# European geography in a global context from the Vendian to the end of the Palaeozoic

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**Abstract:** A succession of palaeogeographical reconstructions is presented, covering half the globe and the time interval from the latest Proterozoic (Vendian) at 550 Ma to the end of the Palaeozoic (latest Permian) at 250 Ma, mostly at 20 or 30 Ma intervals. The various terranes that today constitute Europe are defined and their margins discussed briefly; these are Gondwana, Avalonia, the Rheno-Hercynian Terrane, the Armorican Terrane Assemblage, Perunica, Apulia, Adria, the Hellenic Terrane (including Moesia), Laurentia, and Baltica. As time elapsed, many of these terranes combined to form first Laurussia and subsequently Pangaea. The further terranes of Siberia and Kara adjoined Europe and were relevant to its Palaeozoic development. Brief sections are included on the individual history and geography of the Vendian and the six Palaeozoic systems, with emphasis on their importance in the building of Europe.

During the 300 Ma from 550 to 250 Ma the geography of the Earth evolved greatly. At the beginning of this period there was only one superterrane, Gondwana, with a large number of other terranes at varying distances from each other, some separated by wide oceans. By the end of the Palaeozoic, at the end of the Permian, most of the other terranes had coalesced, and had also joined Gondwana, to form Pangaea, by far the largest superterrane in Phanerozoic history.

Evolution of the biota over this huge time interval had progressed enormously, with great consequent diversity: at 550 Ma there were no animals or plants with substantial hard parts, and the colonization of the land by animals had not yet begun. In contrast, by the Permian there were probably millions of different animals and plants, not only in the marine habitats, but also over much of the land, a great part of which was covered with forests and jungles comparable in size with those known today. The end of the Permian also saw the largest faunal and floral turnovers and extinction event in the whole Phanerozoic.

At no time in the 300 Ma period that we review here was Europe the geographical unity that it is today. It is the chief purpose of this paper to set a substantial part of Europe's geographical evolution in global context so that this book may be better appreciated by a wide audience. The Europe of today is made up of many terranes, some of which did not join the present continent until after the Alpine Orogeny during the Tertiary. Excellent and detailed reviews of the geology of Europe as it developed through time from the latest Silurian onward have been given by Ziegler (1989, 1990). We here present (Fig. 1) a simple flow diagram showing the break-up and amalgamations of the major European terranes and their associated orogenies from the Vendian to the end of the Palaeozoic.

To reconstruct the successive ancient geographies we have pooled our different expertises of palaeontology and palaeomagnetism, and combined them with sedimentology and, to a lesser degree, structural evidence to produce a kinematically valid series of successive maps. We have already set out in detail elsewhere the criteria by which we work and have also reviewed much of the period in different time slices (Cocks 2000; Cocks & Torsvik 2002, 2004; Torsvik *et al.* 2002; Torsvik & Cocks 2004, 2005). The present shorter review both integrates some of our previous results and also focuses particularly on the terranes that make up modern Europe. It also depends heavily on the work of a great number of researchers who are not quoted in this brief paper: reference will be found to many of them in the landmark publication edited by McKerrow & Scotese (1990) as well as in our own previous papers listed above.

After a short review of each of the more important European and adjacent terranes, this paper presents a brief history of the events in Vendian and Palaeozoic Europe. The chief terranes are labelled in Figure 2.

## Major terranes relevant to Palaeozoic Europe

### *Gondwana*

During the Early Palaeozoic this vast superterrane stretched from the South Pole to the Equator and beyond, and included at least South America, Africa, Madagascar, peninsular India, Antarctica and Australasia. None of what is termed 'core' Gondwana is today preserved in Europe; the nearest part of it is in northern Africa. However, at various times in the Palaeozoic, several terranes (termed peri-Gondwanan) that had originally formed integral parts of Gondwana separated and rifted from it. The principal ones that now form part of Europe are Avalonia, the Rheno-Hercynian Terrane, the Armorican Terrane Assemblage, Perunica, Apulia, Adria, the Hellenic Terrane and Moesia, and they will now be reviewed in turn, with a brief note on the Gondwana-derived Early Palaeozoic fragments caught up in the Cenozoic Alpine Orogeny.

### *Avalonia*

Avalonia today includes the eastern North America seaboard from Newfoundland as far south as Cape Cod, Massachusetts, and in Europe includes southern Ireland, Wales, England, Belgium, the Netherlands and parts of northern Germany, and its boundaries were described by Cocks *et al.* (1997). Its northern margin is defined by the closed Iapetus Ocean suture with Laurentia, its eastern margin by the closed Tornquist Ocean part of the Trans-European Suture Zone (TESZ), rather than the Elbe Line as stated by Cocks *et al.* (1997), and its southern margin by the Rheic Ocean suture. Some workers use the terms West Avalonia and East Avalonia, but we believe that the terrane was a single entity during its relatively short Ordovician independent existence and do not consider that the two halves now separated by the

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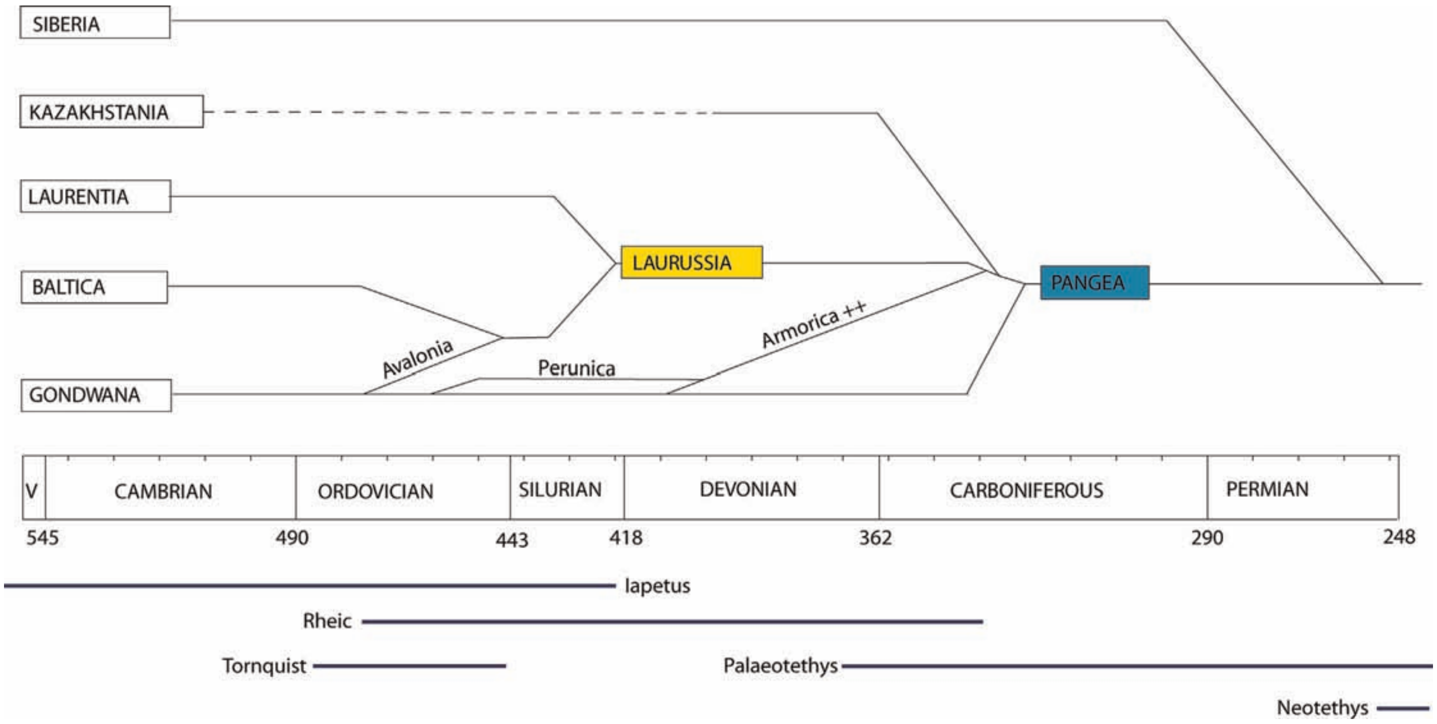


**Fig. 1.** Flow chart showing the break-up and amalgamations of the various European terranes with time from the Vendian to the end of the Palaeozoic. At the base is shown the longevities of the oceans whose sutures are included in modern Europe.

