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Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review

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Abstract: Palaeomagnetic and faunal data have been re-evaluated on a global basis for the period from 400 Ma (early mid-Devonian) to 250 Ma (latest Permian). The boundaries of the major terranes are considered and defined. Six new palaeogeographical maps at 30 Ma intervals, which ensure kinematic continuity, are presented for this period. The palaeomagnetic data are very useful for positioning terranes for the present-day North Atlantic area, of variable value for China and Tarim, and for much of the large superterrane of Gondwana (being notably poor during the Early Devonian and the Early Carboniferous), and are sparse or non-existent for much of the rest of Asia. The relative positions of Laurussia and Gondwana at the end of the Palaeozoic when they united to form Pangaea are discussed, and it is concluded that the most convincing reconstruction (Pangaea A) is obtained by assuming an octupole contribution of 10–15% in combination with the main dipole of the Earth's magnetic field. As well as faunal and palaeomagnetic data, the disposition of the major sediment types, including coal deposits, evaporites and glacial deposits, has also been considered, especially in the late Carboniferous and Permian.

Keywords: Late Palaeozoic, palaeogeography, palaeomagnetism, brachiopods, fish, plants.

In our previous review (Cocks & Torsvik 2002) we considered Earth geography from late Cambrian to early mid-Devonian time, 500–400 Ma ago. In it we set out our principles for the use of palaeomagnetism and for the selection of key faunas, with subsidiary sedimentological and climatic criteria, for the identification and positioning of the major terranes through time, and these principles we also follow here. Prior to the earliest *in situ* ocean floor preserved today, which is of mid-Jurassic age, the relative positioning of old terranes can be recognized only by palaeomagnetism (which can only constrain palaeolatitude and plate rotation), and by identifying and discriminating between the distributions of the various faunas and floras in their successive provinces, which can indicate terranes with similar faunas as close to each other or, conversely, indicate their separation. A strength of our work is that these two methods are entirely independent of each other. The disposition of key sediments, such as glacial deposits, coals and evaporites, can also be useful, although they are largely latitudinal rather than terrane specific. We have largely omitted islands and island arcs from our reconstructions, but they were no doubt present throughout the interval. Of course terranes could move, divide or collide only through the normal plate tectonic processes of ocean-floor spreading, subduction or transform faulting. The history of the various orogenies and the identification and dating of old sutures must also be taken into account, and a paramount factor is the kinematic continuity necessary for plausible successive reconstructions. We indicate some spreading centres and zones of subduction (their polarity can often be uncertain or disputed) on our maps, which were essential for the movement of the terranes, but more were undoubtedly present. Each terrane shown on our maps has boundaries that are delineated today entirely by post-Palaeozoic tectonic processes and thus do not represent real Late Palaeozoic geography. A landmark publication was the review of Palaeozoic palaeogeography and biogeography edited by McKerrow & Scotese (1990). In the introduction to that volume Scotese & McKerrow (1990) presented a new set of maps, and it is instructive to compare those maps with the ones published here to demonstrate the integration of new data and the progress and development of fresh ideas since 1990. Equally significant was the substantial review by Van der Voo (1993), which remains an invaluable database for palaeomagnetism and global and regional plate reconstructions.

At the start of our time interval for this paper, at 400 Ma in the early to mid-Devonian, the geography was dominated by two major superterranes, Gondwana (which included South America, Africa, peninsular India, Antarctica and Australia, among other areas) and Laurussia (which included North America, northern Europe and other areas merged along the Caledonian sutures); their delinations are described in more detail below. Before the end of our time interval, at the end of the Permian, these two superterranes, and others such as Siberia, had amalgamated into the Pangaea supercontinent that dramatically changed the distribution of land and sea areas. In contrast to our earlier work (Cocks & Torsvik 2002) on the Early Palaeozoic, in which the overall quality of the palaeomagnetic data deteriorates as the time interval progressed, the quality of the palaeomagnetic data from 400 Ma to 250 Ma improves with time, and at 250 Ma is very well constrained for the major terranes. Throughout the interval, and continuing from the Early Palaeozoic, world geography was dominated by the immense Panthalassic Ocean, which was comparable in size with the Pacific today.

There is a substantial controversy on the junction and configuration of Pangaea near the end of the Palaeozoic. All researchers have agreed that by the mid-Jurassic at 170 Ma, the so-called Pangaea A reconstruction of Figure 1 is accurate. Yet for the Carboniferous and the Permian there are several contrasting reconstructions (Van der Voo 1993; Torsvik & Van der Voo 2002), one of which shows South America adjacent to North

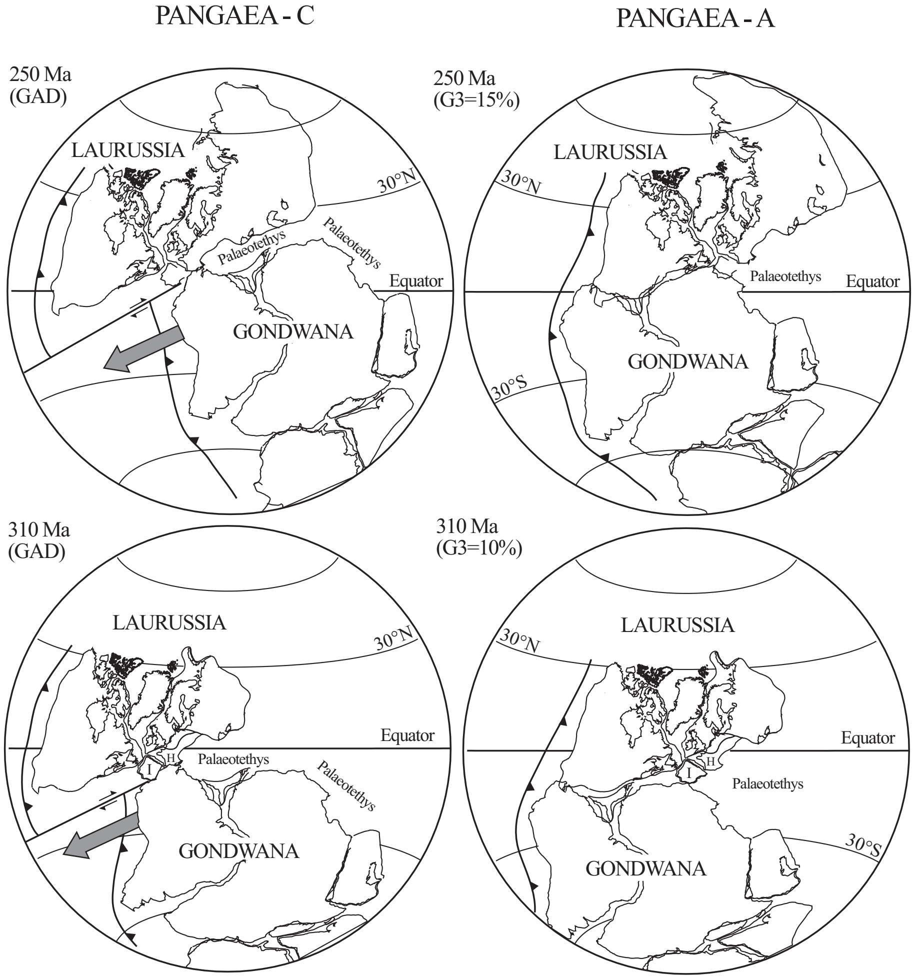

Fig. 1. Examples of contrasting reconstructions for Gondwana and Laurussia at 310 Ma (late Carboniferous) and at 250 Ma (late Permian), based on geocentric axial dipole (GAD) models (left) and partial octupole (G3 in percent) contributions (right). The GAD reconstruction causes considerable overlap between Laurussia and Gondwana, and thus Gondwana has been moved 6000 km sideways, and the arrows show that Gondwana must be displaced dextrally to achieve a Pangaea A fit (the well-established starting point for Pangaea break-up in the Jurassic). The right-hand diagrams remove most of this overlap, but not all the terranes present then are shown here. I, Iberian peninsula; H, central European Hercynian amalgamated terranes. Modified from Torsvik & Van der Voo (2002).

