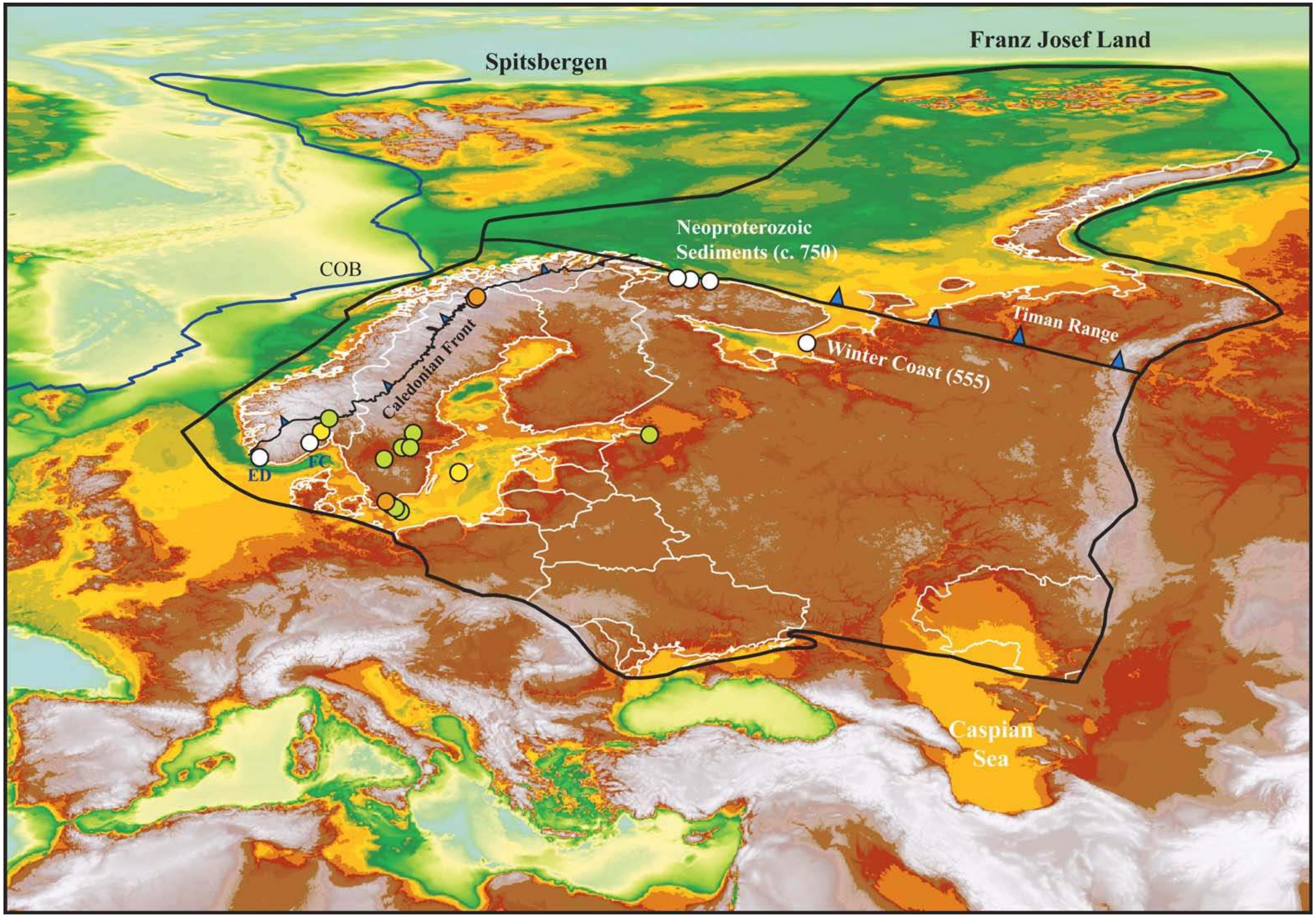

Fig. 1. Satellite bathymetry–topography map orthogonal projection of Smith and Sandwell (1997), superimposed on which are the margins of Baltica and the Timanide accretion boundary (thick black lines). The thin white lines within Baltica denote modern political boundaries. COB, early Tertiary continent–ocean boundary. Circles indicate selected sites of palaeomagnetic data: white—Precambrian; orange—Cambrian; green—Ordovician; yellow—Silurian. ED—Egersund dykes; FC—Fen Complex.

subduction to oblivion or accretion to another terrane. A famous terrane, aspects of which have been the subject of much investigation since the earliest days of geology, is that of Baltica. However, its integrity as a separate terrane has only been realised for about 30 yr, originally for Lower Palaeozoic time and subsequently for a considerable part of the latest Precambrian as well. The area identifiable as Baltica today is approximately 8 million km^2 in area on land, and occupies most of northern Europe as far east as the Ural Mountains and, in general, north of the Trans-European Suture Zone (TESZ) and its extension further eastwards to the Caspian Sea (Fig. 1). In addition, much of the floor of the North Atlantic and the Barents Sea probably also formed part of the terrane and it underplates some more of Europe well south of the TESZ. Although the isolation of Baltica as a separate terrane after more than a hundred million years of independence technically ended with its amalgamation with Avalonia at about Ordovician–Silurian boundary time (443 Ma), we extend our story to include an appreciation of those parts of the Caledonide (including the Scandian) Orogeny which dramatically affected Baltica in Silurian and earliest Devonian time, after which the former Baltica formed only the eastern part of the superterrane of Laurussia and subsequently Pangea, and today the northwestern part of Eurasia.

Much has been published on the many very varied aspects of Baltica's geology and geophysics in recent years (a simplified modern geology is shown in Fig. 2), and thus we feel that a review integrating key elements of this flood of fresh data with those known for many years is timely, and that is the chief purpose of this paper. In particular, no Baltica palaeogeographic maps showing land and shallower and deeper shelf areas, as well as its neighbouring island arcs, have been published since the Late Cambrian and Early Ordovician rotation of Baltica has been demonstrated: the chief implication flowing from that discovery is that the various margins of modern Baltica faced in hitherto unexpected directions in relation to the neighbouring terranes in the Lower Palaeozoic. That has profoundly affected our perspectives on the plate tectonic interrelationships of the area during Baltica's time as an independent terrane.

We firstly review the margins of the terrane and then present a geological history of the area which concentrates chiefly on Baltica's independent existence from the late Precambrian to the mid-Palaeozoic, as well as providing new palaeogeographical and facies maps for the Cambrian, Ordovician and Silurian.

2. The margins of Baltica

As with all old terranes, the margins of Baltica today consist entirely of sutures which represent tectonic activity which took place many eons after the terrane lost its independent identity. Thus the margins shown must be incorrect in that they were not the same in the Precambrian or Lower Palaeozoic, but nevertheless we choose to use them since they are objectively based on the rocks of those parts of the original Baltica which remain today. A specific example of distortion is the arcuate curve extending north of the Urals and parallel to Novaya Zemlya: that displacement was certainly caused by the tectonics associated with the eruption of the Siberian Trap flood basalts at the end of the Permian (Torsvik and Andersen, 2002). This is in contrast to the situation in the terrane centre, which in Baltica has been remarkably well-preserved and tectonically resilient due to the great thickness of Archaean and Proterozoic continental rocks making up the underlying craton, all of which makes the Lower Palaeozoic sediments relatively flat-lying over much of the area.

We have constructed new maps on today's coordinates, the first of which (Fig. 1) shows both modern topography and the edges of Baltica in detail. The plotted terrane boundaries supercede all others, such as those in Scotese and McKerrow (1990), Nikishin et al. (1996) and Cocks and Fortey (1998), and in our own previously published reconstructions (Cocks and Torsvik, 2002). The second map (Fig. 2) plots our new terrane margins on the modern GIS maps produced by Hearn et al. (2003), and that outline has been transferred to the GMAP system developed by Torsvik over many years (Torsvik and Smethurst, 1999), to form the base map for the creation of fresh palaeogeographical reconstructions and facies maps for the late Precambrian and Lower Palaeozoic presented later in this paper.

Baltica's margins will now be reviewed in turn, proceeding clockwise from the southwest.

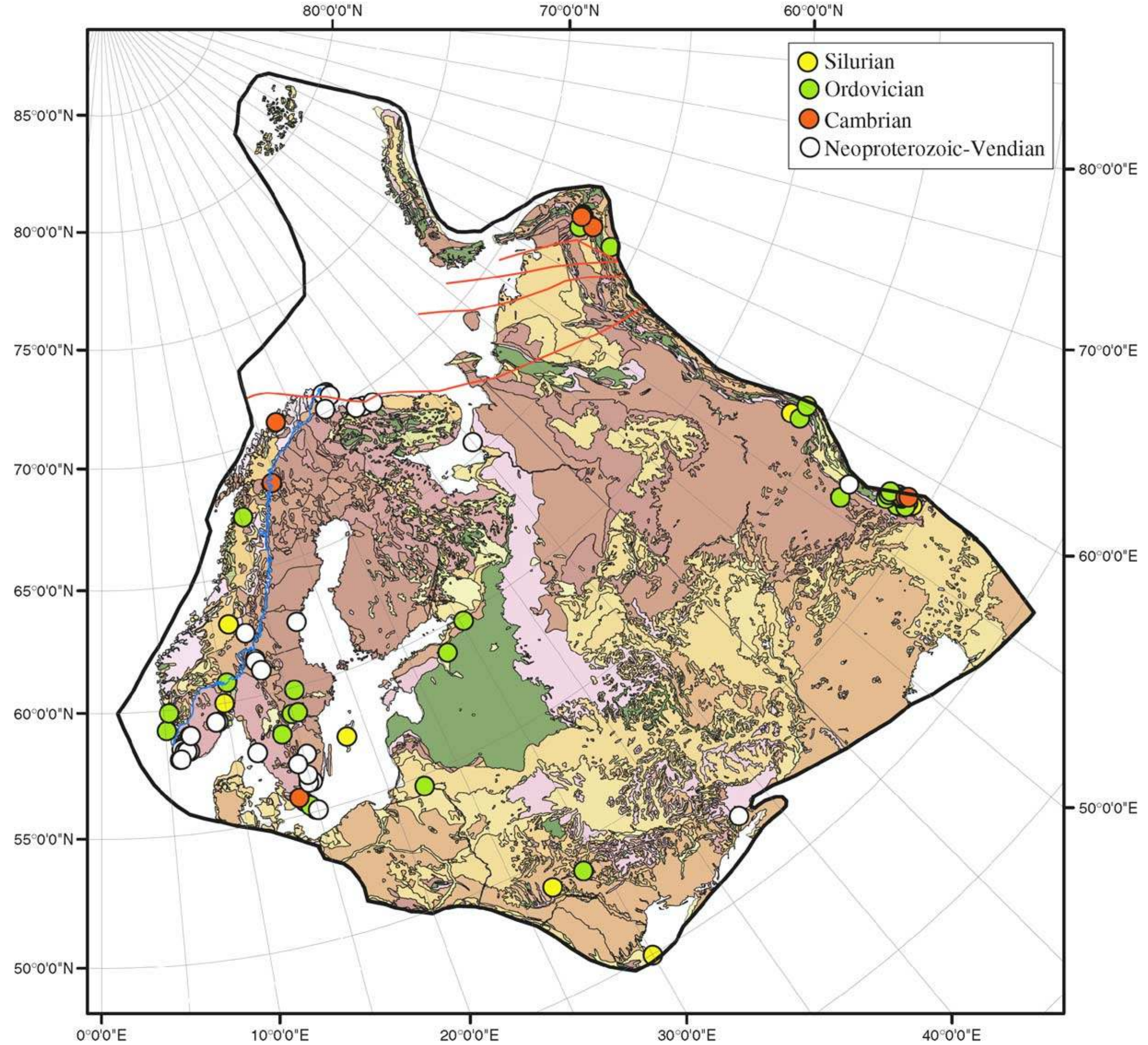

Fig. 2. Baltica, with today's geology simplified from Hearn et al. (2003). The red lines in the north of Baltica represent the various terranes accreted during the Timanide Orogeny. Coloured circles are selected sites of palaeomagnetic data.