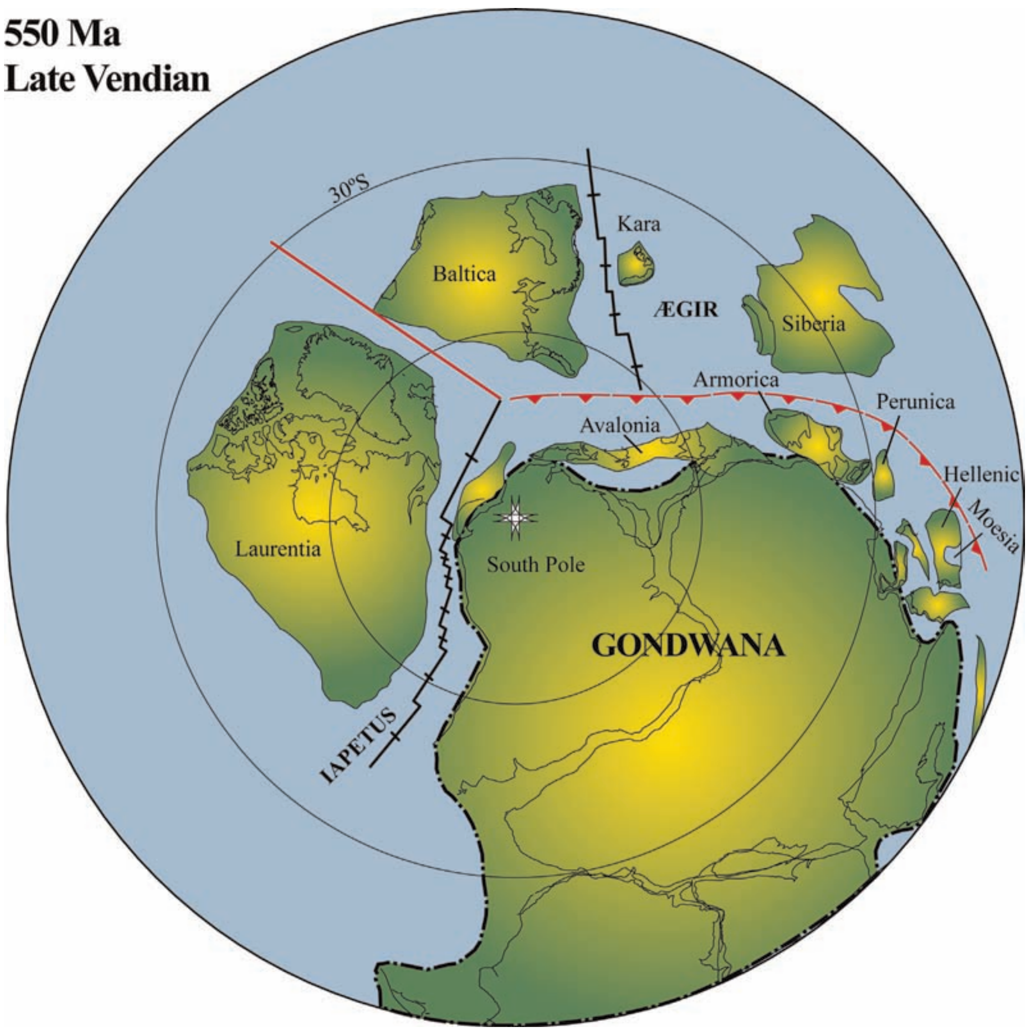


**Fig. 2.** Reconstruction of the Southern Hemisphere in the Late Vendian (550 Ma), modified from Hartz & Torsvik (2002) and Rehnström *et al.* (2002). Figures 2–7 are Schmidt's Equal Area Projection, with projection centre at the South Pole. Spreading centres are shown as black lines, subduction zones as red lines with ticks, and transform faults as red lines with no extra ornament.The alternately dashed and dotted black line marks the limit of 'core' Gondwana. The terranes are also identified in Figure 9. In Figures 2–14, small terranes and island arcs are mostly omitted.

Atlantic Ocean were divided in the Palaeozoic. The terrane broke off from Gondwana before the Llanvirn Stage of the Ordovician; before that time a variety of palaeontological and sedimentological evidence suggests that it originally adjoined, and formed part of, core Gondwana and was probably adjacent to the northern part of South America (McKerrow *et al.* 1992).

### *The Rheno-Hercynian Terrane*

The Rheno-Hercynian belt, which is chiefly within today's Germany, has been described by Franke (e.g. Franke 2000) and Stampfli and coworkers (e.g. Stampfli *et al.* 2002), and probably represents the opening and closing of the Rheno-Hercynian Ocean. From that it can be deduced that there was probably a separate Rheno-Hercynian Terrane, which was independent only from the Devonian (Emsian) to the early Carboniferous. The area today is largely tectonized and has few fossils that could be used to identify the terrane, and its limits consist entirely of post-Devonian structures; we show it with an arbitrary shape in our Devonian reconstructions (see Figs 9 and 10).

### *The Armorican Terrane Assemblage*

This includes the Iberian Peninsula and most of France. The area is much tectonized and its geological history is contentious. However, the Cambrian to Devonian faunas and sediments clearly indicate that Armorica (as it is often called) remained an integral part of Gondwana at least until the end of the Silurian (Robardet 2003), and, as can be seen from the distributions of its higher latitude Early Palaeozoic 'Mediterranean Province' benthic faunas, was apparently located withrin Gondwana not far from its present location with respect to northern Africa. Robardet *et al.* (1990) have presented data that they interpret as indicating that Armorica remained part of Gondwana during the Devonian as well; however, in our 400 Ma Mid-Devonian map we show it as having left the superterrane with other terranes, following rifting and the opening of the Palaeotethys Ocean of Stampfli *et al.* (2002). Some workers have included Perunica (Bohemia) as part of the Armorican Terrane Assemblage, but we believe the two were separate in the Early Palaeozoic.

### *Perunica (Bohemia)*

This area, most of which today forms the western part of the Czech Republic, has late Cambrian faunas and sediments that definitely link it to the Armorican and northern African part of Gondwana. However, palaeomagnetic (Tait *et al.* 1994) and faunal (Havlíček *et al.* 1994) evidence both demonstrate that Perunica left Gondwana in the early Ordovician and pursued an independent course, separate from the history of the Armorican Terrane Assemblage, across the Rheic Ocean before merging with what is today's northern Europe in the Variscan Orogeny. The faunal analysis by Havlíček *et al.* (1994) demonstrates that Perunica was at its most isolated in the late Ordovician (Caradoc). Some workers unite Perunica and the Rheno-Hercynian Terrane within a 'Saxo-Thuringian' Terrane, but because of the palaeomagnetic and fossil data we treat the two as separate.

### *Apulia, Adria, Hellenic and Moesia terranes*

These terranes make up most of the eastern part of southern Europe. We follow Stampfli *et al.* (1998, 2002) in the outlines and integrity of Apulia (southern Italy), Adria (the Adriatic Sea and adjacent areas) and the Hellenic Terrane (Greece and adjacent areas). However, there are no diagnostic palaeomagnetic or palaeontological data from any of these three regions before the Carboniferous. We have grouped Moesia with the Hellenic Terrane; Yanev (2000) reviewed the Palaeozoic faunal data from there, which, although sparse, indicate that Moesia probably had peri-Gondwanan rather than Baltic trilobites during the Ordovician. Stampfli *et al.* (1998, 2002) suggested that Adria, the Hellenic Terrane and Moesia may have left Gondwana at about the end of the Silurian with the opening of the Palaeotethys Ocean, but Apulia probably did not leave Gondwana until the Permian, as part of the opening of the Neotethys Ocean.

### *Alpine fragments*

Although these are not shown on our maps, there are today in the Alpine regions, particularly of Austria, a number of Palaeozoic fragments preserved in a variety of tectonic settings. Schönlaub (1997) and von Raumer (1998) have reviewed these and concluded that they represent peri-Gondwanan areas of unknown size and integrity. They chiefly consist of Cambro-Ordovician arc-related metavolcanics rocks and Ordovician granitoids; the oldest fossils there are mid-Ordovician brachiopods that are undoubtedly attributable to the higher latitude West Gondwanan (often termed Mediterranean) faunal province, which included Armorica, Perunica and northern Africa (Havlíček *et al.* 1994).

### *Laurentia*

This substantial terrane included most of North America; and, in Europe, Greenland, Bjornøya, Svalbard, northwestern Ireland, Scotland and the upper parts of the nappes in the Scandian Caledonides (the Uppermost Allochthon). It was an independent entity from before the beginning of our study period, with the Iapetus Ocean to its east originally widening in the Proterozoic, at its maximum width in the latest Cambrian, starting to close in the earliest Ordovician, and continuing to close until the Silurian, when Laurentia collided with Avalonia–Baltica during the Caledonian (locally termed the Scandian) Orogeny to form the much larger terrane of Laurussia. At least two island arcs that also lay in the Iapetus Ocean were also involved in those orogenic events to eventually form the complex pattern of small terranes seen within the Iapetus Suture Zone today and illustrated by Armstrong & Owen (2001).

### *Baltica*

Most of the northeastern part of modern Europe is attributable to this terrane, which includes the ancient and substantial Precambrian East European Craton of many workers (e.g. Bogdanova *et al.* 2001). Baltica is approximately triangular in modern outline, with its eastern limit defined by the Ural Mountains (extending northwards to include Novaya Zemlya), its northwestern edge defined by the British and Scandinavian Caledonides orogenic belt and its southwestern margin in general by the TESZ. Important exceptions are the Lysogory and Małopolska terranes exposed in the Holy Cross Mountains of Poland, which today lie south of the TESZ but which formed an integral part of Baltica in the Early Palaeozoic (Cocks 2002). Baltica was inverted in relation to its present-day orientation from the Neoproterozoic (Hartz & Torsvik 2002) until the mid-Cambrian, when it started to rotate anti-clockwise; a rotation that was largely completed by the end of the Ordovician. Baltica first collided obliquely and relatively softly with Avalonia at about 443 Ma, the end of the Ordovician (Torsvik & Rehnström 2003), and then, fairly soon afterwards, in a more dynamic way with Laurentia to form Laurussia in the Caledonide Orogeny. The Uralian Orogeny, when the eastern part of Laurussia collided with Kazakhstania and intervening island arcs, took place in the late Carboniferous. The Baltica part of Laurussia did not merge with Siberia until the late

Permian. The palaeogeography and history of Baltica during its Neoproterozoic to Silurian existence as a separate terrane has been described by Cocks & Torsvik (2005).