America (very similar to the 170 Ma Pangaea A), and at the other extreme with South America adjacent to southern Europe (termed here Pangaea C); a relative difference of about 6000 km in Figure 1. Van der Voo & Torsvik (2001) and Torsvik & Van der Voo (2002) have explained the probable basis of these large differences: Pangaea C (or B, in which Laurussia and Gondwana occupy intermediate positions between A and C: see discussion by Van der Voo (1993)) can be generated by assuming a geocentric axial dipole (GAD) field throughout Earth history, and Pangaea A by assuming a non-dipole, octupole, field contribution of about 10–15% for the Permian (of the same sign as the main dipole field), or a combination of octupole field contributions and sedimentary inclination shallowing, as the latitude error for inclination shallowing and octupole fields are similar (Fig. 2). This is discussed further below.

The chief purpose of the present work is to present reconstructions showing all the Earth's major terranes for this 150 Ma interval, and these have been compiled to take account of both the palaeomagnetic data where available and also the distributions of a few of the terrane-diagnostic faunas at 30 Ma intervals across this important part of the Phanerozoic. Unlike our work on the Early Palaeozoic (Cocks & Torsvik 2002), which considered only marine faunas, in the Late Palaeozoic there are considerable terrestrial floras and faunas also preserved. The latter underpin the elegant maps of Ziegler and his colleagues (e.g. Ziegler *et al*. 1997, 1998; Gibbs *et al*. 2002; Rees *et al*. 2002) for the Permian, in which lands of varying heights are also shown. Their reconstructions demonstrate that in the Permian there was a comparable amount of dry lands to today, in great contrast to, for example, the Ordovician, during which many large continents (e.g. Laurentia) appear to have been largely flooded by the sea (the Iapetus Ocean).

We will commence with a brief analysis of the key faunal and floral groups and climatic data useful for analysing palaeogeography in this long period, and follow with characterizations and descriptions of each major terrane. We continue by introducing the Pangaea problem and then presenting new maps of integrated global geography and key faunal elements for each of our 30 Ma intervals, together with a short historical narrative for each of the successive periods. We conclude with our resolution of the problems concerning the different reconstructions of Pangaea. The time scale we use mainly follows McKerrow & van Staal (2000), rounded to the nearest 1 Ma.

Biota and climatic data useful in analysing palaeogeography

The principles used in this paper are the same as those stated by Cocks & Torsvik (2002) and Fortey & Cocks (2003). Different fossil groups can be used in the elucidation of old geographies, depending not only on their actual distributions during a particular geological time interval but also on the work that has

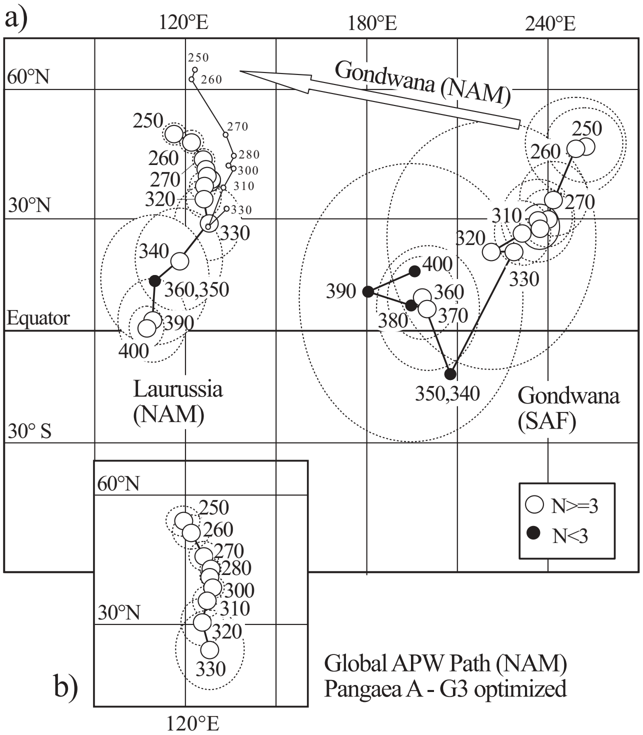

Fig. 2. (**a**) Apparent polar wander (APW) paths for Laurussia (NAM, in North American coordinates) and Gondwana (SAF, in South African coordinates). Both APW paths are GAD running mean paths (20 Ma window lengths from 400 to 250 Ma) and shown with A95 confidence circles. ○, Mean poles are of high quality; ●, mean poles are of poor quality. We also show the GAD-based Gondwana APW path rotated into NAM coordinates, but shown without A95 cones for diagram simplicity. (**b**) A combined APW for Laurussia and Gondwana, but with all mean poles recalculated with non-dipole octupole contributions (10–15%) to maintain a Pangaea A configuration. Galls projection. Mean north poles and relative continental fits after Torsvik & Van der Voo (2002).

currently been achieved on each group; climatic and sedimentological data can also help. Those fossils and sediments we have used to help determine Late Palaeozoic palaeogeography in this paper are now reviewed briefly in turn, but the individual significance of the papers cited is developed in the historical narrative later in this paper.

Brachiopods

Articulated brachiopods are important parts of the terrane-dependent benthos throughout our period, and the faunal provinces defined by Boucot & Blodgett (2001) and others for the Devonian and Shi & Archbold (1998) and Angiolini (2001) for the late Permian are used here. Inarticulated brachiopods have a long larval life and are less useful than articulates in identifying terranes.

Molluscs

Cephalopods, particularly nautiloids, are vital for dating, but because of their swift dispersal and ability to cross oceans, have not been used here. Bivalves and gastropods are part of the benthos when adult and can be useful; for example, Eager (1984) demonstrated that the distribution of the non-marine bivalves indicates that all the Variscan sutures in Europe had closed by the late Carboniferous (Westphalian).

Benthic Foraminifera

There are no planktonic Foraminifera until the Mesozoic: the benthic Foraminifera are known from the Cambrian, but only in the late Palaeozoic do they become important indicators. The fusulines, in particular, were highly provincial in the later Carboniferous and Permian: their perforate schwagerinid outer walls were probably symbiotic with algae and they were thus confined to the photic zone.

Other invertebrates

Trilobites became progressively less abundant and diverse with time, in contrast to their great importance in the Early Palaeozoic (e.g. the early Ordovician). Although a minority were nektonic, most were part of the benthos, but we have not used them. Other arthropods were evolving during this time, some within terrestrial environments, but their global distribution is not yet known exhaustively enough to be considered relevant here. The distribution of corals, bryozoans and stromatoporoids can be important in showing provinciality (e.g. the corals used by Smith (1988) in the Carboniferous of SE Asia). Although each of the last three groups occur to some extent at most latitudes, carbonate buildups and great diversities in all three are present only in tropical areas. We use some of the bryozoan distributions of Ross (1981) in our early Carboniferous reconstruction (see Fig. 8). Enough is not yet known for any distribution of the other phyla, such as echinoderms and worms, to be useful in assessing the relative position of terranes; however, various animals were temperature dependent and could provide a useful check on the palaeogeography.

Vertebrates

Fish, both marine and non-marine, are important in distinguishing between ancient terranes (e.g. Young 1990, 1993; Ahlberg cited by McKerrow *et al*. 2000), and we show some of them on our late Devonian (370 Ma) map (see Fig. 7). Although this was an important time for the vertebrates, including the initial colonization of the land, groups other than fish were not distributed widely enough to be useful; apart from the conodonts, which, although important for dating, dispersed too quickly to leave terrane-specific signatures. However, the various conodont provinces do reflect palaeolatitudes, and these have been shown in the Permian by Mei & Henderson (2001).

Plants and their microfossils

The distribution of early trees is important in distinguishing between some terranes during the Carboniferous and Permian (e.g. Rees *et al*. 2002); the main floral provinces have been known for many years and are shown on our Early Permian reconstruction (see Fig. 10). However, the other plant groups, including the abundant planktonic microfossils such as acritarchs, chitinozoans and spores, although they are often useful for dating and can also reflect ambient temperatures and thus palaeolatitudes, are not usually linked to any particular terrane, and thus have not been used in this paper.