The most southwesterly part of Baltica is marked by the triple junction between Laurentia to the west, Avalonia to the south and Baltica to the east. This is today under the North Sea, and is estimated to be at a point approximately 200 km east of Inverness, Scotland. Northeasterly from that point, and stretching all the way to the Arctic, the suture between Baltica and Laurentia can only be determined by unravelling the complexities of the Scandinavian Caledonides, whose deformations occurred in both the late Precambrian and the early Palaeozoic, culminating in the largely Silurian Scandian Orogeny. The situation is complicated by the progressive accretion around the northwestern margin of Baltica (see also under Ordovician below) of small terranes representing parts of island arcs and sometimes carrying distinctive faunas. These did not originate as integral parts of either Baltica or Laurentia, although their rocks now form parts of the Scandinavian Caledonides: they came from island arcs in the Iapetus Ocean. Many of these faunas were reviewed, and their continental affinities reassessed, by Fortey and Cocks (2003). For example, the highest nappes, termed the Uppermost Allochthon, which are best developed onshore in the Trondheim region of Norway, carry Lower Ordovician benthic faunas which have been known since the paper by Reed (1932) to have originated from or near the quite separate Lower Palaeozoic terrane of Laurentia, which was at some distance from Baltica (Cocks and Torsvik, 2002). These faunas, and others nearby in Norway today, which were originally near Laurentia or on island arcs originally in the Iapetus Ocean, have been reviewed by Bruton and Harper (1988), Harper et al. (1996) and Neuman et al. (1997). Table 1 summarizes the events affecting both Baltica and the allochthonous terranes which only became parts of Baltica in the Caledonide Orogeny.

In Figs. 1 and 2, we have included all the Scandinavian Caledonides within Baltica since it seems certain that the ancient pre-Caledonide cratonic crust of Baltica underlies the alien allochthons today. It seems probable that the lowest allochthons originated along (and relatively close to) the pre-Caledonide margins of Baltica, whilst parts of the Upper and all of the Uppermost Allochthon are exotic. In addition to the onshore outcrops of rocks deformed by the Scandian Orogeny, oceanographic and geophysical evidence show that the craton of Baltica extends offshore from Norway at varying distances into the North Sea: its margin is shown in Fig. 1 as COB, the continent–ocean boundary or transition zone defining the suture which was created when the North Atlantic Ocean opened in early Tertiary times at about 54 Ma.

Table 1
Differentiation of events affecting Baltica directly and those on rocks which reached Baltica after the listed event

Events on Baltica	(Ma)
Start of Rodinia break-up	c. 800
Timanian Orogeny end	c. 555
Completion of Iapetus Ocean opening	c. 560
Tornquist Ocean closure (Shelveian Orogeny)	c. 445
Iapetus Ocean closure (Scandian Orogeny)	c. 420
Pangea assembly	from 330
Events outside Baltica affecting Baltica elements	
Finnmarkian (Middle Allochthon)	c. 500
Trondheim ”Orogeny” (Uppermost Allochthon)	c. 485
Taconic Orogeny (Uppermost Allochthon)	c. 445

There is no evidence that any of the old Baltica underplates the eastern part of North America today: it seems more likely that the late Mesozoic and Tertiary rifting of the North Atlantic was initiated along lines of weakness which probably corresponded to the western margin of the ancient terrane of Lower Palaeozoic Baltica.

The position of the margin of Baltica extending from north of the COB to the west of Norway to Novaya Zemlya beneath the Barents Sea is contentious. As a reference point, it is very clear from the Early Ordovician faunas (Fortey, 1975; Cocks and Fortey, 1982; Smith, 2000) that most of the Spitsbergen Archipelago and Bear Island (Bjørnøya) were parts of Laurentia in the Lower Palaeozoic. However, a critical area within the Barents Sea is Franz Josef Land. The only borehole in that area which penetrates the relevant older rocks shows relatively undeformed Lower Carboniferous strata unconformably overlying tightly folded turbidites dated by non-terrane-diagnostic acritarchs to be of Vendian age and which also include 600 Ma detrital micas (D.G. Gee, personal communication, 2004). It has been postulated (e.g., Nikishin et al., 1996; Cocks and Fortey, 1998; Gee et al., 2000, Fig. 1) that Frans Josef Land and the island of Kvitøya to the east of Svalbard formed part of Baltica, but the evidence for that is not yet supported by either palaeomagnetic or faunal data; however, we have included the area within the Lower Palaeozoic Baltica Terrane as the most likely probability on the sparse data available. We assume that that area became accreted to Baltica at about the same time in others in the late Vendian as a part of the Timanide Orogeny. However, in contrast to the above, from seismic data in the Barents Sea, Breivik et al. (2002) have characterised a belt southeast of Franz Josef Land which they interpreted as representing “a possible Caledonide arm.” If that was true, then Franz Josef Land must have been on a separate terrane from Baltica in pre-Caledonide times, but which particular terrane is not clear.

The northwesterly margin of Baltica then extends from north of Franz Josef Land to just beyond the north of Novaya Zemlya (Fig. 1); the latter includes undoubted Lower Palaeozoic Baltic faunas. Although we show this northern part of the northeasterly margin as forming the edge of Baltica, note should be taken here of the evidence from the area stretching from northern Norway, through the northern end of the Kola Peninsula and southwards into the Timanian Mountains which form the western margin of the Pechora Basin of Russia. Siedlecka et al. (2004) have summarized the outcrops and Neoproterozoic history of that belt, which includes rocks representing the Timanide Orogeny, which we agree represents an important part of Baltica's history (see below).

It has been postulated by some authors (e.g., Nikishin et al., 1996) that Baltica might have extended even further eastwards than Novaya Zemlya to include part of the Taimyr Peninsula of northern Siberia. That supposition was tentatively supported following the description of a Late Ordovician Middle Ashgill brachiopod fauna from Taimyr by Cocks and Modzalevskaya (1997) which showed some affinities with contemporary Baltic faunas from Sweden, in particular those from the Boda Limestone. However, on further analysis of more terrane-diagnostic Early Ordovician trilobite faunas by Fortey and Cocks (2003) from southern Taimyr, it has become clear that central and southern Taimyr formed an integral part of the passive margin of Siberia rather than part of Baltica in the Lower Palaeozoic. Northern Taimyr and the Severnaya Zemlya Archipelago, as well as the crust underlying the neighbouring parts of the Arctic Ocean, together formed the independent Kara Terrane in the Lower Palaeozoic (Metoelkin et al., 2000).

From near the northern end of Novaya Zemlya, the margin of Baltica takes a sharp turn in a generally southwards direction to continue eventually into the Ural Mountains. As mentioned above, the northern part of that margin today has a substantial embayment which parallels the east coast of Novaya Zemlya and curves round into the northern Urals which was caused by part of the tectonics associated with the extrusion of the end-Permian flood basalts in Siberia (Torsvik and Andersen, 2002). All of Novaya Zemlya and Pai-Khoi (an island between Novaya Zemlya and the northern Urals) lay entirely within Baltica in the Lower Palaeozoic, as can be adduced from the characteristic endemic Baltic faunas which occur there; for example, the Lower Ordovician megistaspidine trilobites from Pai-Khoi described by Bursky (1970).

The Urals were formed by the collision of Laurussia and the Kazakh terranes in the mid- to late Palaeozoic, but within that series of Uralian tectonic melanges are preserved a variety of Lower Palaeozoic fragments. Zonenshain et al. (1990, Fig. 20) have mapped their relative distributions, and distinguished between those (largely in the western zones of the Urals) which consist of shallow-water sediments, and those (largely to the east) which consist of deeper-water off-shelf facies. However, the latter (although conjectured in Fig. 7) are not present in the northern and polar parts of the Urals and Novaya Zemlya (north of 65 °N), indicating that fewer of Baltica's original eastern fragments are preserved in that area. The position of the eastern margin of Baltica can be clearly constrained by the recognition to the east of it of the oldest known mid-ocean hydrothermal vent deposits and faunas, preserved today in the south-central Urals (Little et al., 1997).

Although it is clear that, in general, the Ural Mountains today form the eastern margin of ancient Baltica, the identification of the actual terrane boundary there is more complex. Zonenshain et al. (1990, Fig. 20) show that both shallow-water and offshore Ordovician rocks form parts of the Uralian melange, and it is certain that the apparently straight outcrop line of the Urals today was caused by much strike–slip movement during the tectonics involved in the Uralian Orogeny, which peaked in the Latest Carboniferous to earliest Permian (300 to 290 Ma). Thus the remnants of the eastern margin of the original Baltica have been compressed, fractured and distorted, indicating that in the Lower Palaeozoic, the area of the terrane extended further in an easterly direction, with Lower Palaeozoic island arcs offshore at an active margin. Scarrow et al. (2002), partly synthesizing the research of earlier workers, have divided the southern Urals into six zones, with (from west to east) the Pre-Uralian, Central Uralian, West Uralian, Tagil–Magnetogorsk, East Uralian and Trans-Uralian zones. The first two zones were always part of the craton of Lower Palaeozoic Baltica, but the remaining zones contain a complex mix of fragments of island arcs, igneous intrusions and continental crust: these are discussed below in the sections on geological history. On the modern maps (Figs. 1 and 2), we have placed the Baltica terrane margin just to the east of the easternmost continental deposits mapped by Zonenshain et al. (1990). At the southern end of the Urals, Lower Ordovician Baltic faunas confirm the extension of the terrane there, which continues further southwards as far as Kazakhstan, where there is a triple junction to the east of the northern part of the Caspian Sea between Baltica, the Mangyshlak Terrane and the complex series of amalgamated island arcs collectively termed the Altaids (Cocks, 2000, Fig. 6; Fortey and Cocks, 2003, Fig. 13). Near that triple junction, the Lower Palaeozoic rocks are very deeply buried within the Caspian depression.

From that triple junction to the east of the northern part of the Caspian Sea, the margin of Baltica swings westward through the northern part of the Black Sea to join its western coast in Romania. Some previous authors, for example Stampfli and Borel (2002), have considered the area of Moesia, in Bulgaria and Romania, as part of Baltica, but after analysis of the admittedly somewhat sparse Lower Palaeozoic faunal data presented by Yanev (2000), we concluded (Torsvik and Cocks, 2004) that Moesia can probably best be included within the Hellenic Terrane, which formed part of the extensive peri-Gondwanan collage in the Lower Palaeozoic. The definition and geological histories of the numerous and varied peri-Gondwanan terranes are outside the scope of this paper.

From Romania to the triple junction already mentioned under the North Sea, the southwestern margin of Baltica is intimately bound up with the Trans-European Suture Zone (TESZ), often termed the Tornquist–Teisseyre Lineament or the Thor Suture in the northwestern part. That zone has been the subject of extensive recent research, much of it summarized within the volume edited by Winchester et al. (2002). In general, the TESZ forms the suture between Baltica, on the one hand (to the northeast of the TESZ throughout its length, apart from in the Holy Cross Mountains; see below), and, on the other hand, Avalonia (in its northwestern part) and Gondwana (in its southeastern part). However, the structures within the TESZ were formed as part of the complex series of late Palaeozoic events termed the Variscan or Hercynian Orogeny, and which affected various parts of the southern margin of the pre-existing Baltica Terrane in different ways, and thus the Upper Palaeozoic TESZ does not represent the Lower Palaeozoic margin of Baltica along all its length.

A classic area for geology is the Holy Cross Mountains of southern Poland. There are two distinct blocks in the area, the Łysogóry Block to the north and the Małopolska Block to the south, and they are separated today by an east–west fault running through the Holy Cross Mountains. Most authors (reviewed in Cocks, 2002, p. 39) have concluded that the two blocks were essentially adjacent to each other in the Lower Paleozoic or even formed a single amalgamated block, and we agree with that conclusion. Although the Holy Cross Mountains lie to the south of the TESZ today, the Late Cambrian and Ordovician faunas from the area confirm without doubt the position of the Holy Cross Mountains as an integral part within Baltica rather than as part of peri-Gondwana, as claimed by some authors (e.g., Belka et al., 2002). These diagnostic Baltic faunas include Late Cambrian trilobites (Zylinska, 2001, 2002), Early Ordovician faunas including *Lycophoria* and other terrane-diagnostic brachiopods (Cocks, 2002), and Ordovician ostracods, as reviewed by Williams et al. (2003, p. 200). The presence of 1500 m thick late Silurian turbidites in the Łysogóry Block (Belka et al., 2002) indicates that the Holy Cross Mountains probably lay not far from the original margin of the old Baltica Terrane at that time. However, the Bruno–Silesian Block, which lies to the south of the Małopolska Block and east of Bohemia (which was a peri-Gondwanan terrane named Perunica), could have formed part of either peri-Gondwana or peri-Baltica: it contains no terrane-diagnostic Lower Palaeozoic faunas (Cocks, 2002, p. 43), but we do not show it as part of Baltica in the present paper.