### *Siberia*

No part of the old Siberian (sometimes termed Angaran) Terrane is today in Europe. As well as much of north–central modern Siberia, the terrane included the southern and central parts of the Taimyr Peninsula. It had been previously postulated by some workers (e.g. Cocks & Fortey 1998) that the central and southern parts of Taimyr formed part of Baltica in the Early Palaeozoic, but further palaeontological and palaeomagnetic work negated that hypothesis; the evidence has been summarized by Cocks & Torsvik (2002), and these two more southern parts of Taimyr are now seen as having formed integral parts of the Early Palaeozoic Siberia. For all of the Palaeozoic, Siberia was inverted relative to its present-day orientation; rotation to today's orientation began in the Late Devonian and ended in the Permian upon its collision with Pangaea (see Fig. 14). Today's northwestern margin of Siberia collided with Kazakhstania and intervening island arcs during the late Carboniferous, but the terrane was not finally accreted to Laurussia to become part of Pangaea until the Permian.

### *Kara*

Severnaya Zemlya, the northern part of the Taimyr Peninsula and parts of the adjacent Arctic Ocean, despite being parts of Siberia today, for most of our study period formed the centre of an independent terrane (Torsvik & Rehnström 2001), known as the Kara Terrane. Kara collided with Siberia at some time after 300 Ma. Zonenshain *et al.* (1990) used the term Arctida for a rather larger terrane area that they identified in the same vicinity.

### *Pangaea*

Near the end of the Palaeozoic, from Late Carboniferous (330 Ma) times onwards, Laurussia and Gondwana merged to form the supercontinent of Pangaea, and they were subsequently joined by Kazakhstania and Siberia in turn. However, the Palaeotethys Ocean to the east of Pangaea separated the northern from the southern parts of today's European collage during the later Palaeozoic (Stampfli *et al.* 2002). Our reconstructions of Pangaea use the so-called Pangaea A configuration, which is the only one of several alternatives (some others being termed Pangaea B and C) that can resolve the tectonic, faunal and sedimentological evidence on the one hand and palaeomagnetic data on the other. Pangaea A can be true to the palaeomagnetic data only if it is assumed that the Earth's magnetic field had a 10–15% octupole component at the time (Torsvik & Van der Voo 2002; Torsvik & Cocks 2004), rather than entirely a dipole field, as presumed by many palaeomagnetists (e.g. Muttoni *et al.* 2003).

## Geological history

Despite the fact that our maps (Figs 2–14) show considerably greater parts of the world, only the European sectors of them will be discussed here. We treat the geological history system by system. We have omitted from these reconstructions all the many island arcs and smaller terranes that were undoubtedly present at each period. For example, it is now well documented (e.g. Harper *et al.* 1996; van Staal *et al.* 1998) that in the Ordovician there were two subparallel island arcs in the Iapetus Ocean, which acted as stepping stones for the spread of benthic faunas at that time. These arcs are represented today by rocks in largely tectonized areas in the eastern seaboard of North America (van Staal *et al.* 1998) and the British Isles (Armstrong & Owen 2001), and in the higher nappes of the Scandinavian Caledonides (Cocks & Torsvik 2005). The progressive accretion of the arcs to Laurentia, Avalonia and Baltica and their accretion to each other represent important phases in the widespread Ordovician to early Devonian Caledonian Orogeny. Most of the other side of the world, the northern hemisphere, which we do not illustrate here, was taken up by the vast Panthalassic Ocean, which was comparable in size with the Pacific today. That ocean included all the latitudes and longitudes now occupied by modern Europe.

### *Latest Proterozoic*

The Vendian started at 600 Ma and continued until the beginning of the Cambrian at 543 Ma. However, we start our reconstructions here at 550 Ma (Fig. 2) because at that time the data concur that Gondwana, Laurentia and Baltica were certainly all separate continents. Before that, palaeomagnetic and some sedimentological and tectonic data have been used for tentative reconstructions (e.g. Torsvik *et al.* 1996), but the same degree of confidence is not present in those maps as in the ones for the Phanerozoic (Figs 3–14), and so we will not repeat those maps or discussions here. Knoll (2000) has reviewed both the basis for relative dating and also the glaciations in late Precambrian time; there is little evidence for glaciation within our study area in the late Neoproterozoic, except perhaps in Algeria. Figure 2 is modified from Hartz & Torsvik (2002) and Rehnström *et al.* (2002). The opening of the southern Iapetus Ocean between Laurentia and the South American part of Gondwana was at an early phase at this time (550 Ma), as were the openings of the northern part of the Iapetus between Baltica and Laurentia, the Ran Ocean between Baltica and the Avalonian part of Gondwana; and the Ægir Sea between Baltica on the one hand and Kara and Siberia on the other. Avalonia, Armorica, the Rheno-Hercynian Terrane, Perunica and the other terranes now in southern Europe all formed part of Gondwana: they and North Africa were affected by the Cadomian Orogeny, which lasted throughout this period and finished in the early Cambrian at about 530 Ma. The Cadomian takes its name from NW France, but the scope and definition of that orogeny has been treated in different ways by different researchers and requires more stringent usage. For example, so-called 'Cadomian' rocks have allegedly been recorded from the Uralian margin of Baltica; these must surely represent an independent (although contemporaneous) orogeny that was perhaps linked with, or even formed part of, the Timanian Orogeny of northern Europe (Gee & Pease 2004). Although the Vendian Ediacaran Fauna soft-bodied fossils are well documented from this period, their distribution apparently occurs in a variety of terranes, and we have not found them relevant in determining terrane positions. During this period Laurentia moved from temperate and high latitudes into slightly warmer ones. From those early times to the mid-Ordovician, Baltica was independent and inverted in relation to its present-day orientation, with the fastest rotation occurring from the late Cambrian to the earliest Ordovician (references have been summarized by Torsvik & Rehnström 2001).

### *Cambrian*

The duration of the Cambrian, from 543 to 490 Ma, was a substantial 47 Ma, and we present two maps (Figs 3 and 4) showing the palaeogeography at 535 and 500 Ma. The former has been constructed chiefly from palaeomagnetic data, with some tectonic input, and modified from Torsvik & Rehnström (2001), and the latter from a combination of palaeomagnetic and faunal data (Cocks & Torsvik 2002, fig. 3). Figure 3 shows a wide and still

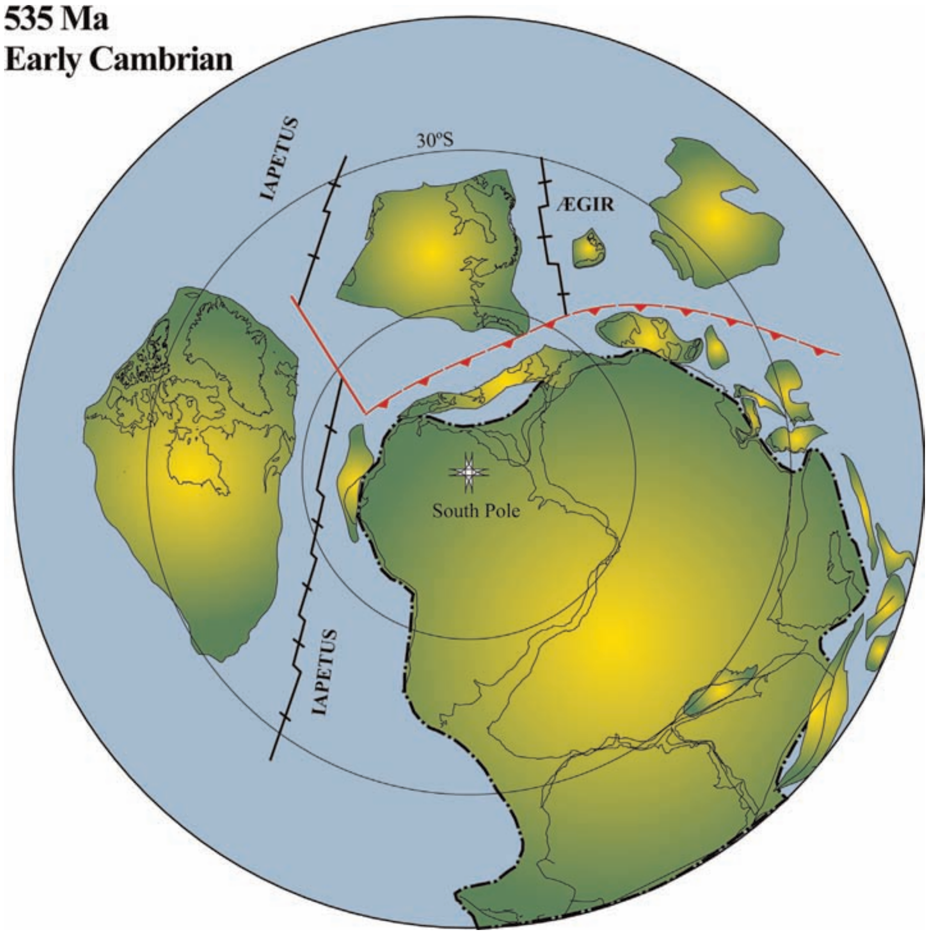


**Fig. 3.** Early Cambrian (535 Ma) reconstruction, modified from Torsvik & Rehnström (2001). Symbols as in Figure 2. The terranes are labelled in Figures 2 and 9. The Sibumasu, South China and Annamia terranes were then NE of Siberia: parts of them may or may not have overlapped into the Southern Hemisphere, although they are not shown here.