Climates and sedimentological data

Carbonates, particularly in massive buildups such as reefs, are more common in lower latitudes, although there has been no space to include carbonate deposits on our maps. Evaporites too were mostly located in desert belts, which were usually situated within 20 and 30 degrees north and south of the Equator; we show their distribution in Figures 9–11. In contrast, glacial and periglacial deposits, such as dropstones, were formed at high latitudes; these are notably important in the late Carboniferous and early Permian. Coals, which we show on the maps for the late Carboniferous and Permian (Figs 9–11), tend to form in the cooler higher latitudes of both hemispheres in humid wet belts as well as in the hot wet equatorial regions. The Late Palaeozoic glacial interval could have lasted as long as 50 Ma, from about 330 Ma, the Viséan (Veevers & Powell 1987) to 280 Ma, the Sakmarian (Gibbs *et al*. 2002). Much work has been achieved on climatic reconstructions based on sediment type, largely for the Permian (e.g. Ziegler *et al*. 1998; Rees *et al*. 2002), and we have also taken this into consideration where appropriate.

The terranes and their margins

Here we review and partly revise the outlines and margins of the major terranes in turn. Their names and positions are shown on a modern map for Eurasia (Fig. 3), and at 400 Ma for most of the world in Figure 5. However, nearly all the terrane margins are the result of post-Palaeozoic tectonics and thus the margins shown in our diagrams are very different from those actually present at the various time intervals shown in Figures 5–11. We list first the Laurussian, Gondwanan and peri-Gondwanan terranes, followed by the others. No separate entry is made in this section for Pangaea, which is shown in Figures 1 and 9–11 and discussed in more detail later in this paper. Some modern coastlines are included on some of the terranes in our maps, but only to aid recognition. The basic palaeomagnetic data that we have used in the positioning of our major terranes through time are shown in Table 1, and many of the sampling sites in Figure 3. The availability and quality of the palaeomagnetic data are shown in Figure 4.

Laurussia and Laurasia

The earlier terranes of Laurentia (which had comprised most of North America, the Chukot Peninsula of Siberia (Fig. 3), Greenland, Spitsbergen and the NW British Isles), Avalonia (parts of eastern North America and some of NW Europe), and Baltica (northern Europe eastward to the Urals) had combined in the Caledonide Orogeny before 400 Ma to form the superterrane of Laurussia (Ziegler 1989; Torsvik *et al*. 1996). Other smaller terranes undoubtedly existed near North America, but for lack of data we have omitted these, apart from in our Early Permian reconstruction (Fig. 10), in which the Wrangellia–Alexander, Stikinia and Eastern Klamath terranes are shown based on faunal data (Belasky *et al*. 2002). Elements of what had been Baltica, particularly along the modern southwestern margin and near the Trans-European Suture Zone, are still in dispute, but we include the Malopolska and Lysogory terranes of Poland, which today include the Holy Cross Mountains, within Baltica (Cocks 2002), in contrast to Moesia, which was peri-Gondwanan (see below under the Hellenic Terrane). Laurussia was further enlarged to form Laurasia, commencing with its merger with the Altaids during the peak 290–300 Ma Uralian Orogeny. There was a further phase lasting until about 250 Ma or the Earliest Mesozoic, by which time Siberia and Kara had also joined the supercontinent. However, because this was after the Laurussia–Gondwana collision that formed the initial Pangaea, Laurasia never existed as an independent terrane in the Palaeozoic. The internal Laurussian fits that we show on our figures follow Model

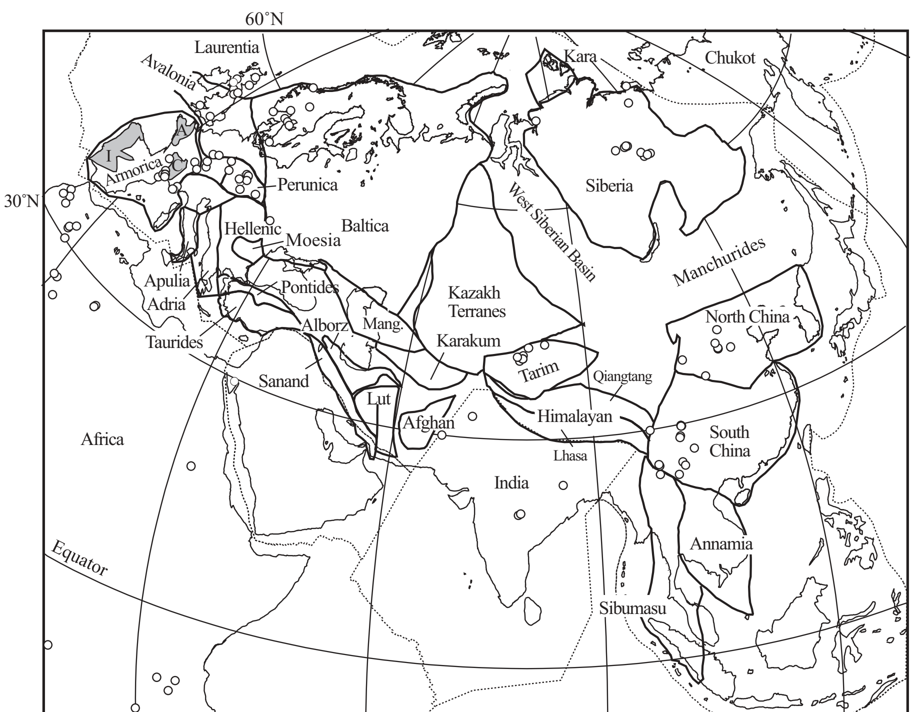

Fig. 3. Europe, Asia and northern Africa today; fine dotted lines indicate modern plate boundaries, and bold lines outline the major terranes discussed in this paper. I, Iberia; A, Armorica; C, Central France; Mang., Mangyshlak Terrane. The Tarim Terrane includes Qaidam. ○, palaeomagnetic sampling sites we have used within the 400–250 Ma range (a single circle often represents multiple sampling sites). Sites outside the map area in Gondwana have been shown by Torsvik & Van der Voo (2002) and those in Laurentia byTorsvik *et al*. (1996, 2001).

Table 1. *Mean palaeomagnetic north poles for selected continents with reasonable or some data coverage*

Continent	370 ± 10 Ma GAD	340 ± 10 Ma GAD	310 ± 10 Ma G3 = 10%	280 ± 10 Ma G3 = 12.5%	250 ± 10 Ma G3 = 15%
Pangaea A[1]	NR	NR	36/127	44/128	54/119
Laurussia[2]	10/110	19/118	Pangaea	Pangaea	Pangaea
Gondwana[3]	9/199	−2/208	Pangaea	Pangaea	Pangaea
Siberia[4]	10/117	16/150	36/146	49/145	Pangaea
North China[5]	56/336	54/342	56/353	54/001	54/006
South China[6]	−9/198	No data	−12/250	No data	52/223
Sibumasu[7]	−66/314	No data	−33/238	No data	33/339
Tarim[8]	0/156	20/162	52/166	61/159	71/155

REFNO, Global Palaeomagnetic Data Base Reference Number (McElhinny & Lock 1996). GAD, geocentric axial dipole model; G3, octupole contribution (see Torsvik & Van der Voo 2002); all poles recalculated from original sources. NR, not relevant.

[1]Running mean path in North American coordinates (Torsvik & Van der Voo 2002).

[2]Running mean path in North American coordinates (this study; based on Torsvik *et al*. 1996, 2001).

[3]Spline path in South African coordinates (Torsvik & Van der Voo 2002).

[4]Running mean path (this study; based on Smethurst *et al*. 1998, and REFNO 3486).

[5]Running mean path/interpolation (this study; based on REFNO 2706, 3086, 2704, 2460, 2710, 2327, 3086, 1722, 2327, 2714, 2701, 2327, 3299).

[6]Running mean path/interpolation (this study; based on REFNO 1682, 2713, 2763, 2702, 1621, 2764, 2763, 2348, 2369, 2697, 2369, 1428, 2369, 2369, 1722, 2703, 2714, 2764, 2697, 1722, 2778, 2699, 2327, 2479, 1682, 2700, 2697, 3215, 2534, 2534, 2550).

[7]Early Devonian (370 entry), Late Carboniferous (310 entry) and Early Triassic (250 entry) poles (Chan *et al*. 1984; Fang *et al*. 1989; Huang & Opdyke 1991).

[8]Running mean path/interpolation (this study; based on REFNO 1425, 1389, 2388, 2388,1951, 2569, 2569, 1951, 2569, 1951, 2313).