Another area lying to the south of the TESZ which has also been in dispute as to its terrane affiliation is the island of Rügen, which lies in the Baltic Sea off north Germany. There the folded and obviously deep-water origin turbidites, although lacking in the more terrane-diagnostic benthic macrofossils, contain Lower and Middle Ordovician carbonate sedimentary particles which were thought to be more indicative of the warmer Baltica than the cooler and higher-latitude Gondwana–Avalonia (Cocks et al., 1997). However, following more detailed work on the micropalaeontology (e.g., by Servais and Fatka, 1997; Vecoli and Samuelsson, 2001), it is now thought more likely that those rocks represent sediments deposited in a deep-water sedimentary oceanic basin within the Ran and Tornquist Oceans, which lay between Baltica and Avalonia/Gondwana, rather than representing immediately marginal facies to Baltica itself. Bergström et al. (1988) have reviewed the Lower Palaeozoic basins near the TESZ in southern Scandinavia and concluded that there was a deepening trend from the shallower-water origin Cambrian and Ordovician basins outcropping in Bornholm and Scania, and also identified within offshore wells, to deeper-water deposits found in basins further south. Samuelsson et al. (2002) confirmed the timing of the progressive Avalonia–Baltica convergence across the TESZ by analysis of the chitinozoan biotas in northern Germany and Poland.

3. The palaeomagnetic record and Baltica's rotation in the Lower Palaeozoic

Late Precambrian and Palaeozoic palaeomagnetic data for Baltica were listed in Torsvik et al. (1996), Torsvik and Rehnström (2001) and Torsvik and Cocks (2005), and portrayed in Figs. 3 and 10 here. We considered all of these data (sites shown in Figs. 1 and 2) and made a selection upon which the reconstructions shown here are based. Largely between Middle Cambrian and Middle Ordovician times, the whole large terrane of Baltica underwent a very substantial rotation of about 120°, and the maximum rate of this rotation occurred in Late Cambrian and Early Ordovician times (Torsvik et al., 1990; Torsvik, 1998). However, that rotation is not directly reflected in the faunal distributions within Baltica, which appear to have been relatively uniform over the whole terrane for much of the period before the Silurian (Fortey and Cocks, 2003). When Baltica was reviewed by Cocks and Fortey (1998), the palaeomagnetic data were sparse for the terrane between the late Vendian and the Early Ordovician. Some doubts on the reality of the Baltica rotation were initially aired by some workers because of the lack of palaeomagnetic data for the critical Cambrian period. However, those doubts have now been dispelled through the additional work of Torsvik and Rehnström (2001) and Rehnström and Torsvik (2003) through which the Cambrian part of Baltica's APW is now well known, and the rotation confirmed.

However, not all authors have agreed with this analysis. Fig. 4 shows three alternative positions of Baltica in the late Vendian (560–550 Ma). A is the position favoured here, not least because it has kinematic continuity with the earlier maps at 750 Ma (Fig. 3) and the later maps of the Cambrian (Fig. 5; and see also Cocks and Torsvik, 2002, Fig. 3). B and C are the rather surprising and controversial positions for Baltica either in the Northern Hemisphere or at very low to intermediate latitudes in the Southern Hemisphere, both of which can be adduced from the data presented by Popov et al. (2002). Options A and C are also shown in Fig. 10 at the end of this paper. In the late Vendian, Gondwana stretched from the South Pole to north of the Equator (Australia and East Antarctica). Laurentia was initially at high latitudes during the Vendian but drifted towards the Equator in the latest Vendian or Cambrian. The timing of that transition from high to low latitudes is not yet precisely known, but we show Laurentia at low latitudes in our reconstructions. Option B for Baltica, the implication of the Popov et al. (2002) polarity choice, would leave Baltica essentially alone in the Northern Hemisphere and hence nothing could have collided with or rifted off the terrane. An implication of Option C is that the convergent Timanian margin of present-day northern Baltica would have faced the Iapetus Ocean at that time, which negates the subsequent terrane rotation now firmly established to have occurred in the Lower Palaeozoic. Thus Option C would dramatically (and implausibly) change our understanding of the Timanides and the history of the Iapetus Ocean. Option A is favoured by us, in which the Timanian/Baikalian, Avalonian and Cadomian arcs and terrane accretion may have been linked in a Pacific-type scenario after the breakup of Rodinia (Torsvik, 2003). A revised APW path and diagram showing Baltica's changing palaeolatitudes from about 1000 Ma to today is published in Torsvik and Cocks (2005).

4. Precambrian prelude

The East European Craton forms the core of Baltica today and within it are rocks among the oldest known. During the Precambrian, Baltica was made up of three terranes: Fennoscandia, Sarmatia and Volgo–Uralia. Fennoscandia may be divided into two, a northeastern Archaean domain, with rock dating from 3.5 to 2.7 Ga, and a southwestern Proterozoic zone, with rocks and orogenic belts dating from 2.5 to 1.7 Ga (Bogdanova et al., 2001). Soon after 1.9 Ga, Fennoscandia was accreted to the previously-combined Volgo–Uralia

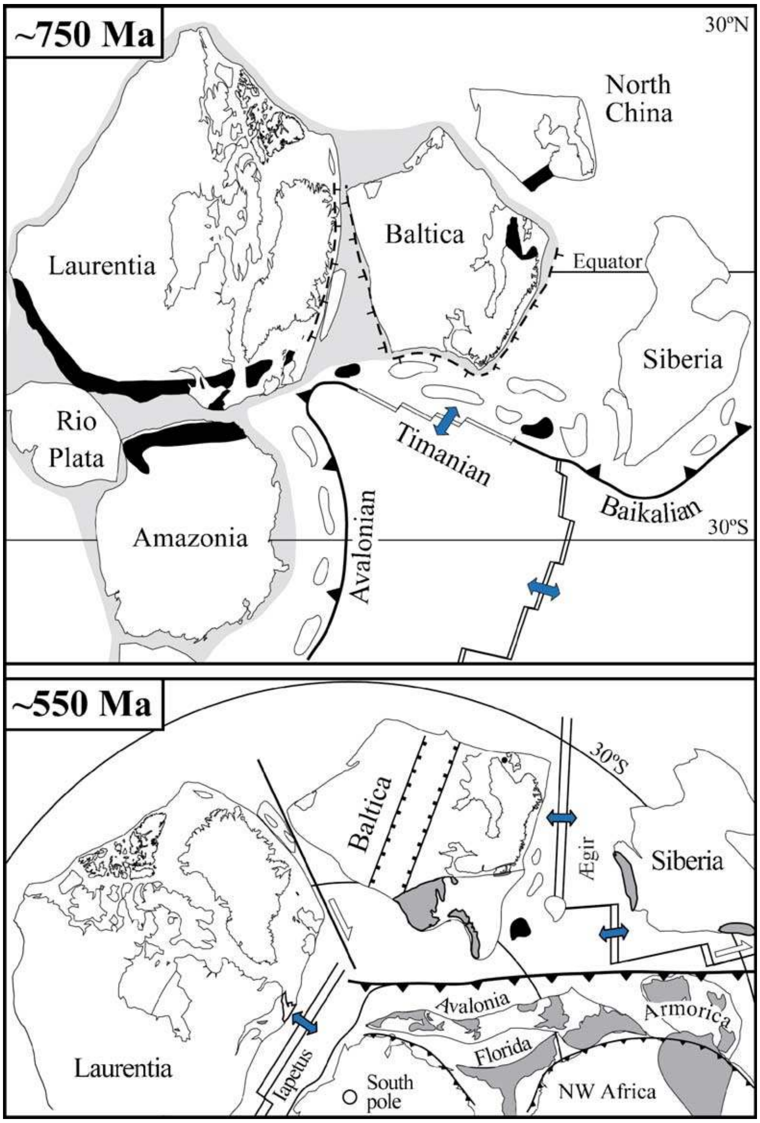

Fig. 3. The early postulated positions of Baltica in relationship to the surrounding terranes. Above, Mollweide Projection at about 750 Ma and shortly after the break up of Rodinia. Protobaltica was still attached to Laurentia, which was in turn attached to the South American terranes of Rio Plata and Amazonia at that time. The relative longitudinal positions of North China and Siberia are poorly constrained at that time, but are as shown by Torsvik (2003). The dispositions of the Avalonian, Timanian/Baikalian island arcs are modelled on the peri-Pacific system today. Black shaded areas are Grenvillian–Sveconorwegian–Kibaran mobile c 1Ga mobile belts. Below, Equal Area Polar Projection at about 550 Ma, modified from Hartz and Torsvik (2002), when the southern Iapetus Ocean was existent, but when a rift–trench–strike–slip regime was starting the inauguration of the northern Iapetus and leading to the independent existence of Baltica for the first time as it left Laurentia. Grey areas are Timanian–Baikalian–Avalonian–Cadomian–Pan–African mobile belts.

and Sarmatia, creating a Protobaltica Terrane. However, current thinking supports the existence of a subsequent supercontinent termed Rodinia in which Protobaltica formed a unit and which consolidated at perhaps 1100 to 1000 million yr ago and most probably disintegrated somewhere before 800 Ma (Meert and Torsvik, 2003). Within the Rodinian collage, the Baltica area was adjacent to, and probably welded to,

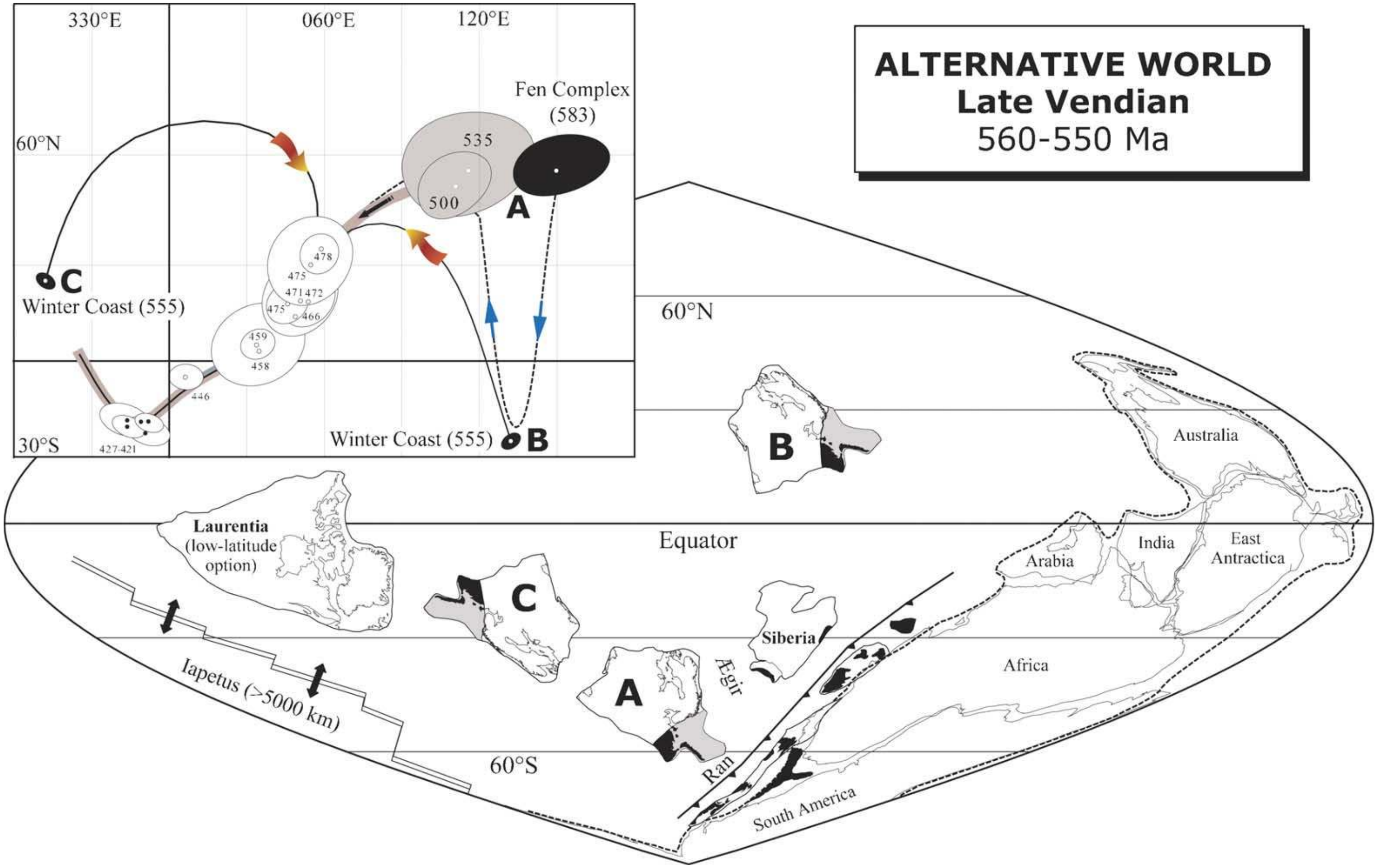

Fig. 4. Alternative positions for Baltica in a global context in the late Vendian (560 to 550 Ma). Black areas are the Cadomian and Timanide orogenic areas: the Barents Sea area is shaded. Part (A) is the 550 Ma position from Hartz and Torsvik (2002), based on interpolation between the 583 Ma Fen Complex (Fig. 1) and two Cambrian poles from Norway and Sweden (Torsvik and Rehnström, 2001); part (B) is the position in the Northern Hemisphere, based on data from the Winter Coast, White Sea, Arctic Russia (Popov et al., 2002; Fig. 1 here); part (C) is based on the same pole as part (B), but with inverted pole polarity in order to locate Baltica in the Southern Hemisphere: for further discussion see text. Laurentia, Baltica B and Baltica C are shown with unconstrained palaeolongitudes in this diagram. Inset: Vendian to Silurian palaeomagnetic poles from Scandinavia with dp/dm 95% confidence ovals (Torsvik and Rehnström, 2001), shown with the new palaeomagnetic pole from the Winter Coast. Black ovals are Vendian, shaded Cambrian, and unshaded Ordovician and Silurian. The four different APW paths are (A) from Torsvik and Rehnström (2001); (B) path of Popov et al. (2002); (C) as part (B) but with Winter Coast pole polarity inverted (parts [B] and [C] ignore Vendian and Cambrian data from Scandinavia). The fourth path (dotted and running from part [A] to part [B] and back again) uses the combined data from all three quoted papers and would imply either remarkable drift rates or two phases of True Polar Wander in the Late Vendian!