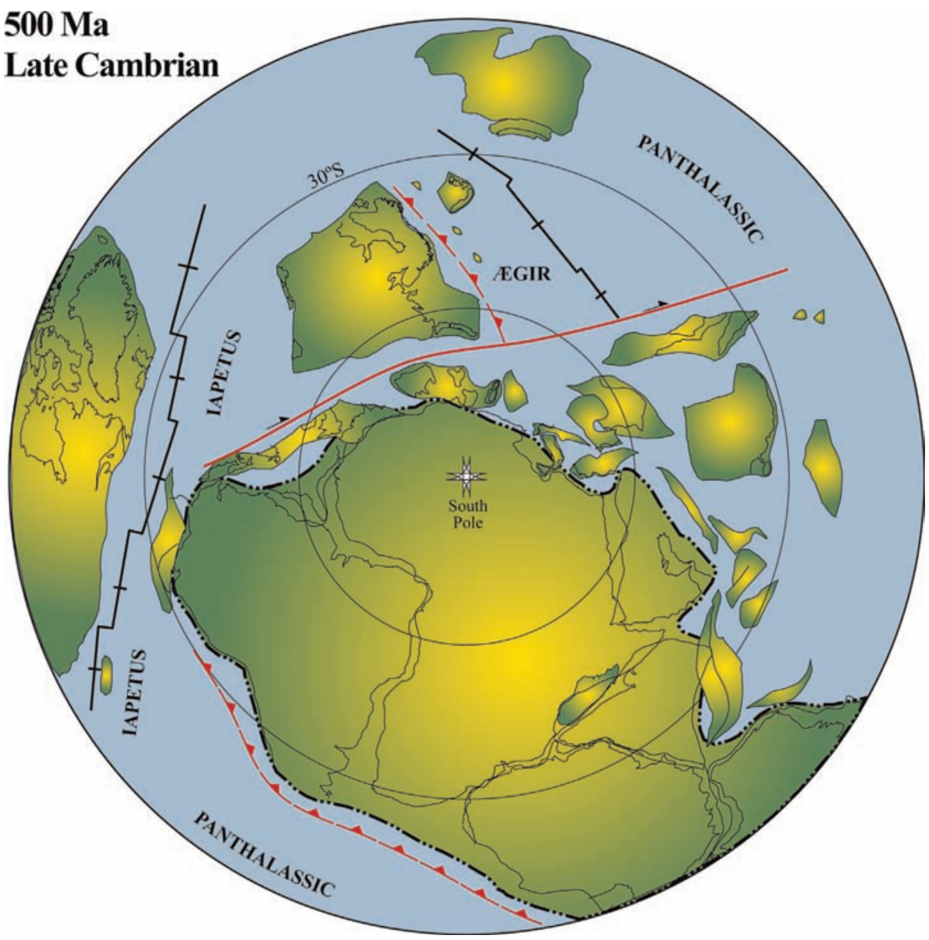


**Fig. 4.** Late Cambrian (500 Ma) reconstruction, modified from Cocks & Torsvik (2002, fig. 3). Symbols as in Figure 2; the terranes are labelled in Figures 2 and 9. The Annamia, South China and Tarim Terranes to the north of the Hellenic Terrane (labelled in Fig. 9) appear in our figures for the first time; also shown are the Sibumasu Terrane west of South China and the Precordillera Terrane to the then north of central South America. Two small triangles, representing idealized parts of what were later to accrete to form Kazakhstania, are shown to the then west of Tarim.

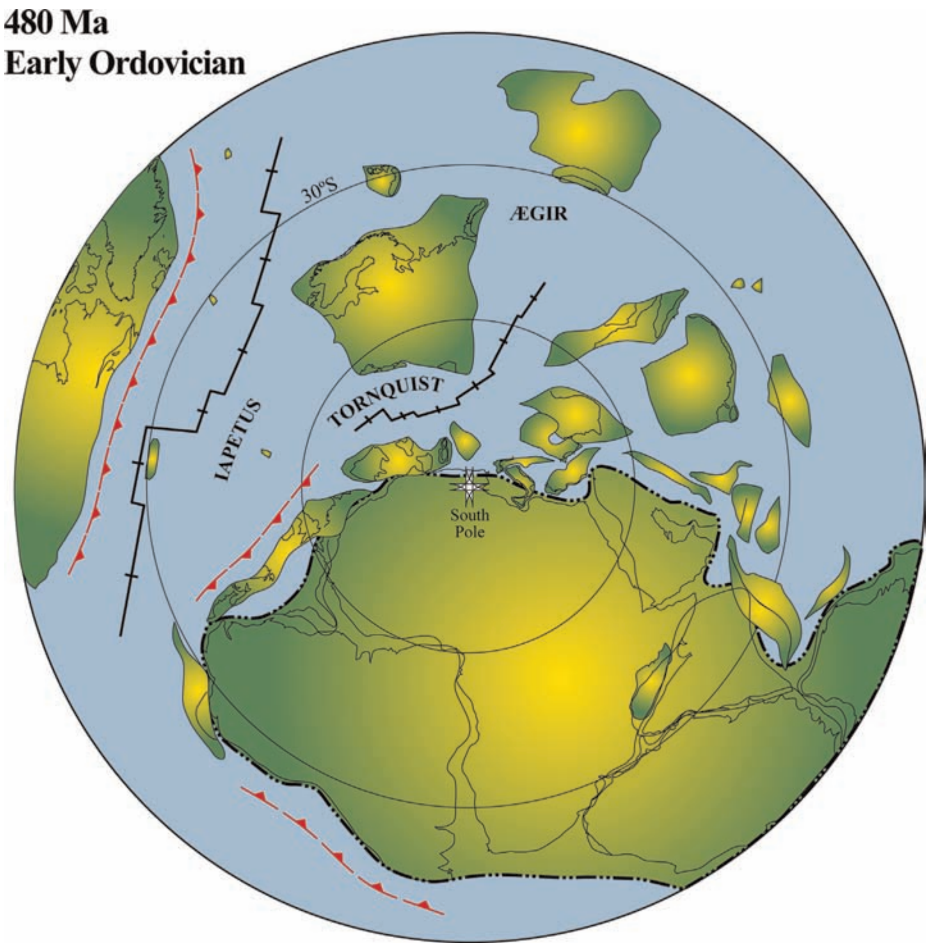


**Fig. 5.** Early Ordovician (Arenig, 480 Ma) reconstruction, modified from Cocks & Torsvik (2002, fig. 4). Symbols as in Figure 2; terrane names as in Figures 2 and 9. Those intra-Iapetus islands with reliable palaeomagnetic data (Cocks & Torsvik 2002) are also shown.

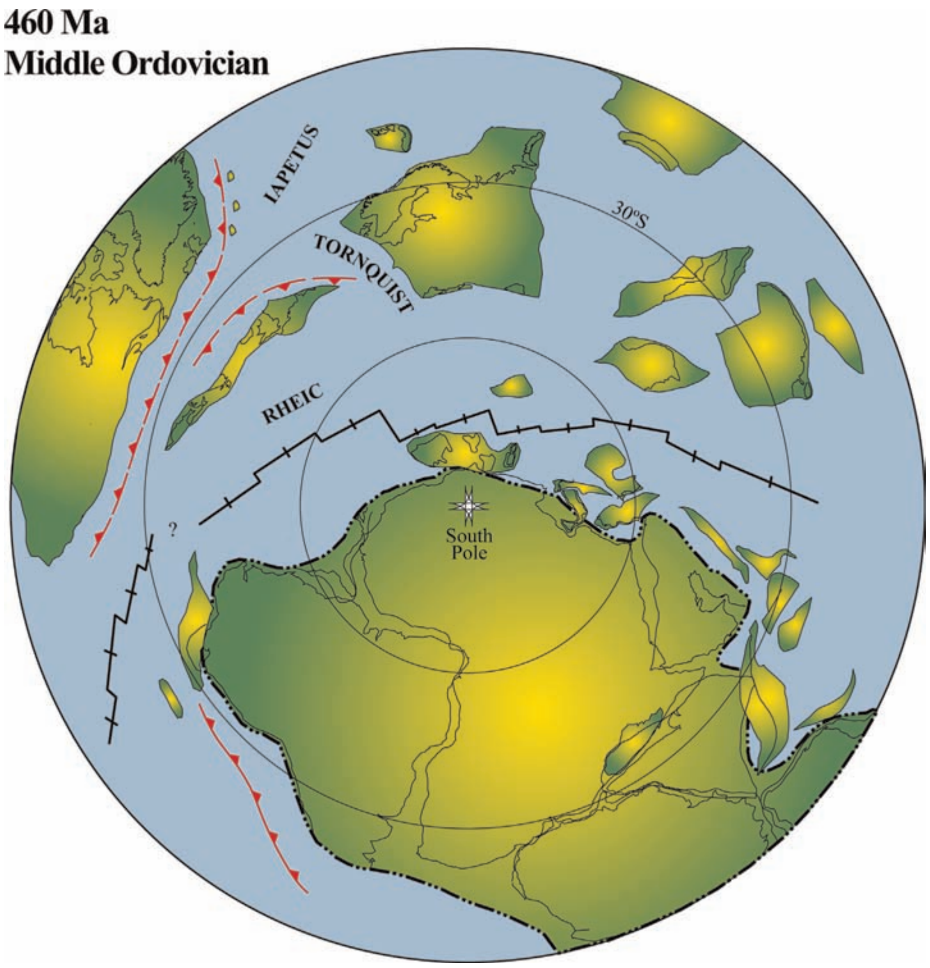


**Fig. 6.** Mid-Ordovician (Caradoc, 460 Ma) reconstruction, modified from Cocks & Torsvik (2002, fig. 5). Symbols as in Figure 2, terrane names as in Figures 2 and 9.