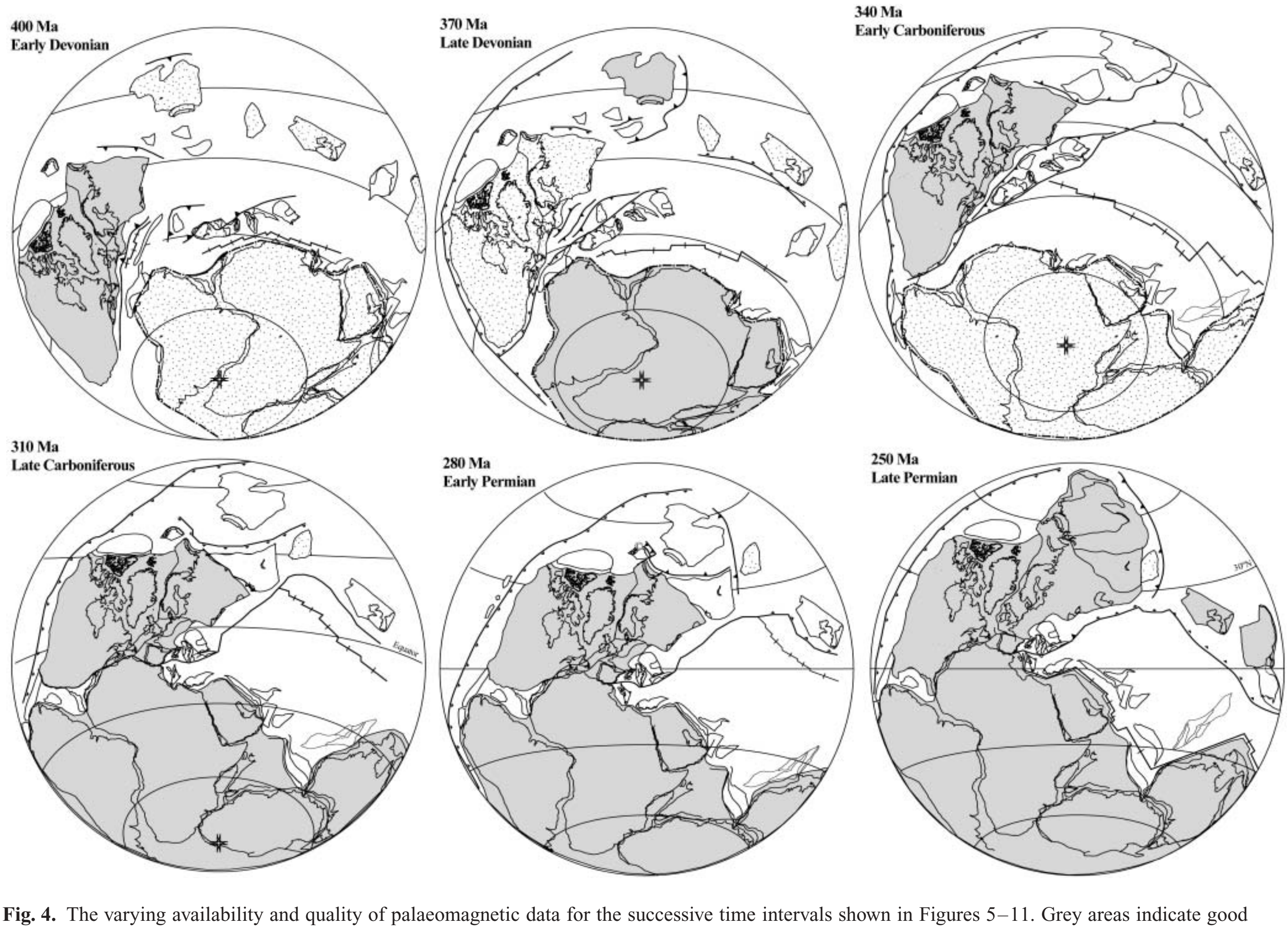

Fig. 4. The varying availability and quality of palaeomagnetic data for the successive time intervals shown in Figures 5–11. Grey areas indicate good quality data (well-defined APW or two or more consistent poles); fine dotted areas indicate some confidence; white areas, little or no confidence.

I of Torsvik *et al*. (2001), except Figure 1, which follows Model II of Torsvik *et al*. (2001).

Gondwana

The Gondwanan core, whose perimeter is shown by the bold dot–dashed lines in Figures 5, 6 and 8, consisted of Africa, most of Sicily, Arabia, Madagascar, peninsular India, most of Antarctica, most of Australia, New Guinea, and most of South America. Our outline and internal fits follow various workers and have been summarized and modified by Torsvik & Van der Voo (2002). New Zealand was divided into North and South. Timor was a Late Palaeozoic extension of Australia (Charlton *et al*. 2002). Florida was also an integral part of Gondwana and is included using the fit of Lawver & Scotese (1987). Gondwana formed at about 550 Ma, but several terranes had already left Gondwana between 500 and 400 Ma (Cocks & Torsvik 2002), including Avalonia and Perunica; however, the superterrane had gained by the accretion of the Argentinian Precordillera Terrane during the Silurian. During the period between 400 and 250 Ma, Armorica and various other terranes in southern Europe and the Middle and Far East also left Gondwana (see below). Gondwana merged with Laurussia to form Pangaea at about 330 Ma (Figs 9–11).

Armorica

This is often termed the Armorican Terrane Assemblage, as it includes not only the classic Armorican area of NW France but also the Massif Central and the Iberian Peninsula (apart from the westernmost South Portuguese Zone; Cocks 2000) with which we associate Sardinia and Corsica. We exclude Perunica (see below). The relative positions of NW Armorica and Iberia are corrected for the Bay of Biscay movements during Cretaceous time, and there are also corrections that reflect the late Tertiary opening of the western Mediterranean Balearic Basin between Iberia on the one hand and Corsica, Calabria and part of Sicily on the other. Workers have agreed that Armorica was originally part of core Gondwana, but have differed substantially on its time of departure from Gondwana, which has been shown as ranging from the Cambrian onwards. We have modified our earlier positioning of Armorica (Cocks & Torsvik 2002) for both palaeomagnetic and faunal reasons (Robardet *et al*. 1990): we again show it as separate from Gondwana before 400 Ma, but not to have progressed so far across the Palaeotethys Ocean (see the 400 Ma section below).

The Rheno-Hercynian Terrane

All the margins of the Rheno-Hercynian Belt of north–central Europe are tectonically deformed, but for a short period within the Devonian this formed a separate terrane, after the Rheic Ocean had closed between Avalonia and parts of Armorica (within the Northern Phyllite Zone) and then reopened as the Rheno-Hercynian Ocean along a different suture. The latter is seen today between the Northern Phyllite Zone and the Mid-German Crystalline High (Franke 2000).

Perunica

Often termed Bohemia and sometimes the Tepla–Barrandian terrane. We have arbitrarily included the area north of the Bohemian basin so as to coincide with the SE boundary of Laurussia, with which it collided in the Hercynian Orogeny in the early Carboniferous. Originally undoubtedly part of Gondwana, but opinions differ on whether or not it formed part of Armorica; we treat it as a separate terrane for the faunal and palaeomagnetic reasons stated by Cocks & Torsvik (2002).

Apulia, Adria, Hellenic and Moesia terranes

We follow Stampfli *et al*. (1998) in the outlines and integrity of Apulia (southern Italy apart from Calabria and most of Sicily), Adria (Adriatic and adjacent area) and the Hellenic Terrane (Greece and adjacent areas) as separate terranes, although there are no useful palaeomagnetic data for the Late Palaeozoic (except Permian data from Adria summarized by Muttoni *et al*. (2001)), and terrane-contingent fossils have not been identified on any of the three terranes for our periods. However, we have grouped Moesia with the Hellenic Terrane and placed all these terranes in the peri-Gondwana area, as the data from Bulgaria summarized by Yanev (2000), although sparse, suggest that Moesia carried peri-Gondwanan rather than Baltic trilobites and also relatively high-latitude acritarchs during the Ordovician. Adria, the Hellenic Terrane and Moesia, together with the Pontides and Armorica, separated from core Gondwana perhaps in the latest Silurian, but Apulia probably did not leave Gondwana until the Neotethys Ocean opened in the mid- to late Permian.