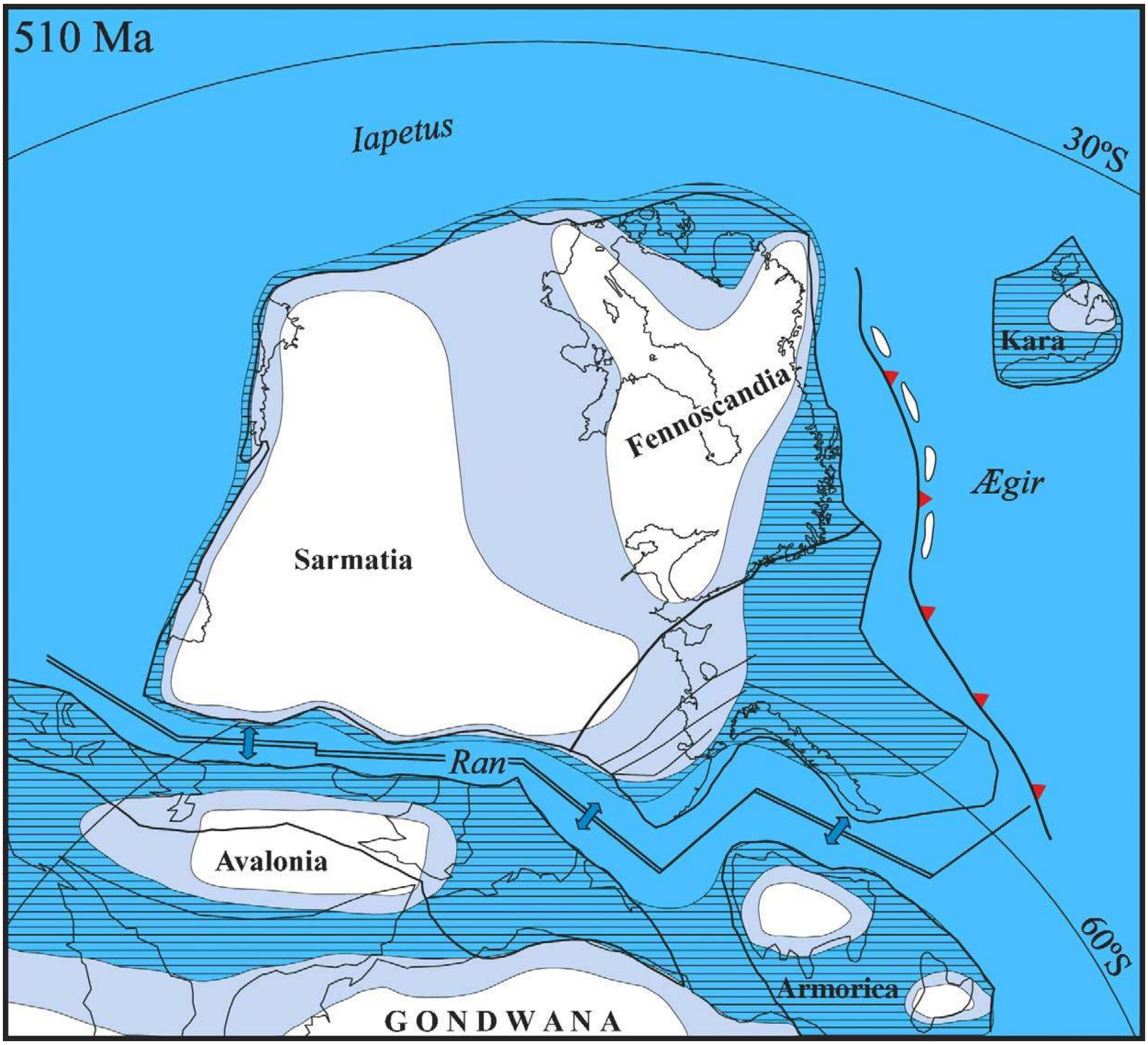

Fig. 5. Lower and Middle Cambrian (510 Ma) sediments and basin configuration across Baltica and adjacent terranes. The latter include the Kara Terrane and part of the superterrane of Gondwana, which included at that time the areas of Avalonia and Armorica, both of which later became terranes separate from Gondwana in the Early Ordovician and Early Devonian respectively. The Ran Ocean lay to the south of Baltica and includes an area of substantial strike–slip faulting. Land, shallow shelf, deeper shelf, and oceans are shown.

Laurentia, a terrane which included most of North America, Greenland, and the northern parts of the British Isles, with the modern eastern (Uralian) part of Protobaltica conjugate with the north of Laurentia. Laurentia was in turn attached to the South American terranes of Rio Plata and Amazonia, and possibly also West Africa. A reconstruction at about 750 Ma, shortly after the breakup of Rodinia (Torsvik, 2003, modified within Fig. 3 here), shows a spreading ocean between the combined Laurentia–Protobaltica and other terranes to the east, and Australia, East Antarctica and further entities to the west. Close by the part of Rodinia which included Laurentia–Protobaltica were Siberia, perhaps North China, and a series of ill-defined smaller terranes which are today partially represented in the Timanides of northern Eurasia. However, the constraints of that suggested configuration are not tight and the reconstruction shown can only be regarded as provisional. Also included diagrammatically are a number of terranes representing the many microcontinents and island arc fragments which were eventually incorporated within Palaeozoic mobile belts, such as Avalonia, the Timanides and the Baikalides. Although the term "Baikalian Orogeny" has sometimes been applied to events within Baltica, it is now clear that the use of the term should be confined only to Siberia in the late Proterozoic.

5. Birth and early history of the terrane

Baltica became an independent terrane when it split off from Laurentia, leaving a widening Iapetus Ocean between the two. When this rifting actually commenced is a matter of some uncertainty; however, the southern part of the Iapetus, between Laurentia and South America, appeared to have opened first soon after 580 Ma (Hartz and Torsvik, 2002), and the rifting migrated gradually northwards until Baltica finally separated from Laurentia somewhen between 570 and 550 Ma, relatively near the end of Precambrian time. Our diagram (Fig. 3, lower) shows the postulated tectonic situation at the time when the northern Iapetus Ocean was just opening between Baltica and Laurentia.

During the mid- and late Vendian at about 560 to 550 Ma (Fig. 3), today's northern part of the northwestern margin of Baltica changed from an extensional tectonic regime to an active margin. These changes caused what is termed the Timanide (or Timanian) Orogeny in that area, whose outcrops and tectonics have been reviewed by Siedlecka et al. (2004). This was a period of active accretion in which various microcontinental blocks in the Timan–Pechora, northern Ural and Novaya Zemlya areas were united with Baltica to form a much expanded terrane area in Lower Palaeozoic times. The boundaries of these accreted blocks are shown in Figs. 2 and 5. Scarrow et al. (2001) have documented an island arc active at about 670 Ma in the northern Urals: however, the analysis of all the Timanide units accreted to today's north of Baltica is far from final.

In the northern part of the terrane, there is substantial sedimentological evidence, reviewed by Nikishin et al. (1996), for an early Vendian glacial interval: those data tie in well with the high palaeolatitudes for Baltica revealed by the palaeomagnetic studies.

6. Cambrian

In general, the Cambrian sediments of Baltoscandia lie unconformably upon the metamorphosed Precambrian and thus represent a transgression, which had started in the late Vendian, onto the more or less peneplained Precambrian basement of the Baltic Shield (Martinsson, 1974). Judging by the thinness of the Middle Cambrian of Norway, Sweden and the East Baltic, and the extensive lateral extent of many of the facies, as well as the general lack of coarse clastic rocks, it may be inferred that the centre of the terrane was relatively low in topography, and hence sediment supply, for most of the period. Much of the craton of Baltica appears to have been submerged under shelf seas for long parts of the Cambrian, which lasted from 544 to 490 Ma. It has been concluded by some authors that this formed part of a global trend towards steadily rising eustatic sea levels as the Cambrian progressed. As a consequence, the olenid trilobite fauna, whose representatives occur so abundantly in Sweden and elsewhere, represent a fauna living largely in niches which were probably relatively deep on the shelf and in which the aeration was below normal. The same animals are also found in comparable conditions in other terranes, such as Laurentia and Siberia. In contrast to the high sea level stand found postulated in much of the literature, Artyushkov et al. (2000) analysed the Cambrian sea level changes in great detail in Estonia and the St Petersburg area of Russia, which lay close to the land area of Fennoscandia (Fig. 5). They concluded that the sea level changes were predominantly cause by tectonic factors (which resulted in changes of up to 150 m in some parts of the area) rather than by eustatic variations (which they interpret as both relatively infrequent and in being responsible for no more than 10 m of sea level change at the most). However, there are no known tectonic events which might have caused these sea level changes, and a wider survey is needed.

It may just be that the unusual distributions of the olenid faunas were more due to global low seawater oxygenation, rather than that the trilobites lived at any great water depths over the majority of the craton of Baltica. It is also relevant that Baltica was in greater proximity to nearby terranes across the relatively narrow Ran Ocean (Fig. 5) during this period by comparison with the much wider oceanic separations in the Early Ordovician (which was represented by far greater endemicity of the benthic shelly fauna: see below), and thus the Cambrian distribution of the larvae of the olenids would have been facilitated.

It is notable too that the very limited distribution and occurrences of Cambrian articulated brachiopods can be explained by the relative isolation of Baltica as well as its relatively high palaeolatitude. Only *Oligomys* from the Middle Cambrian and *Orusia* from the Upper Cambrian are known from the very well-collected sections of Sweden, and in Novaya Zemlya only *Diraphora* from the uppermost Middle Cambrian and *Billingsella*, *Ocnerorthis* and *Huenellina* from the Upper Cambrian are recorded. There are no substantiated reports at all of articulated brachiopods from the equally well-known St Petersburg and Estonian localities until the rocks of Arenig age, despite the two centuries of work in those areas. That lack of brachiopods may be due to the lack of original suitable ecological niches in the available biofacies; however, it could in fact have been due to the post-mortem diagenetic destruction of calcitic-shelled faunas by the acidic fluids present within the Alum Shales (Schovsbo, 2001).

The Early and Middle Cambrian sedimentary basins of Baltica are shown on our map (Fig. 5), which portrays the Middle Cambrian at about 510 Ma. The land/shallow-shelf/deeper shelf facies belt boundaries follow Bruton and Harper (2000) for the western part of southern Norway and Sweden: the shallow-water facies include conglomerates and glauconitic sandstones off shore of which the Andrarum Limestone can be traced in an arcuate belt from Ritland in the west coast of Norway, northeastwards to Valdres (within the Lower Allochthon of the Scandinavian Caledonides, which, despite its name, consists there of materials derived only from Baltica) and Billingen and curving southwards through Mjøsa, Bohus and Scania to Bornholm. The deeper shelf facies to the southeast of that belt consists mainly of the famous Alum Shales. The trilobites and brachiopods of the Andrarum Limestone are relatively cosmopolitan (Bruton and Harper, 2000): some of the same genera are found as far away as Australia. This confirms the hypothesis that some of the neighbouring oceans to Baltica were not nearly as wide as they subsequently became at about Cambrian/Ordovician boundary time. In the Uralian sector, we incorporate some of the land/shallow sea/ocean floor data presented by Zonenshain et al. (1990, Fig. 36). Their diagram shows substantial Late Cambrian thrusting and folding offshore of the Urals which they state was caused by the collision of the Baltic margin with “island arcs and some microcontinents.” The latter statement is supported by the sub-Ordovician angular unconformities overlying Lower Cambrian rocks, but the detailed ages and scope of these orogenic events remain somewhat obscure. In particular, previous authors have not been aware that, due to the substantial rotation, the terrane which lay opposite the Uralian margin of Baltica during this time was the supercontinent of Gondwana, rather than any part of the complex collage which makes up the Altaids of Central Asia today described by Sengor and Natalin (1996).