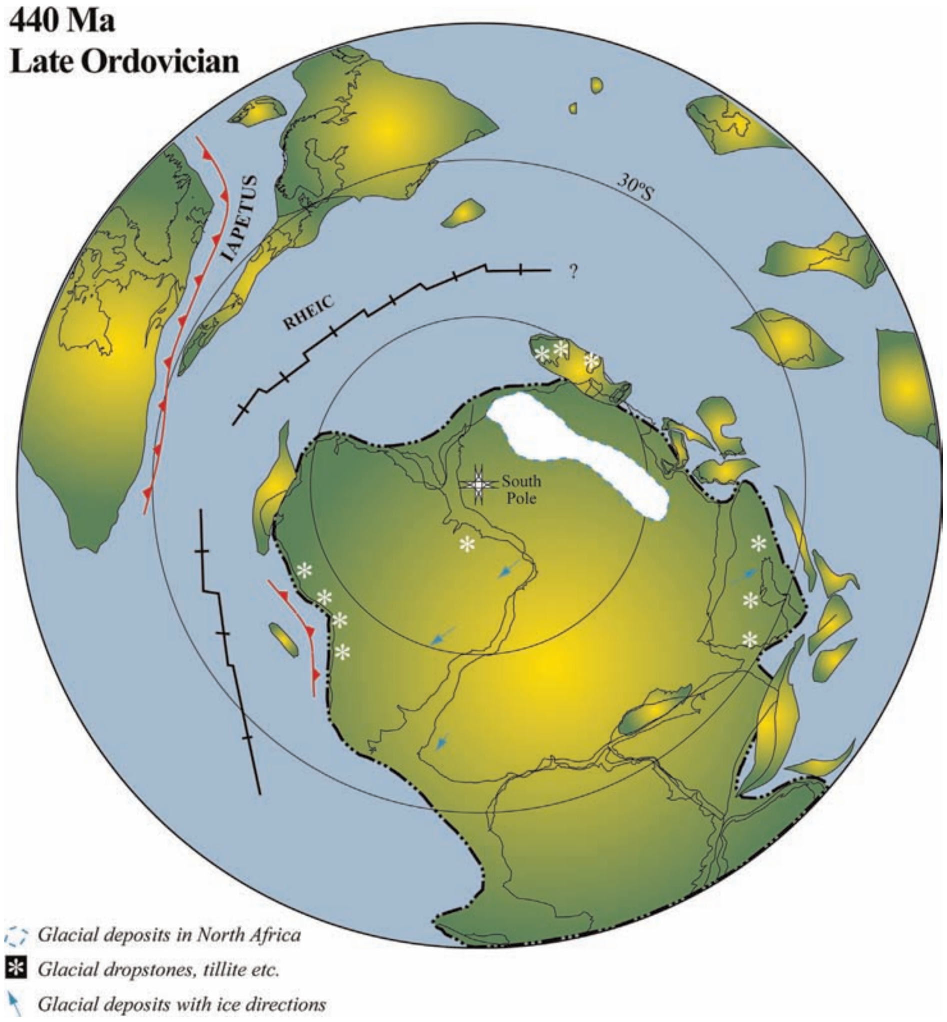


**Fig. 7.** Latest Ordovician–earliest Silurian (440 Ma) reconstruction, modified from Cocks & Torsvik (2002, fig. 6), showing the latest Ordovician (Hirnantian) glacial deposits. Symbols as in Figure 2, terrane names as in Figures 2 and 9.

spreading Iapetus Ocean between Laurentia on the one hand and Baltica and Gondwana on the other. In the earliest Cambrian (Tommotian), before its northward movement, Laurentia was not too far separated from Baltica, a position reinforced by the similarities of the archaeocyathids on both terranes at that time (Debrenne *et al.* 1999). There was a substantial Tornquist Ocean between Baltica and Gondwana. The evidence from the faunal distributions of terrane-dependant benthos, such as brachiopods and most trilobites, shows that Avalonia, Armorica and Perunica were all integral parts of Gondwana at this time; and all at temperate to high palaeolatitudes, with the then South Pole situated in the NW African part of Gondwana.

After moving northwards, Laurentia reached the palaeoequator by the end of the period, where it remained for most of the Palaeozoic, with rich Cambrian and early Ordovician benthic faunas very different from those of the European parts of Gondwana, and generally different again from the faunas of Baltica. Siberia and Kara were clearly not too distant from Baltica at the time, because, although most of their faunas were distinct from Baltica and there were many endemic genera, particularly the articulated brachiopods, there were some key late Cambrian trilobites in common between the three terranes (Rushton *et al.* 2002). However, most of Baltica was inhabited by the widespread Olenid trilobite realm during the late Cambrian, whose distribution was controlled by relatively poor bottom-water circulation and consequent reduction in oxygen levels. That realm is known from several areas and is not terrane-specific, and its widespread late Cambrian distribution makes the identification and elucidation of Cambrian terrane-related faunal provinces much more difficult than at other times.

*Ordovician*

The start of the Ordovician is dated at 488 Ma and its end at 443 Ma, giving a duration of 45 Ma. Exactly when the Iapetus Ocean reached its widest point is uncertain in detail, but it was probably in about the late Tremadoc or early Arenig (*c.* 480 Ma), after which subduction and consequent closure started, with the ocean steadily narrowing through the rest of Ordovician time. Avalonia rifted off from the South American part of Gondwana in the earlier part of the Ordovician, and probably also in the Arenig, with a widening Rheic Ocean to its south. Whether or not that rifting and ocean-floor spreading was part of the same tectonic process as the Iapetus closure is uncertain. The Tornquist Ocean (Cocks & Fortey 1982) between Avalonia and Baltica was also narrowing throughout the Ordovician, with subduction beneath Avalonia, and finally closed at about Ordovician–Silurian boundary time with the soft oblique Avalonia–Baltica docking (Torsvik *et al.* 1996; Torsvik & Rehnström 2003). Thus Avalonia was an independent terrane for less than the total duration of the Ordovician. Perunica also rifted from Gondwana during the early Ordovician and proceeded across the Rheic Ocean; Havlíček *et al.* (1994) concluded that it had its highest proportion of endemic terrane-specific brachiopod and trilobite genera in the mid-Ordovician (Caradoc), indicating substantial oceanic separation around it. In contrast, southern Europe (Armorica and the terranes to the east of it) clearly remained part of Gondwana itself, as can be deduced from both the facies and faunas (Robardet 2003). That part of Gondwana was close to the South Pole, whose probable position was in modern Libya. We present three Ordovician reconstructions. The first map (Fig. 5), is for the Early Ordovician (Arenig, 480 Ma),

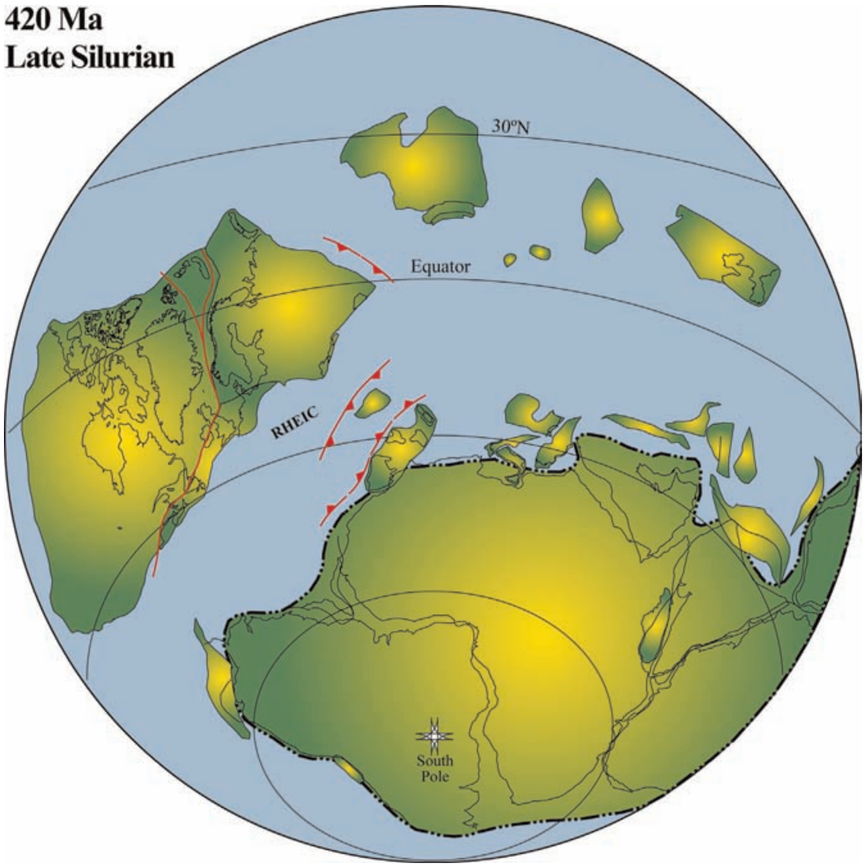


**Fig. 8.** Late Silurian (Ludlow–Přídolí, 420 Ma) reconstruction, modified from Cocks & Torsvik (2002, fig. 8). Symbols as in Figure 2; terrane names as in Figures 2 and 9. Figures 8–10 are Schmidt's Equal Area Projection, with projection centre at 30°S.