Pontides and Taurides

These two terranes, both of which are largely in modern Turkey, are separated today by Mesozoic and later rocks and tectonic zones. They were separate parts of peri-Gondwana, as discussed by Fortey & Cocks (2003), with the Pontides of northern Turkey at a higher palaeolatitude than the Taurides of southern Turkey in the Early Palaeozoic, and they were still apparently separate at the end of our period. From the contained late Ordovician and early Silurian fossils, we include the Istanbul area within the Pontides, rather than as a separate terrane adjacent to Baltica (like Moesia) as shown by Stampfli *et al*. (1998); and consider the Pontides as having been adjacent to the Adria and Hellenic terranes in the Late Palaeozoic. Again, there are no useful Palaeozoic palaeomagnetic data, and terrane-contingent fossils are sparse, but we can postulate fewer subduction zones and tectonic events if the Pontides were linked with Armorica, Adria, the Hellenic Terrane and Moesia in leaving Gondwana together during the Silurian (with the opening Palaeotethys), and the Taurides, Apulia and the Middle Eastern terranes were amongst those leaving Gondwana during the Permian with the opening of the Neotethys.

Mangyshlak and Karakum terranes

As there are no rocks older than mid-Devonian known from within the Mangyshlak Terrane, it was not identified and differentiated on our Early Palaeozoic maps (Cocks & Torsvik 2002). Today its northern boundary is the SE of Baltica to the west and the Karakum Terrane to the east (Fig. 3), and its southern boundary is adjacent to the Mesozoic and later South Caspian Terrane (Cocks 2000), which we do not show separately on our maps. Its Late Palaeozoic terrane movements are obscure, but the Permian brachiopods indicate Gondwanan affinity. The boundaries of the Karakum (variously known as Karaku or Karakorum) Terrane, which lies to the north of the Mangyshlak Terrane, follow Yakubchuk (2002); once again, there are few distinctive faunal or palaeomagnetic data from that terrane, apart from the Permian brachiopods documented by Angiolini (2001), which indicate Gondwanan affinity.

Middle Eastern Peri-Gondwana

The Lut, Alborz and Sanand terranes, mostly today in Iran, and also the Afghan Terrane to the east of them, were separate tectonic units. However, we follow Millson *et al*. (1996) in grouping them together for the purpose of our evolving reconstructions. Von Raumer *et al*. (2002) showed a Palaeotethys Ocean and a spreading centre between these terranes and Gondwana in their earliest Ordovician map (490 Ma), and they also showed the same ocean (but no wider) in their Silurian (420 Ma) map. However, we know of no evidence for any such opening of the Palaeotethys in that area until the Carboniferous or Permian, and we have also found no compelling faunal or tectonic evidence to link the Middle East terranes directly with the Taurides, Pontides, Apulia and the Hellenic terranes. We thus disagree with the reconstructions of Stampfli & Borel (2002), which show a so-called Hun Superterrane uniting the two terrane groups.

Himalayan terranes

The Lhasa Terrane of south Tibet and the Qiangtang Terrane of north Tibet were eventually independent. However, although there is an absence of palaeomagnetic data, they are treated as part of Gondwana on our maps in view of the Gondwanan biota present there during the Carboniferous and Permian (Smith 1988); that is, until our Late Permian reconstruction (Fig. 11), by which time the Qiangtang Terrane appears to have left Gondwana: the evidence has been reviewed by Metcalfe (2002), who in contrast also concluded that the Lhasa Terrane left Gondwana only in the Late Triassic.

Mexican terranes

Several separate terranes between the southern margin of Laurussia (the Ouachita Front of the USA) and NW South America were present as independent entities. They were apparently peri-Gondwanan in the Early Palaeozoic, apart from the relatively small Caborca Terrane of NW Mexico (not shown on our maps), which was part of Laurentia. In our 400–340 Ma reconstructions we show the Mexican terranes diagrammatically as a single entity attached to South America, but as three separate terranes from 310 Ma onwards. These three, termed the Chortis, Oaxaquia and Yucatan terranes, are positioned following Keppie & Ramos (1999), and all three had apparently joined Laurussia by 310 Ma.

Siberia

This is restricted to include the old Angaran craton of modern political Siberia, and also the Baikalides, which accreted to Angara in the late Precambrian. We follow the outline of Rundqvist & Mitrofanov (1993), which includes most of the Baikalides, and treat also the central and southern parts of the Taimyr Peninsula as integral parts of the terrane. The terrane merged with the Laurussian part of Pangaea at around 260–250 Ma, well after the peak of the Uralian Orogeny, which was at 300–290 Ma: by comparing our Figs 9–11 it can be seen that the convergence was very oblique and this resulted in the relatively straight lineament of the Urals today. Our later date for the convergence of Siberia is substantially different from all other published reconstructions (e.g. Scotese & McKerrow 1990). To the west of Siberia is the very large early Mesozoic and later Western Siberian Basin, which covers the Palaeozoic rocks and their sutures (Nikishin *et al*. 1996). The Late Palaeozoic palaeomagnetic database for Siberia is poor apart from Late Permian times.

Kara

This terrane, consisting of northern Taimyr, Severnaya Zemlya and the surrounding shelf seas, was independent in the Early Palaeozoic (references in Cocks & Torsvik 2002). It merged with Siberia in late Carboniferous–Permian times (Torsvik & Andersen 2002), although folding along the northern Siberian margin continued well into the Mesozoic (Late Triassic–Early Jurassic).

North China

The terrane includes most of the Korean Peninsula, but not all of northern China today, and is termed by some workers the Sino-Korean Terrane. We follow the outline of Rong *et al*. (1995) and various other workers in the divisions of China, with North China's southern boundary at the Qinling Line, and the western margin at the western boundary of the Huanghe Region. It includes the North Tarim Terrane of Yin & Nie (1996).

South China

Sometimes termed the Yangtze Terrane, the outline also follows Rong *et al*. (1995) and previous workers. The terrane amalgamated with Annamia before the late Carboniferous (Hutchison 1989; Metcalfe 2002). On geological grounds, the terrane can be judged to have collided with North China in the late Triassic, although palaeomagnetic data indicate differential movements (rotation) between North and South China until the mid- to late Jurassic (Enkin *et al*. 1992).

Tarim and Qaidam

We follow the boundaries of Tarim shown by Zhou & Chen (1992), with the northern boundary at the Tien-Shan fold belt. Although tectonically separate from Tarim, the Qaidam Terrane appears to have been closely connected to the south of it, and we combine the two in our reconstructions. The North Tarim area of Yin & Nie (1996) is included within our definition of the North China Terrane. Tarim appears to have collided with the Kazakhstania Terrane in the Permian (Sengor & Natalin 1996): this is corroborated by palaeomagnetic data.

Other Asian terranes

There are a variety of other terranes in Asia that we do not show on our maps (e.g. Fig. 3), partly through lack of helpful faunas and palaeomagnetism and partly because of lack of consensus amongst other workers. One is the Baoshan Terrane of Wang *et al*. (2001) in SW China and Burma (Myanmar) at around 99°E and 24°N, which includes Lower Permian (Artinskian) basalts. This occupies some of the same ground as the Simao Terrane, which Metcalfe (1998) originally showed as a possible northwards extension of Sibumasu, but later (Metcalfe 2002) considered as adjacent to or part of the South China Terrane. Metcalfe (1998) also showed a separate Kunlun Terrane between the Qiantang Terrane and Tarim–Qaidam; and a West Burma Terrane west of Sibumasu, which may be an eastwards extension of the

Lhasa Terrane, but it probably did not form until the Mesozoic (Metcalfe 2002).