For the centre of the terrane, we incorporate some of the data of Nikishin et al. (1996), particularly in the limits of the two major land areas overlying the Fennoscandian Shield and the Sarmatian Shield, which we term Fennoscandia and Sarmatia respectively. However, there seems little evidence of high relief on the Baltica craton during the Ordovician and Silurian, otherwise far greater sediments thickness would be expected there than we see today.

In contrast to the relatively stable conditions within the centre of the Baltica Terrane during most of the early Palaeozoic, at all of its margins there was often violent tectonic activity at one time or another during the same long period. That means that in the new palaeogeographical maps presented here (Figs. 5–9), there are some areas of both shallow and deep shelf seas shown which are outside the present margins of Baltica (Figs. 1 and 2), and apparently even overlying ocean floors if our diagrams are strictly interpreted. However, the Lower Palaeozoic crust which must have in reality supported those shelf areas has obviously been lost due to subsequent subduction, or possibly in some cases displaced laterally to other areas which we have not been able to identify and restore to their original positions. For example, in the northwest of Baltica today, there were substantial Late Cambrian orogenic events, termed the Finnmarkian Orogeny and reviewed by Andreasson (1994), which peaked from 505 to 500 Ma. These must have been associated with subduction within the Ægir Ocean, and we show some schematic islands in what was probably an island arc on our 510 Ma map (Fig. 5).

Neighbouring terranes to Baltica at that time chiefly consisted of the immense supercontinent of Gondwana to the south. As far as can be determined, what subsequently became the independent terrane of Avalonia had not yet become detached from the main Gondwana Terrane. When that detachment occurred is poorly constrained, although for many years (e.g., Cocks and Fortey, 1982) we have postulated an Early Ordovician detachment age as the most probable: the faunal evidence to support that age, which still seems the most likely, is reviewed in detail by Fortey and Cocks (2003). To the east of Avalonia, along the North African part of the Gondwanan margin, there lay the Armorican Terrane Assemblage (more simply termed Armorica in this paper, although not a single united terrane), whose tectonically complex and varied parts make up most of France and the Iberian Peninsula today. Despite earlier reconstructions to the contrary (e.g., Cocks, 2000), Armorica did not become detached from the main part of the Gondwana Terrane until the Early Devonian: these matters are further discussed in Torsvik and Cocks (2004). Because of Baltica's rotation, which gathered pace in Cambrian times, there must have been progressive and substantial strike–slip movement in the Ran Ocean between Baltica and Gondwana. The Ran initially developed as an arm of the Precambrian Iapetus Ocean (Hartz and Torsvik, 2002). In our later reconstructions (Figs. 7–9), the Ran is shown as united with the Rheic Ocean, but the latter name cannot be used prior to the Early Ordovician, since the Rheic only came into existence after Avalonia left Gondwana, leaving a spreading centre and a widening Rheic Ocean between the two.

More contentious are the contemporary placings of the Kara Terrane (which includes the northern Taimyr Peninsula and Severnaya Zemlya in Arctic Russia today), and the existence or otherwise of island arcs in one or more of the oceans surrounding Baltica. We show Kara in the same general position in Fig. 5 as in the slightly later 500 Ma reconstruction of Cocks and Torsvik (2002, Fig. 3): there are some palaeomagnetic data to support its latitudinal positioning (Metoelkin et al., 2000). The Late Cambrian trilobite and brachiopod faunas described from Severnaya Zemlya by Rushton et al. (2002) have some faunal connections with both Baltica and Siberia, but there are also a proportion of endemic genera and species there, particularly among the brachiopods, which together indicate a fair degree of oceanic separation between Kara and its neighbours. As for island arcs, we postulate the existence of an arc offshore of the Norwegian margin of Baltica, in the Ægir Ocean between Baltica and Siberia. Siberia lay off our map at some distance to the northeast.

7. Lower Ordovician

Upon the main Precambrian craton, a large number of extensive Ordovician sequences are preserved, particularly within the Oslo Region, Norway, southern Sweden and the East Baltic, extending northeastwards to the St Petersburg area of Russia (Dronov and Holmer, 1999). Most are relatively untectonised and unmetamorphosed, apart from the important and extensive sequences in the Oslo Region, which was much affected by the later graben development and associated intrusions of Late Carboniferous and Permian age. Palaeoenvironmental subdivisions within the Ordovician successions have been distinguished and shown on maps as "Confacies Belts" by Jaanusson and other authors (e.g., Jaanusson, 1982). In the north of Baltica there are also extensive shelf deposits in Timan–Pechora, Pai-Khoi and Novaya Zemlya, today in Arctic Russia. In the Urals, outcrops and data are sporadic and sometimes difficult to interpret; however, we include much of the data presented by Zonenshain et al. (1990) and Nikishin et al. (1996). We present three successive palaeogeographical maps (Figs. 6–8) of Baltica for Ordovician times. The first is a Lower to early Middle Ordovician (480 Ma) summary of the basins and shelf sediments (Fig. 6).

Baltica travelled steadily northwards towards the palaeoequator throughout the Ordovician, and it is noticeable that the relatively thin-bedded Early Ordovician limestones in the East Baltic area are of cooler water origin (Jaanusson, 1973). The only carbonate mud mounds known from the terrane at this time are those in the St Petersburg area of Russia described by Federov (2003). Those mud mounds built up around accumulations of siliceous sponges, and, again, such structures can be shown to have formed only in cool-water environments.

The Iapetus Ocean was at its widest at about Cambro-Ordovician boundary times (490 Ma), and

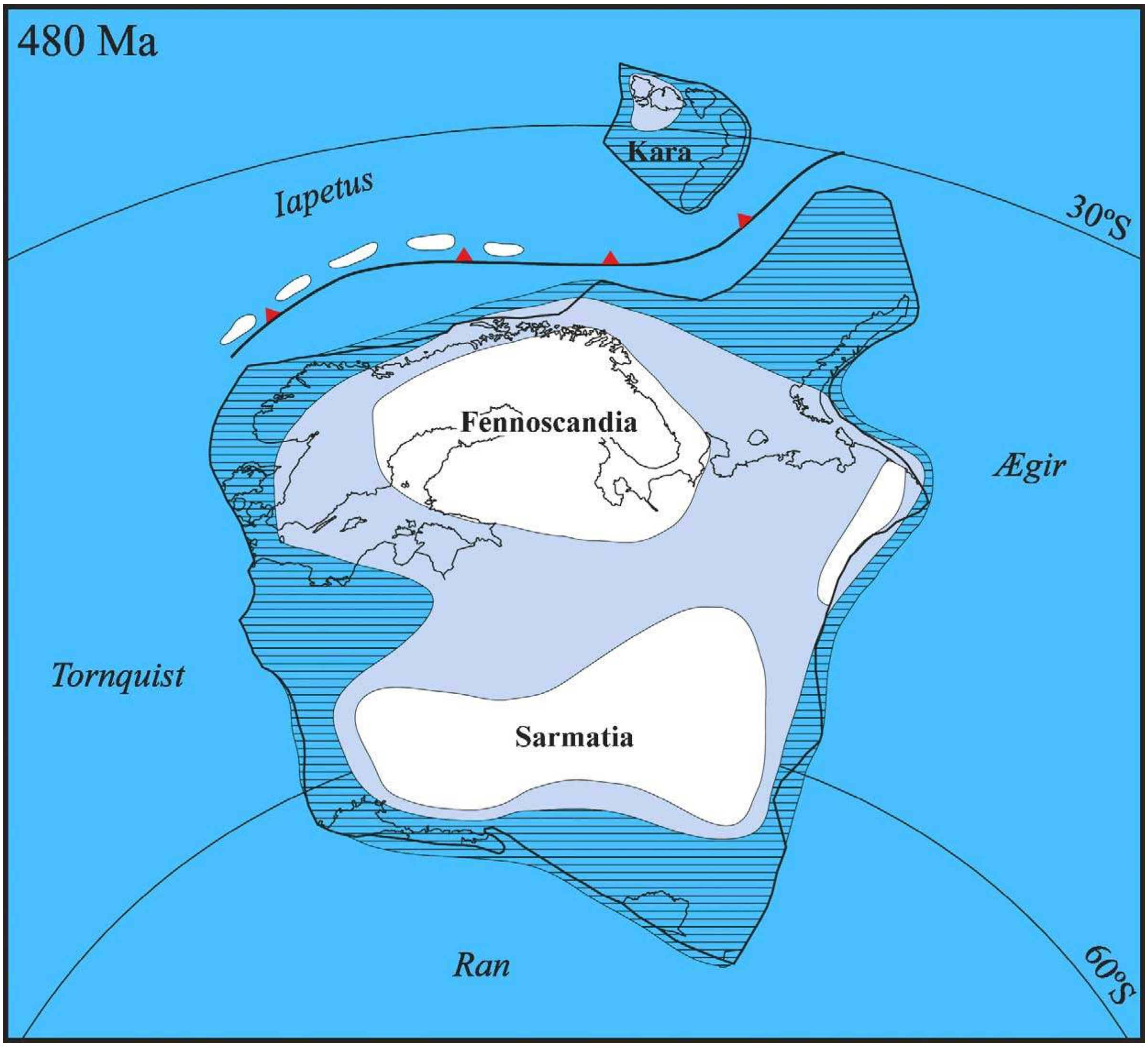

Fig. 6. Early mid-Ordovician (early Arenig, 480 Ma) palaeogeography of Baltica and the adjacent Kara Terrane. The overall palaeolatitude of Baltica had remained more or less the same since the mid-Cambrian (Fig. 5), but the rotation of Baltica had been very substantial during that same 30 Ma interval. Note that, apart from Kara, there were no other nearby terranes, which was the reason for the extensive evolution of endemic benthic faunas in that period. The Iapetus Ocean reached its maximum width at about that time, and the Ran Ocean too had widened considerably since the Cambrian.

the Ran Ocean too can be shown to have widened significantly by the Early Ordovician by comparison with the Cambrian, and thus Baltica was at its most isolated. The benthic invertebrate faunas of the shelf seas therefore underwent independent evolution, and the most abundant macrofauna, the trilobites and the brachiopods, were represented in Baltica not just by different species and genera but even families which were endemic to that terrane. Those faunas have been reviewed for all of the Ordovician and Silurian by Cocks and Fortey (1982) and Fortey and Cocks (2003). Prime examples of this endemicity are the trilobite subfamily Megistaspidinae and the brachiopod family Lycophoriidae, whose representatives occur in almost rock-forming abundance in the Arenig of Estonia and northwest Russia but also abundantly in Norway, Sweden, and the Holy Cross Mountains of Poland (Cocks, 2002): the Megistaspidinae and Lycophoriidae are quite unknown from outside Baltica. The occurrence and immigration of the rhynchonelliform articulated brachiopods in the East Baltic have been well summarized by Hints and Harper (2003): the early Arenig (Billingenian) assemblages include the endemic family Gonambonitidae as well as the Lycophoriidae, the distinctive and often abundant genera *Antigonambonites* and *Porambonites*, and the earliest clitambonitids, plectambonitoids and endopunctate orthoides such as *Angusticardinia* and *Paurorthis* (Popov et al., in press). Thus it can be safely inferred that both the Iapetus Ocean and also Tornquist's Ocean, which lay between Baltica and Gondwana, were wide enough in the Early Ordovician to prevent the successful passage and ecological integration of larvae for a substantial proportion of the benthos. However, as the Ordovician progressed, the surrounding oceans to the south and west of Baltica became steadily narrower, with the result that many faunal elements new to Baltica, and with ancestors in neighbouring terranes, successively established themselves in our area for the first time.