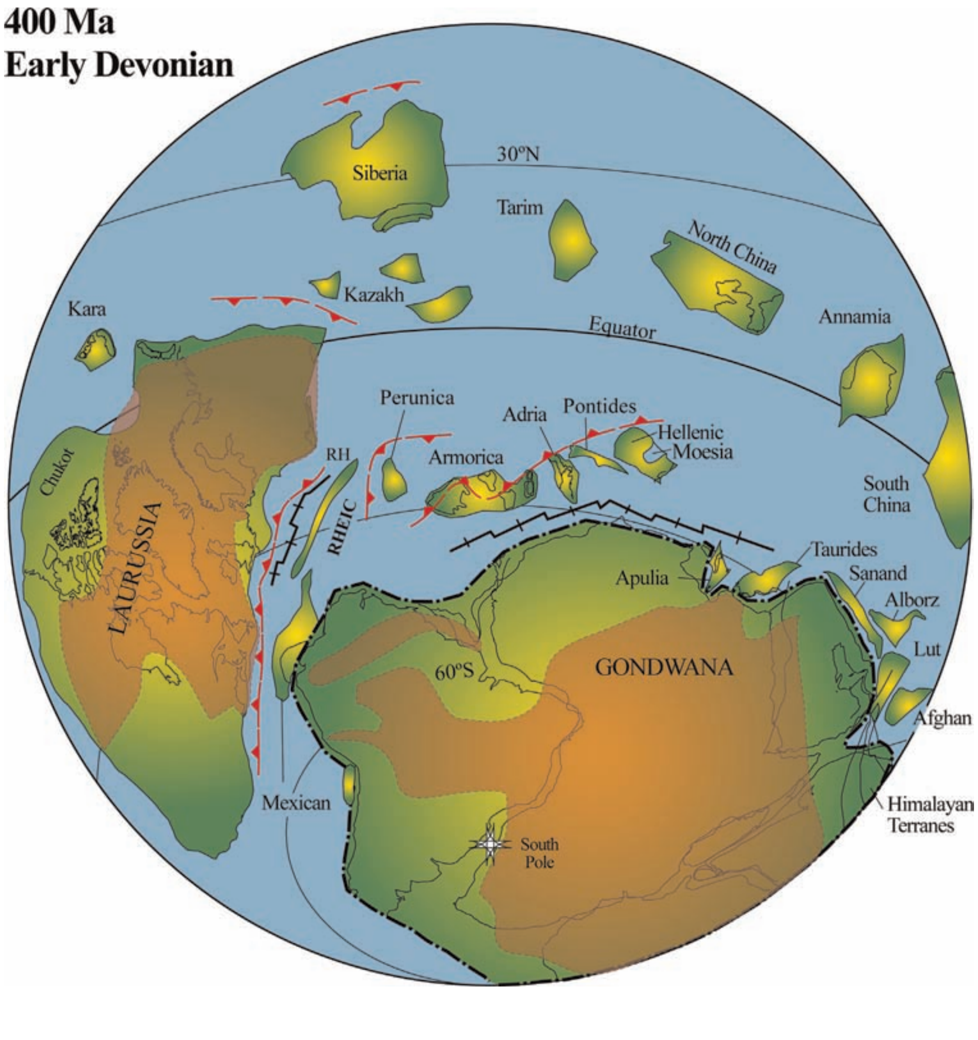


**Fig. 9.** Early mid-Devonian (Emsian, 400 Ma) reconstruction, modified from Torsvik & Cocks (2004, fig. 5), also showing the Old Red Sandstone continents in Laurussia and Gondwana. Symbols as in Figure 2; terrane names are labelled. The outline of the Rheno-Hercynian (RH) Terrane is arbitrary.

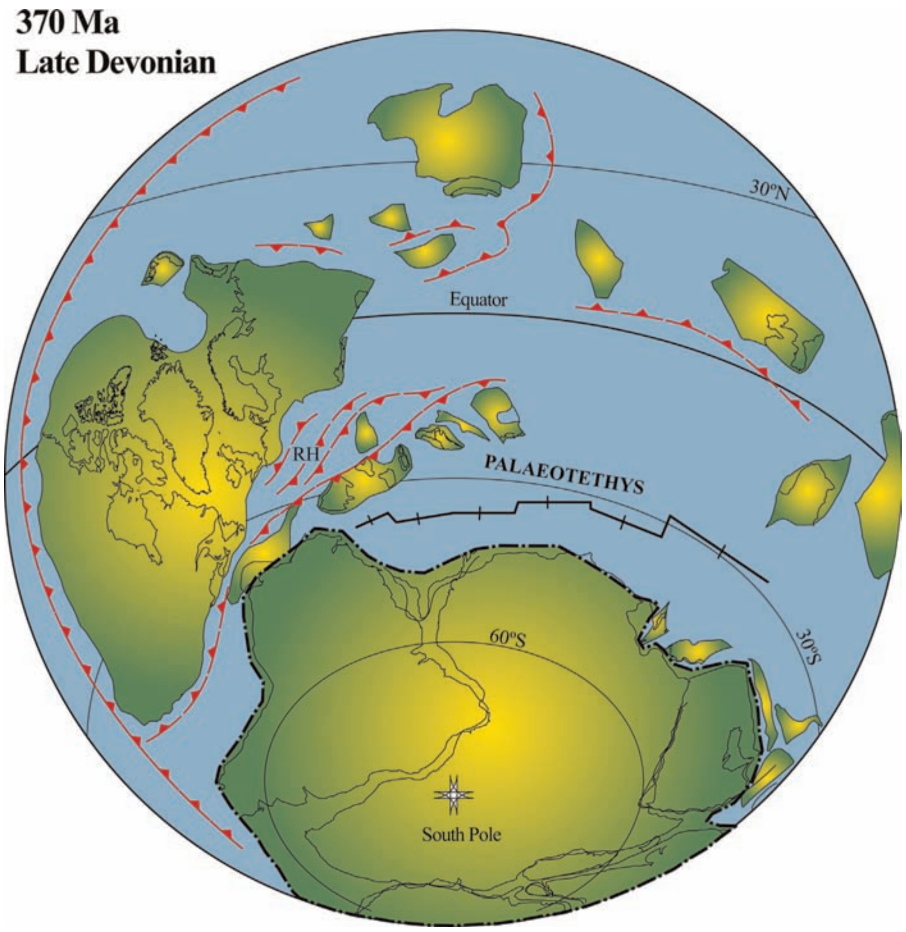


**Fig. 10.** Late Devonian (Famennian, 370 Ma) reconstruction, modified from Torsvik & Cocks (2004, fig. 6). Symbols as in Figure 2: terrane names as in Figure 9. The Rheno-Hercynian (RH) Terrane was in the process of amalgamation with Laurussia at this time.