Sibumasu

Sometimes termed Shan-Thai or Sinoburmalaya, this terrane stretched from eastern Burma (Myanmar) and SW China (eastern Yunnan Province) through western Thailand and NW Malaysia to Sumatra. Its boundaries are as shown by Cocks (2001). Its eastern boundary is plotted in this paper as congruent with the western boundary of Annamia, with which it collided in the latest Triassic or early Jurassic (Hutchison 1989). Its late Palaeozoic positions are controversial and not yet completely resolved. In the Early Palaeozoic its facies and faunas reveal it as close to South China (Cocks & Torsvik 2002; Fortey & Cocks 2003), and a comparable peri-Gondwanan position west of the Australian part of Gondwana is indicated by the distribution of Permian brachiopods (Angiolini 2001). This is also the positioning preferred by Ziegler *et al*. (1997) and Metcalfe (1998, 2002). However, palaeomagnetic data for the terrane indicate an early Devonian palaeolatitude (for the northern part of the terrane) of $43(+8/-7)°$S (Fang *et al*. 1989), and a late Carboniferous palaeolatitude (Huang & Opdyke 1991) of $45(+11/-9)°$S (GAD-based calculations). If these palaeomagnetic results are correct, and if our placing of Gondwana is also correct, the only space available in which to place Sibumasu on palaeomagnetic criteria would be to the east, rather than to the west, of the Australian part of Gondwana (or alternatively in the northern hemisphere; Cocks & Torsvik 2002). However, following Metcalfe (2002) and others, we have decided to position Sibumasu west of Australia; but to do so we have had to adjust the position of Sibumasu 2000 km farther northwards than the existing palaeomagnetic data suggest, to avoid overlap with India and the Himalayan terranes. Our 250 Ma reconstruction (Fig. 11) uses the early Triassic pole of Chan *et al*. (1984), which suggests that Sibumasi had departed by then from the Australian margin, perhaps together with the Qiangtang Terrane during the opening of the Neotethys Ocean. It should be noted that the palaeomagnetic data suggest that Sibumasu had geographically rotated before the end of the Permian (compare Fig. 9 with Fig. 11), although the tectonic processes responsible for the rotation are uncertain.

Annamia

Often known as Indo-China or Indosinia, this terrane includes part of eastern China today, as well as Laos, Vietnam, Cambodia and eastern Thailand. Its northern boundary is emended here to be congruent with the eastern boundary of South China, with which it amalgamated before the late Carboniferous (Hutchison 1989; Metcalfe 2002). The eastern part of the west Malaysian peninsula, in which the earliest known rocks are of early Carboniferous (Viséan) age, is included within Annamia here, although Hutchison (1989) recognized three separate terranes in that area.

Kazakh and adjacent terranes

On structural criteria Sengor & Natalin (1996) identified a substantial number of separate Palaeozoic terranes in the large area of central Asia to the east of the Urals, south of the Siberian Terrane (as defined above), east of North China, and north of the main peri-Gondwanan collage. The area includes the Altaids. From independent Ordovician and Silurian faunal data, and by considering the structural divisions within Kazakhstan today, Fortey & Cocks (2003) have confirmed the separate integrity of four of these Kazakh terranes and suggested their positioning relative to each other and to Baltica, Siberia and the neighbouring peri-Gondwanan terranes in the Early Palaeozoic. These are the Chu-Ili, Tien-Shan, Chingiz and Altai-Sayan terranes. Few reliable palaeomagnetic data are yet published from this substantial area, except North Tien-Shan, which was located at *c*. 15°N and 30°N in the Carboniferous and Permian, respectively (Bazhenov *et al*. 2003). Most of the Kazakh terranes had amalgamated with each other and with Baltica to their west to form part of Laurussia during the Uralian Orogeny from 290 to 300 Ma, but tectonic interaction continued between them until after the close of our period (Sengor & Natalin 1996). In our 400 Ma and 370 Ma reconstructions we show three arbitrary relatively small ‘Kazakh’ terranes as separate, and a so-called Kazakhstania Terrane in our reconstructions from 340 Ma to 250 Ma: its size is smaller in the 340 Ma map than in the later ones. From 370 Ma onwards the outline of Kazakhstania and the subduction zones around it follow Sengor & Natalin (1996). The margins of the Kazakhstania Terrane are likely to be more correct in our 280 Ma and 250 Ma reconstructions, as their positions are delimited by the sutures at the edges of Baltica and Siberia today.

Island arcs

As today, there were several strings of island arcs present during the Mid- to Late Palaeozoic, notably those off SE Australia, northern Laurussia (the Bennett–Barrovia Arc), and elsewhere. In the Mid-Palaeozoic there were certainly arcs to the east of the Urals, as is convincingly demonstrated by the Silurian and Devonian ocean vent faunas now preserved in sulphide ores described by Little *et al*. (1997). Although Late Palaeozoic faunas are known from many microplates within the various arcs, there are no reliable palaeomagnetic data and these small, although undoubtedly in some cases important, areas are omitted from our reconstructions.

Palaeomagnetic data and a lead into the Pangaea problem

Figure 1, which is taken from Torsvik & Van der Voo (2002), shows two different reconstructions of the relative positions of Gondwana and Laurussia at two separate periods (310 Ma and 250 Ma) as they combined to form Pangaea. One reconstruction assumes that the Earth had a GAD field, and the other that the magnetic field was more complex, with a partial non-dipole (octuple) component of the same sign as the dipole field. Most workers have in practice ignored the influence of non-dipole components, and thus the published palaeopoles for Gondwana and Laurussia, if strictly interpreted, have positioned the two chief parts of Pangaea into a reconstruction such as Pangaea C (Fig. 1). The difference between the two assumptions results in contrasting reconstructions that involve relative lateral displacement to each other of about 6000 km or more in the Gondwana–Laurussia docking area (Fig. 1).

Figure 2a shows running mean apparent polar wander (APW) paths for both Laurussia (NAM in North American coordinates) and Gondwana (SAF in South African coordinates) from 400 Ma to 250 Ma at 10 Ma intervals (Torsvik & Van der Voo 2002). In general the quality of data is good for the whole time interval (open circles in Fig. 2a), although there are a few time intervals (filled circles), particularly in the first half of our period (i.e. 400–340 Ma for Gondwana), when the quality of the data is poor. When adjusting for sea-floor spreading and pre-drift extension in the Central Atlantic, it is evident that the APW paths for Laurussia and Gondwana cannot be fully accommodated in a Pangaea A type fit (Fig. 2a). As most other categories of geological data, including those from structural geology and palaeontology, have in practice indicated and favoured reconstructions such as the Pangaea A of our Figure 1, we have opted to recalculate all palaeomagnetic poles to include an octupole field contribution, thus reconciling the palaeomagnetic with the other geological data and conclusions. After incorporating octupole contributions, Gondwana poles were transferred into a Laurussia (North America) frame and a joint APW path is shown for the 330–250 Ma interval (Fig. 2b; Table 1). Palaeomagnetic poles from all the continents for 310–250 Ma were recalculated with time-dependent G3 contributions (10–15%) as concluded by Torsvik & Van der Voo (2002). For older time intervals (340 and 370 Ma) we did not recalculate the palaeomagnetic poles, as we have no precise knowledge of the Earth's magnetic field then. The 400 Ma reconstruction (Fig. 5) is also a GAD-based reconstruction, slightly modified from Cocks & Torsvik (2002), and serves as a template for terrane identification. Reconstruction poles for the major terranes from 370 to 250 Ma are listed in Table 1.

Earth geography from 400 to 250 Ma

In the following sections a narrative and maps (Figs 5–11) are presented for 30 Ma intervals from 400 Ma (the early Devonian) to 250 Ma (the latest Permian: the Permo-Triassic boundary is now placed at 248 Ma). The palaeomagnetic data from the whole of each interval have been used to construct these maps, but only selected faunal and climatically sensitive data have been plotted on each of them. However, those fossils shown are much more time-restricted than the palaeomagnetic data (±10 Ma), optimally to periods of about 2 Ma. Because of space constraints on our diagrams, a single data point represents many localities in most instances.