There is no evidence of any oceanic islands which subsequently amalgamated with Baltica along its southern margins (TESZ and eastwards), but on its western margin, and originally within the Iapetus Ocean, there are a series of suspect terranes, some within the Scandinavian Caledonides, which carry Ordovician faunas, chiefly of brachiopods. These have been described in a series of papers, principally by R.B. Neuman, and summarized by Neuman and Harper (1992) and Harper et al. (1996), and most of them show little affinity with contemporary Ordovician faunas from Baltica. One such Early–Middle Ordovician (Arenig–Llanvirn) age fauna is that from the Hølonda area, Trondheim, Norway (Neuman and Bruton, 1989), in which 8 out of 13 (62%) brachiopod genera and 12 out of 13 (92%) trilobite genera also occur in Laurentia and the remainder are endemic to Hølonda. Thus the Hølonda fauna almost certainly lived on the shelf of an island within an arc in the Iapetus Ocean near Laurentia and within good faunal contact with the latter. It is worth reiterating that, in the Early Ordovician (Cocks and Torsvik, 2002), today's northwestern margin of Baltica faced northwards towards the northern Iapetus Ocean and on into the vast Panthalassic Ocean (Fig. 6); but that the Hølonda area and others were emplaced onto Baltica in the Silurian only after the whole terrane had rotated by about 90°, so that its northwestern Baltica margin by then faced Laurentia. Thus the Hølonda fauna, and others transported eastwards by nappes of Silurian age onto the Baltic craton, represent faunas which originally lived a great distance away from the autochthonous Ordovician faunas of the Baltica Terrane. Those autochthonous faunas are often today to be found in outcrops not far away from other outcrops containing the faunas transported within the nappes.

Our Fig. 6 shows a series of islands, representing an island arc, in the Iapetus Ocean to the then north (today's west) of Baltica. That arc was probably responsible for the increase in rare earth elements found in the organophosphatic shells of inarticulated brachiopods and conodonts of Arenig age in the East Baltic, when compared with their Cambrian predecessors (Felitsyn et al., 1998).

8. Upper Ordovician

High-precision palaeomagnetic data firmly indicate that Baltica was situated at relatively low latitudes by the end of the Ordovician; these low latitudes are further attested by the absence of glaciogenic sediments during the latest Ordovician global glacial interval. The *Hirnantia* brachiopod Fauna reviewed by Rong and Harper (1988) is well known from the Hirnantian of the Holy Cross Mountains of Poland (Temple, 1965), the Oslo Region (Cocks, 1982), which is also known to have extended beneath the sea within the Skagerak Sea (Smelror et al., 1997), and elsewhere upon Baltica. However, the presence of that fauna does not necessarily imply cooler (or periglacial) waters, but rather reflects the greater depths that could briefly support benthic faunas due to the increased oxygenation within the global oceans.

As Baltica's palaeolatitudes steadily decreased with time, so the abundance and diversity of the successive benthic faunas increased proportionately as the average temperatures increased. However, there were marked climatic fluctuations; for example, Ebbestad and Högström (1999) present a summary of the latest Caradoc and early Ashgill facies over most of Baltoscandia in which late Caradoc limestones (the

Solvang Limestone and equivalents) are followed on the shallower shelves by early Ashgill graptolite shales (the Fjäcka Shale and equivalents), which were in turn followed by the Middle Ashgill carbonate mud mounds such as the Boda Limestone discussed below. Podhalanska (1999) has documented the deeper-water shelf facies to the south and east, which include many records from the boreholes of Poland.

The separate terrane of Avalonia, which included the area now forming part of the Maritime Provinces of Canada, Newfoundland, southeastern Ireland, southern Britain, and a substantial area of Europe surrounding Belgium (Cocks et al., 1997), left Gondwana in the Early Ordovician. From that rifting followed the progressive narrowing and eventual elimination of the western part of Tornquist's Ocean, which separated Avalonia from Baltica for most of the Ordovician. There was a soft oblique docking between Baltica and Avalonia at about Ordovician–Silurian boundary time of 443 Ma (Torsvik and Rehnström, 2003). There is published disagreement concerning the direction of the subduction following this docking; for example, Poprawa et al. (1999, their Fig. 8) show Baltica overriding Avalonia with subduction to the north. However, there is no doubt from the geological and geophysical evidence, summarized by Torsvik and Rehnström (2003), that the converse is true, with a substantial slab of Baltica today lying underneath Avalonia to the south of the TESZ, following the subduction of part of Baltica southwards. What is certain is that the centre of Baltica was little affected by the Avalonia–Baltica collision; for example, Dahlqvist and Calner (2004) have reviewed the uppermost Ordovician and lower Silurian in central Sweden (Jämtland), and concluded that the only changes in sedimentary regime there were the regression and subsequent transgression representing the global Hirnantian Ordovician–Silurian boundary glacioeustatic event. That sedimentological evidence is corroborated by the faunal studies of the Hirnantian rocks in the Oslo Region, Norway, from which Brenchley and Cocks (1982) described a regressive sequence of brachiopod-dominated benthic communities from deep shelf to subtidal: these were soon followed by rocks representing a transgressive deepening in the earliest Silurian.

In the mid-Caradoc, when Avalonia was nearing Baltica, there was an immense Plineian Andean-type eruption in or near northeast England, and the consequent bentonite, known as the Kinnekulle Bentonite, was deposited over much of western Baltica, with a thickness dwindling from a maximum of over 2 m in the southwest, for example at Kinnekulle Mountain in southern Sweden, to insignificance in the St Petersburg area of Russia (Bergström et al., 1995; Torsvik and Rehnström, 2003). Some authors have postulated that the equally substantial Milbrigg K-bentonite of eastern North America originated from the same explosion, but, following more exact dating, the two large bentonites are now known to be over 2 million yr different in age.

Williams et al. (2003) have presented a fascinating and authoritative overview of ostracod migration patterns between the North Atlantic terranes over the whole of Ordovician time. They have identified and documented which ostracod genera migrated rapidly and which more slowly, and it is clear that both the dispersal rates and the potential for migration varied greatly between individual families and genera. Baltica, probably partly because of its changing palaeolatitudes, had the highest diversity of ostracods in any of the terranes which they reviewed. Prior to the Llanvirn there were few migrations to and from Baltica, but from late Llanvirn times (464 Ma) onwards, a steady stream of ostracods migrated from and between Baltica, Laurentia and Avalonia and even some Gondwanan and peri-Gondwanan areas such as Armorica and Perunica (Bohemia). There were peaks in migration in the late Llanvirn, Caradoc and mid- to late-Ashgill, all of which reflected both the approach of the terranes surrounding Baltica and also the variations in sea level and climate as well as the individual ecologies of each of the ostracod genera. As would be expected from the progressive closeness of the two terranes and their comparable palaeolatitudes, by the end of the Ordovician, there was very much in common between the ostracod faunas of Baltica, Avalonia and Laurentia. In addition, Samuelsson et al. (2002) have documented the Baltica–Avalonia convergence in the Late Ordovician by a sequential analysis of the chitinozoan microfloras, which gradually became more similar as time progressed; and Vecoli and Samuelsson (2001) have demonstrated that the chitinozoans and acritarchs from Rügen and the southern Baltic Sea became essentially identical at some stage after the mid-Caradoc and certainly by the mid-Ashgill (Rawtheyan). The Caradoc trilobite and brachiopod faunas of the Hadeland area, Norway, described by Harper and Owen (1984) demonstrate a mixture of Baltic forms and genera which had originated in Avalonia (Shropshire), and that trend continued on into the Ashgill.

We present two maps for the Upper Ordovician, one (Fig. 7) representing early Caradoc time (460 Ma) and the other (Fig. 8) for the Middle Ashgill (450 Ma). By the Late Ordovician, in the mid-Ashgill and before the end-Ordovician glaciation, there was a substantial global warming, which led to the formation of substantial carbonate mud mounds (bioherms) with very diverse brachiopods, trilobites, molluscs, echinoderms and bryozoa. That mid-Ashgill global warming event has been named as the Boda Event by Fortey and Cocks (2005). These mud mounds, reviewed by Webby (1984) and Nestor (1995), are best known within the

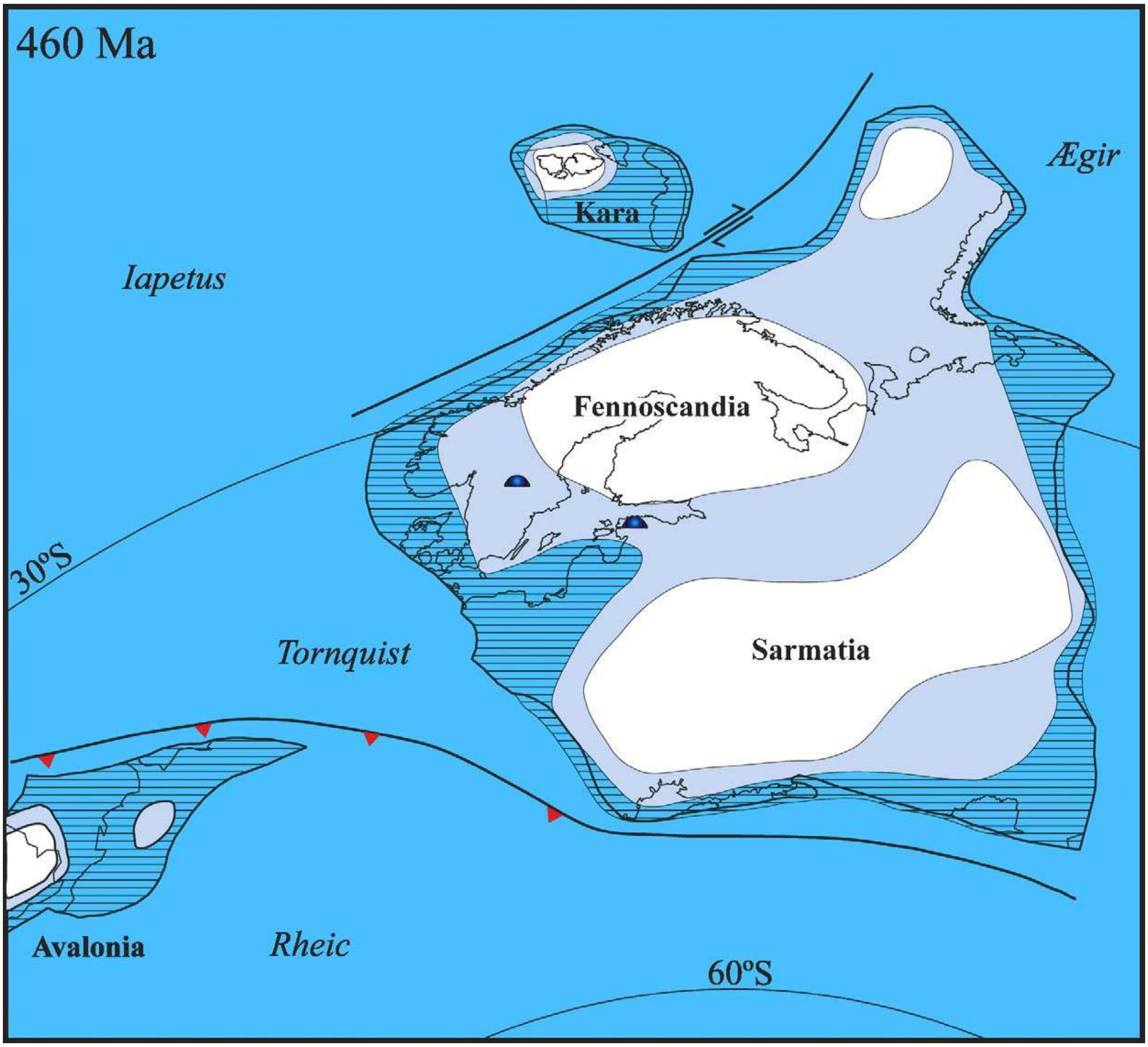

Fig. 7. Early Late Ordovician (early Caradoc, 460 Ma) palaeogeography of Baltica and adjacent terranes. In the intervening 20 Ma period since the early Arenig (Fig. 6), the rotation of Baltica had slowed considerably, but the terrane had started its movement towards lower latitudes and by that time is crossing the 30° S parallel. Avalonia had left Gondwana and was drifting northeastwards towards Baltica cross the closing Tornquist Ocean, and is seen in the southwest of this map. The Rheic Ocean was opening between Avalonia and Gondwana and had subsumed the Ran Ocean within it by that time. The Iapetus Ocean was closing but still wide.