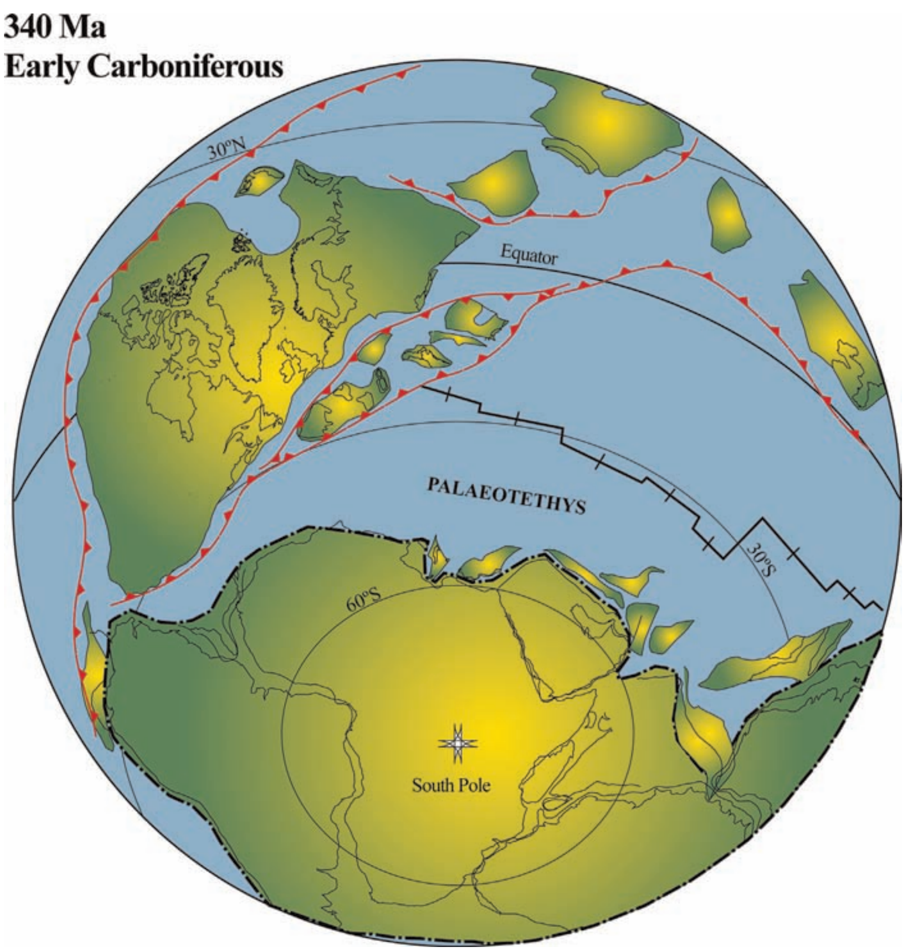


**Fig. 11.** Early Carboniferous (Tournaisian, 340 Ma) reconstruction, modified from Torsvik & Cocks (2004, fig. 8). Figures 11 and 12 are Schmidt's Equal Area Projection, with projection centre at 15°S. Symbols as in Figure 2; terrane names as in Figure 9. The Sibumasu Terrane (unlabelled) is shown as largely attached to the NW Australian part of Gondwana.

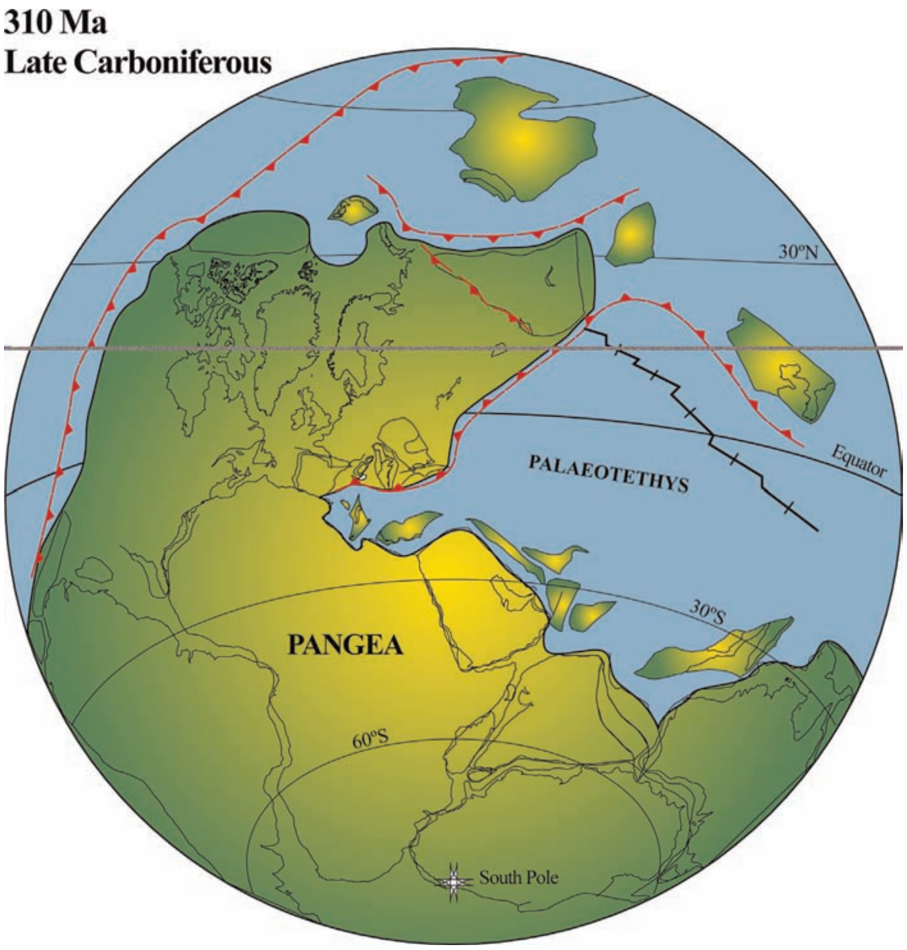


**Fig. 12.** Late Carboniferous (Westphalian, 310 Ma) reconstruction, modified from Torsvik & Cocks (2004, fig. 9). Extensive glacial deposits (not shown) covered much of the Southern Hemisphere. Symbols as in Figure 2; terrane names as in Figure 9.

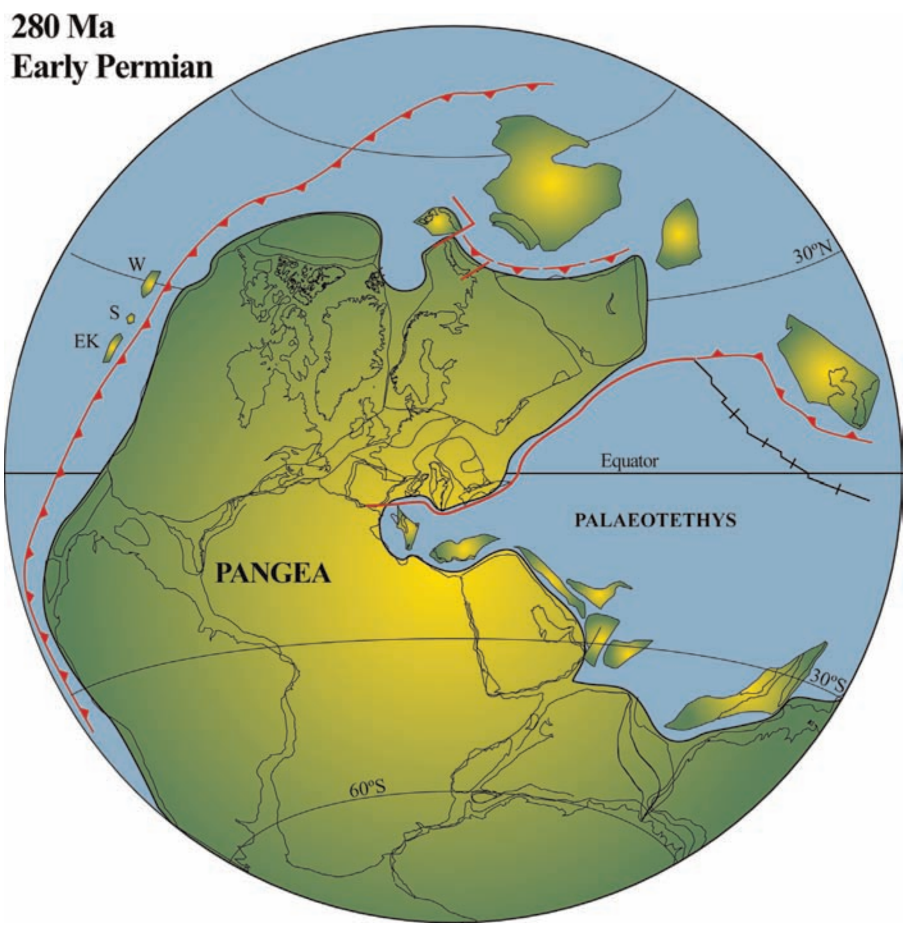


**Fig. 13.** Early Permian (Asselian, 280 Ma) reconstruction of the Western Hemisphere, modified from Torsvik & Cocks (2004, fig. 10). Extensive glacial deposits (not shown) covered much of the Southern Hemisphere. Figures 13 and 14 are Schmidt's Equal Area Projection, with projection centre at the Equator. Symbols as in Figure 2; terrane names as in Figure 9. W, Wrangellia–Alexander Terrane; S, Stikinia Terrane; EK, Eastern Klamath Terrane.