Geography at 400 Ma (early and mid-Devonian)

This interval (Fig. 5) includes the Emsian (beginning at 410 Ma) and the Eifelian (beginning at 394 Ma, ending at 388 Ma). The distribution of the brachiopods in the Emsian on largely the same reconstruction was shown in our previous paper (Cocks & Torsvik 2002, fig. 9), on which was plotted the various faunal provinces from Boucot & Blodgett (2001), and these distributions showed differentiation between the Rhenish–Bohemian (or Old World) Realm, the Appalachian Realm and the high-latitude Malvinokaffric Realm: this geography is well supported by good palaeomagnetic data, particularly from the present-day North Atlantic area. However, in the present paper we have modified the positions of Armorica and the Adria, Pontides and Hellenic terranes: in our previously published map we showed Armorica as having left Gondwana prior to 400 Ma, with a widening Palaeotethys Ocean between Armorica and Gondwana, but with Adria, the Pontides and the Hellenic Terrane still attached to Gondwana. Despite the cogent arguments of Robardet *et al.* (1990), and other workers, that there are no persuasive structural or palaeontological reasons to suppose that Armorica became detached from Gondwana before the late Devonian, we have nevertheless preferred the alternative arguments of Stampfli & Borel (2002) and therefore show a widening Palaeotethys Ocean between these terranes and Gondwana. Whether or not the four terranes were amalgamated to form part of what Stampfli & Borel (2002) termed the Hun Superterrane is, however, doubtful.

We have also changed the positions of North and South China in our reconstruction. Both blocks have been updated with new palaeomagnetic information and we have also inverted the polarity of North China poles; in Figure 4 we show North China low in the northern hemisphere, whereas in our earlier paper (Cocks & Torsvik 2002) we showed it in low southerly latitudes. The South Tien-Shan (Kazakh) brachiopods in the Emsian and Eifelian include *Megastrophia uralensis* and *Zdimir pseodobashkiricus*, which provide direct faunal links with the Urals, and these are not known from Tarim. The true location of Annamia is unknown, and the position for Sibumasu is also uncertain; there are contemporary faunas known from both terranes, but these are not helpful in deciding where the terranes were then (see also discussion under the Sibumasu Terrane above). For example, the brachiopods described from the Devonian of southern Thailand (part of Sibumasu) by Boucot *et al.* (1999) are from a deeper-shelf community, and, despite an endemic genus, consist largely of widespread and cosmopolitan forms.

Geography at 370 Ma (mid- and late Devonian)

This interval (Figs 6 and 7) includes the Givetian (beginning at 388 Ma), Frasnian (beginning at 383 Ma) and Famennian (beginning at 377 Ma, ending at 362 Ma). McKerrow *et al.* (2000) have summarized the evidence to show that the Rheic Ocean between Gondwana and Laurussia was not wide enough to prevent the migration of key faunas in the late Devonian. For example, the fish *Holoptychius* was widespead in Laurussia during the Frasnian and Famennian and reached Australia (in Gondwana) during the Famennian, and the Famennian lungfish *Soederberghia* is represented by the same species occurring in Greenland, the USA and Australia. However, we differ from McKerrow *et al.* (2000) in placing the Rheic Ocean to the north of Armorica (Figs 5 and 6), rather than to the south (where we place the incipient Palaeotethys Ocean), and also in placing the palaeoequator 20 degrees farther north (based on the substantial palaeomagnetic data available).

Figure 6 shows the distribution of late Mid-Devonian (Givetian) brachiopod realms and provinces, the definition of which largely follows Boucot & Blodgett (2001), but the locality points are taken from many sources. This is the final period in which the cold-water Antarctic Malvinokaffric Realm, so important in the Silurian and Early Devonian, can be differentiated: its fauna became combined with the other realms by the end of the Givetian. The period is also near the end of the distinction between the two substantial Old World and Eastern American Realms, although relict faunas representing both are found in a few areas in the succeeding Frasnian. In contrast to the seven provinces or subprovinces that Boucot & Blodgett (2001) recognized in the Early Devonian, only two are definable in the Old World Realm in the Givetian: the Cordilleran Subprovince of western and Arctic North America (apart from Nevada, which yields a provincial mix of brachiopods); and the RBU Province, the latter a combination of the Rhenish–Bohemian and the Uralian Subprovinces, both of which were clearly distinguishable in the Emsian and Eifelian. As well as Europe, the RBU Province encompassed much of the world, including Siberia, North and South China, Annamia and the Australian part of Gondwana; however, the few Givetian brachiopods known from the Sibumasu terrane are too deep-water to betoken provincial affinity. The faunas of the Frasnian had an even lower level of global provinciality than those of the preceding Givetian.

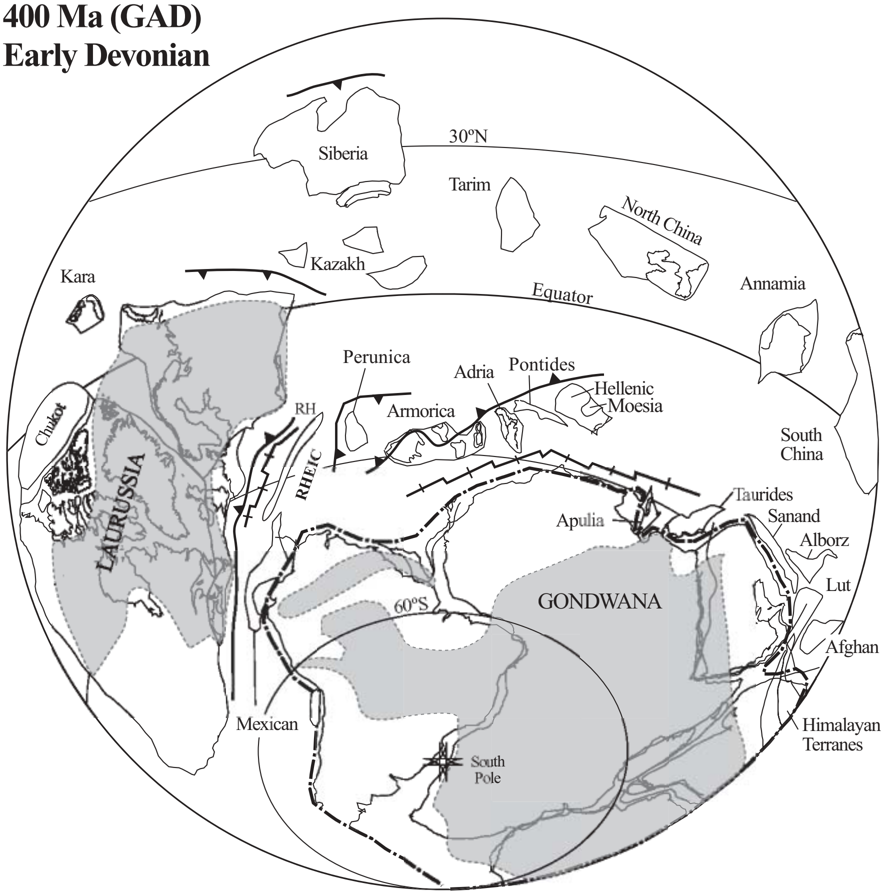

Fig. 5. Reconstruction for early mid-Devonian (400 Ma) times, updated from Cocks & Torsvik (2002, fig. 9), but without the brachiopod faunal provinces and including the names of the various terranes. Bold dot–dashed line shows the margin of core Gondwana. In this figure and in Figures 6–11 some subduction zones (lines with arrowheads indicating subduction polarity), some spreading zones (lines with cross-bars) and some major transform faults (straight lines with no extra ornament) are shown. Within Laurussia the sutures of the previous terranes of Laurentia, Baltica and Avalonia are shown. The Old Red Sandstone continent of Laurussia and other substantial Gondwanan land areas are shaded. The Sibumasu, Lhasa, Qiangtang and Karakum terranes are absent from this diagram, as they were in the other hemisphere; however, the last three were located to the east of the Afghan Terrane and formed parts of the peri-Gondwanan collage. The Kazakh terranes are shown diagrammatically as three arbitrary areas: there were certainly more terranes present and covering a much larger area. RH, Rheno-Hercynian Terrane.

The yunnanolepiform fish had been considered as endemic to South China during this time, but their discovery in Vietnam (part of Annamia) from the Givetian (Thanh *et al*. 1996) has helped us to place the previously poorly constrained latter terrane near South China at that time. We have plotted in Figure 7, which includes the whole world, some of the Givetian fish data from Young (1990), and these clearly demonstrate that some fishes, such as the psammosteids shown, were restricted to Laurussia and adjacent terranes such as Armorica, but that others, such as *Remigolepis*and the sinolepids and yunnanolepids, were restricted to the more easterly terranes such as North China, Annamia, South China and the eastern part of Gondwana. Both these provinces straddled the palaeoequator up to about 30°N and 30°S. However, what we have not plotted in Figure 7 is the distribution data from Young (1990) on the phyllolepid and bothriolepid fish, which are not only found within both the provinces we have plotted but also at higher latitudes in several terranes both north and south of the equator. Figure 7 also underlines how substantial the Panthalassic Ocean continued to be throughout the Palaeozoic.