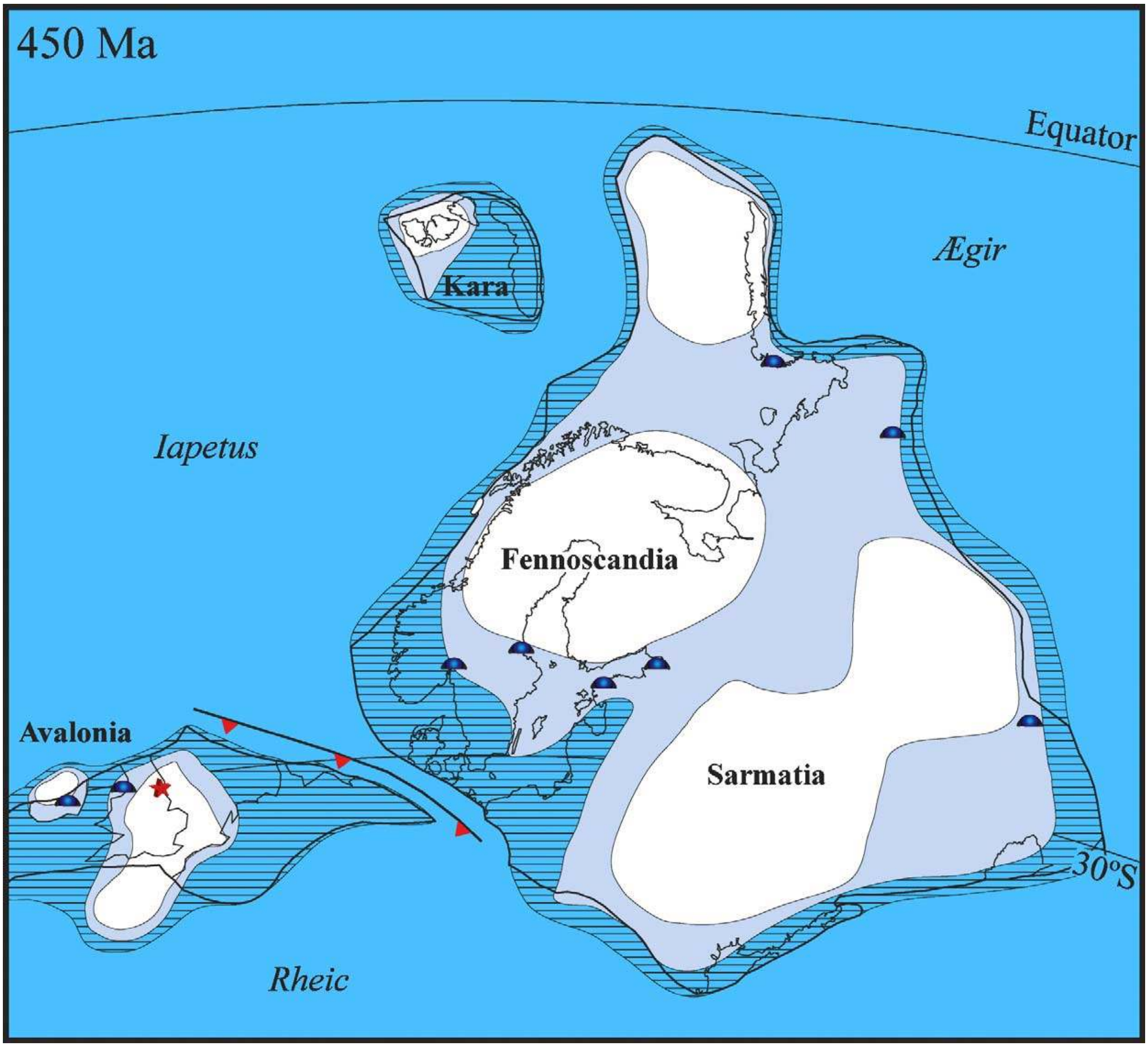

Fig. 8. Late Ordovician (Mid Ashgill, 450 Ma) palaeogeography of Baltica and adjacent terranes. The Tornquist Ocean between Avalonia and Baltica had nearly closed prior to the soft oblique docking of the two terranes at about Ordovician–Silurian boundary time (443 Ma). Baltica had nearly reached Equatorial palaeolatitudes by this time: the Rheic Ocean was still widening, and the Iapetus Ocean continuing to close.

Boda Limestone in central Sweden, the Ullerntangen reef complex in the Oslo region, Norway, and the Pirgu limestones of Estonia. Cocks (in press) has described and revised some of the Boda Limestone brachiopods and recognised an unusually large number of endemic strophomenide genera and species present there. As can be seen in Fig. 8, comparable mud mounds are not only to be found in Sweden, Estonia and Norway, but also in the eastern parts of Baltica (Novaya Zemlya and the Urals), but also in the adjacent terrane of Avalonia at Keisley in northern England, Kildare in Ireland, and elsewhere. That mid-Ashgill situation contrasts with the preceding Caradoc (Fig. 7), in which only the Kullsberg Limestone carbonate mud mound of central Sweden and the Vasalemma mud mound of northern Estonia are known from Baltica, although there are others on terranes elsewhere. The Middle Ashgill also contrasts with the immediately succeeding uppermost Ashgill deposits, in which no bioherms are known from Baltica due to the Hirnantian global cooling and glaciation. As a result, there was therefore a substantial reduction in the number and variety of ecological niches available for the benthic fauna. That niche reduction, combined with generally cooler waters even in the low palaeolatitudes of Baltica, facilitated the very large faunal turnover and extinctions recorded from across the Ordovician–Silurian boundary interval globally.

9. Silurian

The northward movement of the terrane area had continued steadily during the Ordovician, and by the mid-Silurian (Fig. 9), it straddled the palaeoequator. It was during the Silurian that the main collision between Baltica–Avalonia and Laurentia occurred, forming much of the British and Irish Caledonides to the west and the Scandian Caledonides to the east. The detailed history of all the complexities and local areas of the Caledonide Orogeny is outside the scope of this paper, but in summary, there were progressive collisions during the Ordovician and Silurian between all the various island arc chains which had been situated apart from each other within the Iapetus Ocean before the final collision between the two chief (and by then amalgamated and augmented) terranes of Baltica–Avalonia and Laurentia (Cocks and Torsvik, 2002; Roberts, 2003; Torsvik and Cocks, 2005). The chief nappe movement was towards the east, with elements of what had previously been parts of Laurentia, as well as some of the exotic terranes from the mid-Iapetus island arcs, overriding the Baltic craton. The Caledonian Orogeny produced uplift in the west of Baltica, resulting in the terrestrial deposits of the Old Red Sandstone Continent, which started in the late Wenlock in the Oslo area (the Ringerike Sandstone Group) and also Jämtland; however, in contrast, the rocks in Gotland, the East Baltic and Podolia carry on upwards as shallow-water shelf facies which appear to been little affected by tectonic changes until the very end of the Silurian.

A recent review of the Silurian of the Baltica part of Laurussia by Baarli et al. (2003) shows that about one-third of its area was relatively flat and, like the Cambrian and Ordovician, covered by shelf seas with relatively shallow depositional basins over the Baltic Shield. This was apart from in the west of the former Baltica, where the Caledonian Orogeny was progressively generating uplift and mountains. In addition to detailed stratigraphical sections of 25 profiles in central Scandinavia, the East Baltic, Dniestr and Timan–Pechora basins, Baarli et al. (2003) present four maps of successive Llandovery times and two each for Wenlock and Ludlow times which show the progressively deepening Benthic Assemblage (BA) Zones 1 to 6 as well as the areas of no Silurian deposition, and we have followed many of their distributions to construct parts of our Fig. 9. It is notable that Baarli et al.'s mapped BA zones are all truncated abruptly by the Trans-European Suture Zone, providing further proof that most of the southern margin of Baltica was lost in the late Palaeozoic Variscan Orogeny. However, to the south of the TESZ, in the Holy Cross Mountains of Poland, there are relatively thick (about 1500 m) turbidite sequences of Silurian age (Belka et al., 2002), indicating that there the sediments may indicate some closeness to the original border of the ancient Baltica Terrane. This thicker sequence, and also the ones in the late Llandovery and Wenlock of the Oslo Region (Cocks and Worsley, 1993), together indicate a much greater sediment supply, and also much higher topographical relief inland, than was the case in the Ordovician.

In contrast to the two separate land areas of the Caledonides–Fennoscandia and what Baarli et al. (2003) term ”Sarmantia,” our map (Fig. 9) shows a united land area which includes both these two areas and which extended westwards through Greenland and Scotland into the old Laurentia: there seems scant evidence for a seaway separating those two land masses.

The Silurian successions of the Baltica sector of Laurussia are entirely preserved without significant subsequent metamorphism (again apart from in the Oslo region and also some dolomitisation in the East Baltic) upon the Precambrian craton, and include some of the best and well-known Silurian sections in the world, for example on the island of Gotland, whose fossils have attracted attention since the 18th century work of Linnaeus. There are also superbly-exposed carbonate mud mounds in Gotland and Estonia, reviewed by Nestor (1995). The brachiopods from Gotland were reviewed by Bassett and Cocks (1974), who demonstrated that the benthos of the central Baltic area formed part of a very widespread and relatively

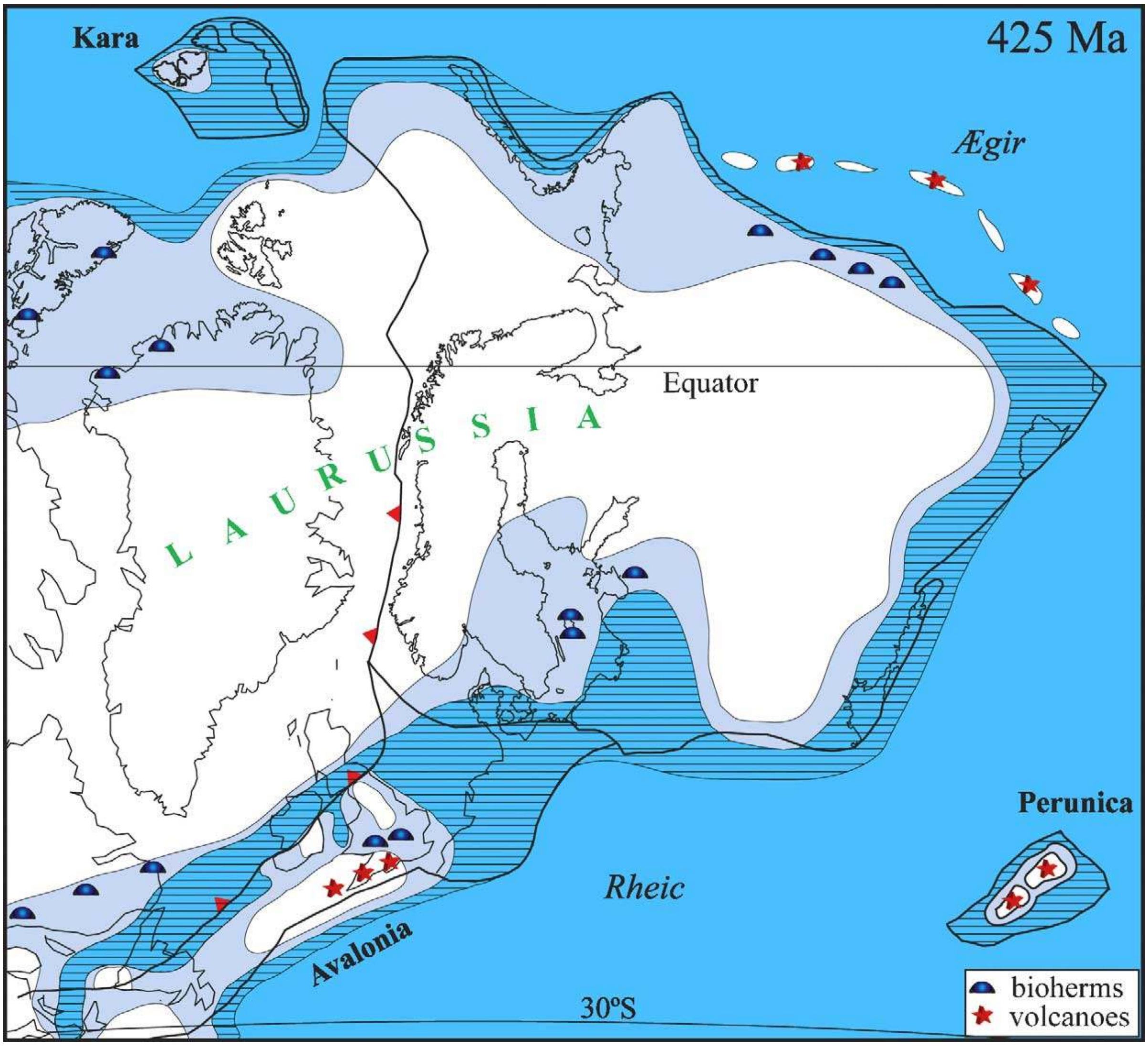

Fig. 9. Palaeogeography of eastern Laurussia in the mid-Silurian (Wenlock, 425 Ma), including the Baltica, Avalonia and eastern Laurentia sectors. Adjacent terranes include Perunica (Bohemia) and Kara. The Iapetus Ocean had closed, and the Rheic Ocean was starting to close, bringing Perunica (Bohemia) closer to Laurussia.

cosmopolitan series of faunas which inhabited nearly all the world's shelves except at the very highest palaeolatitudes. Silurian brachiopods from Scandinavia and the East Baltic are abundant and widely diverse, but rather patchily monographed. Exceptions are, for example, the substantial work on the orthides and strophomenides from the Llandovery of the Oslo Region, Norway (Baarli, 1995), and the review, by Musteikis and Cocks (2004), of all the strophomenides and orthotetides from the Silurian boreholes of the East Baltic area; the atrypides described by Copper (2004) from both Avalonia and Gotland, and the various papers by Modzalevskaya and her colleagues (e.g., Modzalevskaya, 1985) on the spire-bearers in the East Baltic, the Urals and Novaya Zemlya. There are some endemic species in these areas, and even a few endemic genera, but the latter form only a small percentage of the overall genera present; however, there is a tendency towards greater endemicity in the later periods of the Silurian.