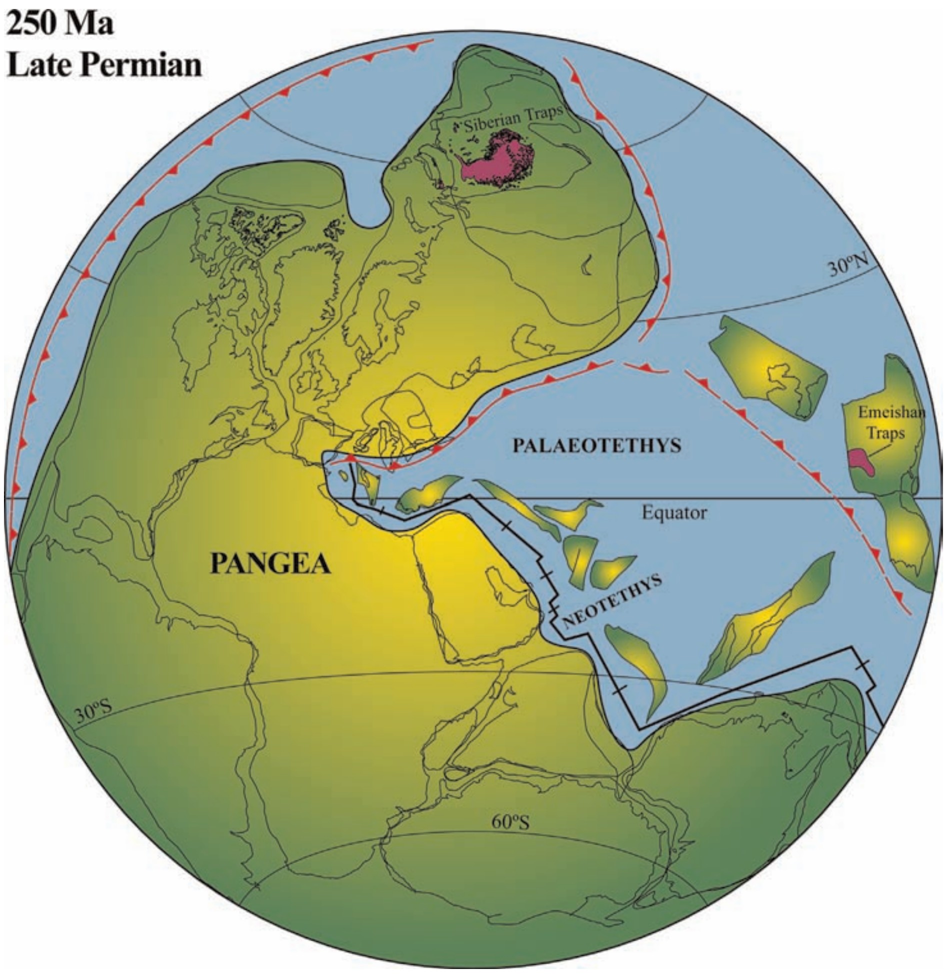


**Fig. 14.** Permo-Triassic boundary (250 Ma) reconstruction of the Western Hemisphere, modified from Torsvik & Cocks (2004, fig. 11), also showing the flood basalts in Siberia and China. Symbols as in Figure 2; terrane names as in Figure 9.

when the different benthic trilobite faunal provinces indicate that the Iapetus was at its widest (about 5000 km), and with Baltica well separated from both Gondwana and Laurentia. The second map (Fig. 6), for the mid-Caradoc (460 Ma), shows an independent Avalonia between a closing Iapetus and an opening Rheic, and also the initial sea-floor spreading of the ocean, which was separating Bohemia and Annamia (Indochina) from Gondwana. Our third reconstruction, at 440 Ma (Fig. 7), although technically representing Silurian time (the Ordovician–Silurian boundary was at 443 Ma), has plotted on it the latest Ordovician glaciogenic deposits, which were laid down during the half-million-year glacial interval of the Hirnantian Stage of the latest Ashgill Series.

### *Silurian*

The start of this system is dated at 443 Ma and the end at 416 Ma, giving a duration of 27 Ma; much shorter than the other systems that preceded and followed it in the Palaeozoic. The major tectonic event was the acme of the Caledonian (including Scandian) Orogeny of eastern North America, the British Isles and Scandinavia, caused by the collision of Laurentia with the combined Baltica–Avalonia. Our first map, for 440 Ma (Fig. 7), shows the Baltica–Avalonia docking completed but with a narrow Iapetus Ocean separating that combined terrane from Laurentia. Although that ocean may have contained islands, it was still an effective barrier to the migration of ostracodes (which have no planktonic larval stages) until near the end of the Silurian. In the early Ordovician, Avalonia had been at high latitudes and Baltica at intermediate latitudes, but they both drifted northwards after that and were in tropical palaeolatitudes during the Silurian, with substantial carbonate deposits, including the famous bioherms of Gotland, Sweden, and Wenlock Edge, England. It is from Wenlock age beds in Britain that the first true land plants from anywhere are known (although trilete spores inferred to have come from land plants are known from as early as the mid-Ordovician). By the time of our second reconstruction, at 420 Ma (Fig. 8), Baltica, Avalonia and Laurentia had all coalesced to form the new superterrane of Laurussia, thus completing the jigsaw for the northern parts of today's Europe. The hydrothermal vent communities of Silurian age found in the central Urals (Little *et al.* 1997) provide a sure indication that that area was in a truly oceanic environment, and thus seaward of the eastern margin of Baltica. Zonenshain *et al.* (1990, Fig. 20) showed both the cratonic and the marginal facies that made up the eastern (Ural) margin of Baltica, as well as the fragmented Cambrian to Devonian island arc fragments. All of these were also caught up in the strike-slip movements of the late Palaeozoic Uralian Orogeny, which accounts for the unnaturally straight outcrop of the Urals today.

### *Devonian*

The start of the system is at 416 Ma and the end at 359 Ma, giving a duration of 57 Ma. We present two reconstructions. The first (Fig. 9), at 400 Ma, the early mid-Devonian (Emsian), shows the substantial and largely desert Old Red Sandstone continents present in both Laurussia and Gondwana, although the latter were fringed by seas rich in marine benthos. The new Palaeotethys Ocean, which had probably started its opening in the latest Silurian, included the spreading centre which was by then separating most of Southern Europe (the Armorican Terrane Assemblage, Adria, the Pontides of Turkey, and the Hellenic Terrane including Moesia) from Gondwana (Stampfli *et al.* 2002). The second reconstruction (Fig. 10) is for the Late Devonian at 370 Ma (Famennian); by that time the Variscan Orogeny was at its maximum in the central part of Europe. Winchester *et al.* (2002) have documented the amalgamation of Central Europe. McKerrow *et al.* (2000) have summarized the evidence to show that the Rheic Ocean between Gondwana and Laurussia was not then wide enough to prevent the migration of key faunas during the Late Devonian. The period also saw the start of the relatively brief independent existence of the Rheno-Hercynian Terrane (Franke 2000).

### *Carboniferous*

The start of this system was at 359 Ma and the end at 299 Ma, making it 60 Ma long, the longest in the Palaeozoic. Our two reconstructions are for the Tournaisian at 340 Ma (Fig. 11) and the Westphalian at 310 Ma (Fig. 12). The northern Europe part of Laurussia straddled the palaeoequator. The Palaeotethys Ocean had widened considerably at its eastern end by the start of the Carboniferous, so that Southern Europe (apart from Apulia) was at some distance from the north African part of Gondwana. However, at its western end, and away from the European region, subduction caused contact between the South American part of Gondwana and Laurussia, which formed the incipient superterrane of Pangaea for the first time. By the end of the Carboniferous (Fig. 12), more of the western part of the Palaeotethys had closed, and the Laurussian–Gondwanan collision zone had progressively stretched as far eastward as the Iberian Peninsula. The Kazakhstania Terrane, which had coalesced from numerous fragments over the previous 200 Ma (Sengor & Natalin 1996), and which continued to enlarge by accretion after that, collided with the Uralian margin of Laurussia to cause the Uralian Orogeny. The late Carboniferous and early Permian were marked by a significant glacial episode, which may have persisted for as long as 50 Ma, but the glacial deposits did not reach the lower latitudes of contemporary Europe. The late Carboniferous also saw the most extensive forests of the Phanerozoic, which are very well represented as coal in Britain, Belgium, Germany, Poland and elsewhere in Europe.

### *Permian*

The Permian extended from 299 Ma at its start to 251 Ma at its end, a duration of 48 Ma. Figure 13 shows the situation in the Early Permian (Asselian) at 280 Ma, by which time most of Europe had moved north of the Equator and the coalescence of Pangaea was more complete than in the Carboniferous. Significant evaporite deposits were laid down within the New Red Sandstone deposits that covered much of Europe. Figure 14, for 250 Ma, shows the situation at the Permo-Triassic boundary times, when the vast flood basalts of the Siberian Traps and the Emeishan Traps of China poured out, a period that coincided with, and probably contributed to the causes of, the greatest biological extinction event in the whole of the Phanerozoic. The amalgamation of Siberia with Laurussia also began in the early Permian. Ziegler and coworkers (e.g. Ziegler *et al.* 1997) have provided excellent accounts of Permian geography and climates on a global basis. Glennie *et al.* (2003) have published detailed palaeogeographical maps of the Central European area, showing the progressive migration of the southern margin of the Boreal Ocean (locally termed the Zechstein Sea) over the North–Central European part of Pangaea.

## Concluding remarks

(1) By pooling our separate expertises of palaeontology and palaeomagnetism and combining the results from the numerous researchers in those fields with selected sedimentological data, we have been able to make revised palaeogeographical reconstructions for the whole of the Palaeozoic.

(2) By considering such a considerable length of geological time, from 550 to 250 Ma, we have been made constantly aware of the imperative need to maintain kinematic continuity in the movement of terranes over that 300 Ma period, which we have striven to implement in our successive reconstructions.

(3) By treating Europe in its global context, rather than confining our reconstructions to its modern boundaries, we have become aware of the influence of the various terranes that do not today form part of Europe but whose presence nearby in the Palaeozoic directly affected the current European terrane patterns and geography.

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