In contrast, the ostracods, most of which did not have a pelagic larval stage, did not disperse so widely as the brachiopods. Williams et al. (2003) demonstrate that there were still some faunal differences in the ostracods between the combined Baltica–Avalonia Terrane, on the one hand, and Laurentia on the other; although they differ from the conclusions reached by Hansch (1993). These analyses indicate that seaways, however shallow, still lay between the two areas in even the latest Silurian. Both fauna and sediments endorse the palaeomagnetic conclusions that Baltica was mostly within tropical latitudes at that time (Cocks and Torsvik, 2002), and it is therefore no surprise to find extensive Bahamian-style limestones and massive reefal bioherms developed in Gotland and elsewhere.

By comparison with the extensive work carried out over many years in southern and central Norway, Sweden and the East Baltic; the northern part of Baltica, including the significant areas of Timan–Pechora and Novaya Zemlya, has until recently been relatively poorly known. However, key sections are now well documented; for example, those on Vaigach Island, which lies between Novaya Zemlya and the northern Urals, were summarized by Nekhorosheva and Patrunov (1999) and Baarli et al. (2003), where Silurian carbonates, including bioherms, are developed to a thickness of over 1400 m. The faunas, for example, the corals there and the brachiopods described by, e.g., Beznosova (1994), are also now much better known than before, and display some differences from the faunas known from Gotland and England. These differences, which are not comparably obvious in the Ordovician, may either have reflected the differences in palaeolatitude or the increased difficulties in free larval dispersal round a much enlarged terrane, or both. The latter would appear to be the more dominant reason, since benthic faunas of the same age in eastern U.S.A. and Arctic Canada on the same enlarged terrane also show some differences from those of the Baltica sector of Laurussia.

To the south and east of the mainly shallow-water origin and well-exposed outcrops of Norway, Sweden and Estonia, Silurian rocks are preserved extensively in the subsurface of Latvia, Lithuania, Poland, Belarus and the Ukraine. The sediments there represent progressive deepening southwards and westwards, with documentation of the varied environments found in the Silurian of the Lithuanian boreholes given by Musteikis and Cocks (2004). Much of the area which is today Poland was submerged too deeply to sustain benthos, and the Silurian rocks are chiefly developed there as relatively thin graptolitic shales. However, in southwestern Ukraine, along the Dniestr River, above an unconformity crossing the Ordovician–Silurian boundary, there are substantial and impressive outcrops of relatively flat-lying Silurian and early Devonian rocks in the Podolia area. These consist of interbedded carbonates and shelf clastic rocks carrying relatively shallower-water benthos, including the brachiopods reviewed by Nikiforova et al. (1985) from the Wenlock to the early Devonian.

10. Postscript

In a masterly way, Ziegler (1989, 1990) has summarized the subsequent history of our area. Some time after the Baltica–Avalonia–Laurentia amalgamation which formed Laurussia in the Silurian, the southern part of Europe was convulsed in the late Palaeozoic Variscan Orogeny, which truncated the southeastern margin of Baltica. That orogeny ended with the amalgamation of Laurussia and the vast Gondwana Terrane to its south, as well as including the complex collage of peri-Gondwanan terranes which surrounded Gondwana, all of which formed the major part of the assembly of the Pangea supercontinent by the end of the Permian (Torsvik and Cocks, 2004). That supercontinent in turn broke up progressively during the Mesozoic and Tertiary, with the initiation and spreading of the Atlantic Ocean, and led to the definition of the northwestern margin of Baltica as we see it today. In contrast to Avalonia and Laurentia, whose Lower Palaeozoic parts were divided on either side of the North Atlantic where we find them today, we have no evidence to suggest that any part of the old Baltica is anything but to the east of the Atlantic.

In a comparable way, the eastern margin of Baltica was defined by the Late Carboniferous Uralian Orogeny, whose considerable strike–slip component resulted in the relatively straight north–south-trending margin so apparent on modern topographic maps. The exception to the latter is at the northern part of the

Urals and its continuation into Novaya Zemlya, where the substantial tectonics connected with the extrusion of the Siberian Trap flood basalts at 251 Ma at the end of the Permian indented the Baltica margin into an arcuate curve (Figs. 1 and 2). From the time of the breakup of Pangea, Baltica has formed an integral part of the great Eurasian Plate, of which it forms a large part of the passive western margin today.

11. Conclusions

Thanks to the thickness and stability of the ancient Archaean and Proterozoic East European Craton, much of the area of the ancient terrane of Baltica has been preserved today, and it forms most of northern Europe. The terrane existed as a separate entity from the time it separated from Laurentia in the Vendian from 570 to 550 Ma until its soft collision with Avalonia at the very end of the Ordovician at about 443 Ma, giving it a career as an independent terrane of rather more than a hundred million years. At about the middle of its time as a separate terrane, Baltica underwent rotation of more than 120°, from which it follows that the present eastern (Uralian) margin of Baltica originally faced towards northeast Laurentia in the late Precambrian.

The overall internal geography of Baltica appears to have remained broadly similar during the Cambrian and Ordovician, with the two substantial land areas of Fennoscandia and Sarmatia apparently persisting over the whole of that period (Figs. 5–8), and there is little reason to postulate high relief over much of these land areas. However, that situation changed dramatically during the Silurian, chiefly due to the Caledonide Orogeny, which showed the much more substantial Old Red Sandstone Continent land area shown on our mid-Silurian map (Fig. 9), some of which no doubt contained high mountains and which apparently stretched westwards into the area which had been Laurentia. Between Fennoscandia and Sarmatia, we have followed various authors, for example Nikishin et al. (1996), in postulating a substantial sea covering shallow shelves during the Cambrian and Ordovician; however, we have little firm data to negate the concept of a land bridge which might have connected the two areas at one or more times during that extensive 60 million yr period.

Fig. 10 shows Baltica and the contiguous terranes with which it was amalgamated through time, and also their progressively changing palaeolatitudes. Although at 750 Ma Baltica was at the palaeoequator, the palaeomagnetic data (based on the Egersund dykes of Norway shown in Fig. 1) indicate that by 615 Ma it was at or near the South Pole (Torsvik and Cocks, 2005); and thus from its independent inception as a separate terrane until its Caledonian collision, in addition to its rotation, Baltica also moved northwards from relatively high to low palaeolatitudes. One result of that movement was that the shelf sediments on Baltica changed from primarily clastic, with a few colder-water origin carbonates, in the Cambrian and Lower Ordovician, to progressively warmer-water sediments during the subsequent Ordovician. The process culminated with the development of tropical reefs by the end of the Ordovician which continued on into the Silurian. That evolution of the sedimentary regimes was paralleled by the changes in the benthic faunas which inhabited them; and those contrasts and developments were underlined by the spectacular increase in the faunal diversity from the Cambrian through to the Silurian.

During the Early Ordovician, the oceans surrounding Baltica were at their widest, with the result that the faunas which inhabited them became progressively more endemic. This endemicity reached its acme in the Lower Ordovician, when many Baltic trilobites and brachiopods, not just species and genera but even subfamilies and families, are unknown from other contemporary terranes; leading to the recognition of a Baltic Province which was essentially confined to this single terrane. However, as the oceans surrounding Baltica dwindled in width during the Ordovician, with other terranes and faunas becoming progressively closer, then the degree of endemism on the terrane also diminished, until by the end of the Ordovician, there were few differences in the benthic fauna between Baltica and Avalonia even before their tectonic amalgamation.

Although Baltica's union with Avalonia at the end of the Ordovician was a soft docking, that contrasts strongly with the collision of the combined Baltica–Avalonia shortly afterwards with Laurentia to form Laurussia. That collision resulted in the Scandian part of the Caledonide Orogeny, a major tectonic event which also raised mountains over much of the area.

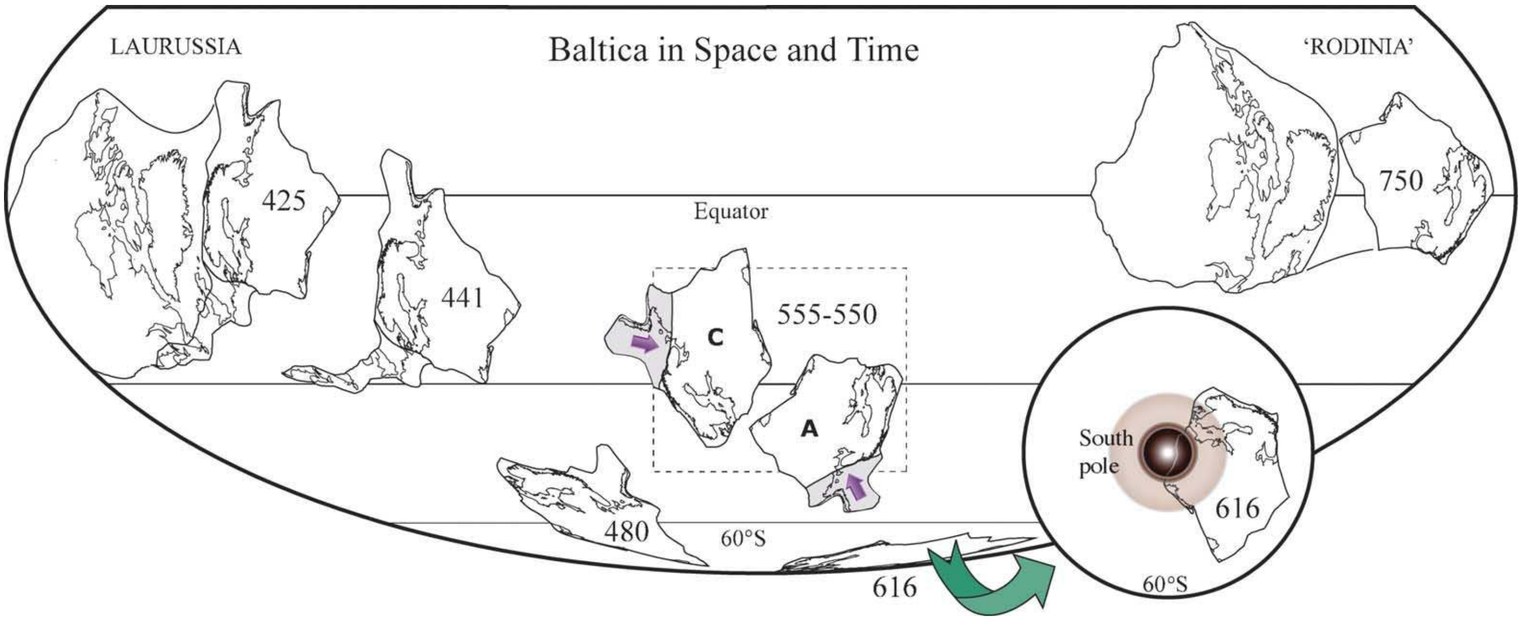

Fig. 10. Progressive palaeolatitudes of Baltica and contiguous terranes through time. From 750 to 570 Ma, Baltica was amalgamated with Laurentia within the reduced "Rodinia"; from 550 to 443 Ma, it was an independent terrane; from 443 Ma, it was amalgamated with Avalonia; and from about 425 Ma with both Avalonia and Laurentia to form Laurussia. At 555 to 550 Ma, when Baltica had accreted the Timanide terranes, we show two alternatives for Baltica: Options (A) and (C) are as in Fig. 4. The high-latitude position of Baltica at 616 Ma is based on new data from the Egersund dykes.

This process continued on into the late Silurian and Devonian, causing the emergence of the Old Red Sandstone palaeocontinent which covered much of the entire area of Laurussia.

Thus we are now much more clearly able to document and appreciate the life span, tectonic movements, and palaeogeography of the substantial Baltica Terrane during its long history as a separate entity.

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