Geography at 340 Ma (early Carboniferous)

This interval (Fig. 8) includes the Tournaisian (beginning at 362 Ma) and the Viséan (beginning at 334 Ma, ending at 325 Ma). A notable event was the western and central Europe Hercynian Orogeny formed by the collision of European terranes (including Armorica and Bohemia) with Laurussia, ably summarized by Franke (2000). The relative palaeolatitudes of Laurussia and Armorica are corroborated by the distribution of the Viséan miospores plotted by McKerrow *et al*. (2000, fig. 4); although, because they were plankton, they are not terrane-diagnostic (they would have been linked to climatic belts) and cannot therefore be used to identify separate continents. McKerrow *et al*. (2000) showed Gondwana to have collided with Armorica by the early Carboniferous. We show a substantial Palaeotethys, with Gondwana situated in much higher southerly latitudes. South China and Annamia accreted to each other during this period; the process was certainly complete before the late Carboniferous (Metcalfe 2002). Surprisingly few papers have been published on the global biogeography of terrane-specific benthos for this period, but we show some of the generic distributions published by Ross (1981) for the bryozoans on our reconstruction, which show a degree of provincialization. However, in general and in a comparable way to the mid-Silurian (Cocks & Torsvik 2002), the major terranes appear to have been sufficiently close to each other and the global climate insufficiently extreme for there to have been major different faunal provinces within the shelf benthos at that time.

Geography at 310 Ma (late Carboniferous)

This interval (Fig. 9) includes the Namurian (beginning at 325 Ma), the Westphalian (beginning at 315 Ma) and the Stephanian (beginning at 305 Ma, ending at 290 Ma). From rocks of Westphalian age, the same non-marine bivalves are known (Eager 1984) from the Appalachians and over much of northern and central Europe, indicating that all the Variscan sutures had

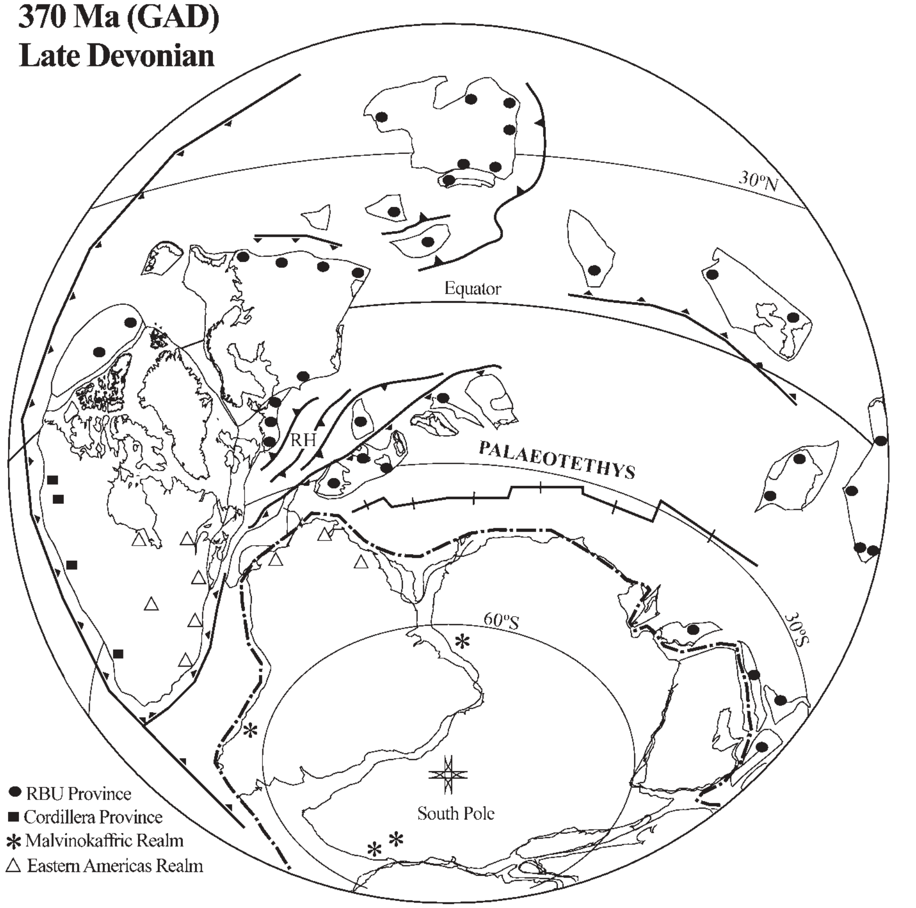

Fig. 6. Reconstruction for mid- and late Devonian (370 Ma) times. Terrane names are as shown in Figures 3 and 5. RH, Rheno-Hercynian Ocean. The three Kazakh terranes are again shown arbitrarily as in Figure 5. The brachiopod realms and provinces for the Givetian are shown, modified from the earlier distributions of Boucot & Blodgett (2001) (for further discussion see text).

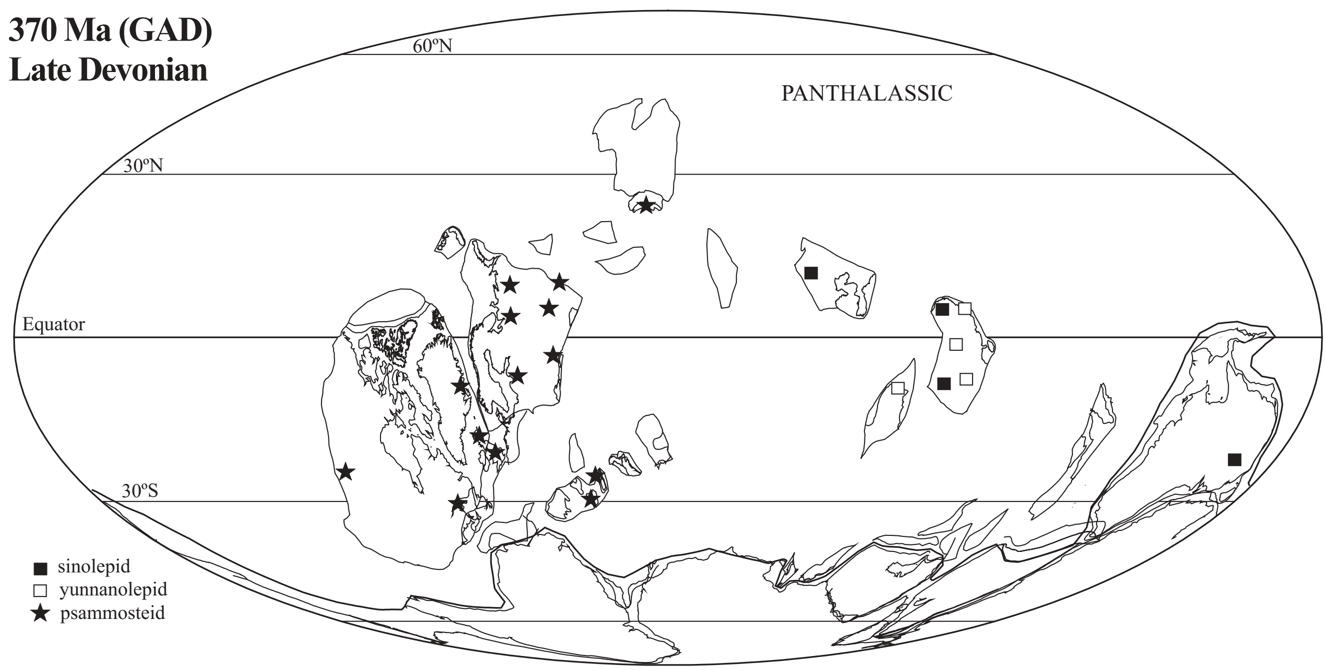

Fig. 7. Global reconstruction for mid- and late Devonian (370 Ma) times on a Mollweide projection, demonstrating the very large size of the Panthalassic Ocean. Selected Givetian fish data are shown from Young (1990) and Thanh *et al*. (1996).

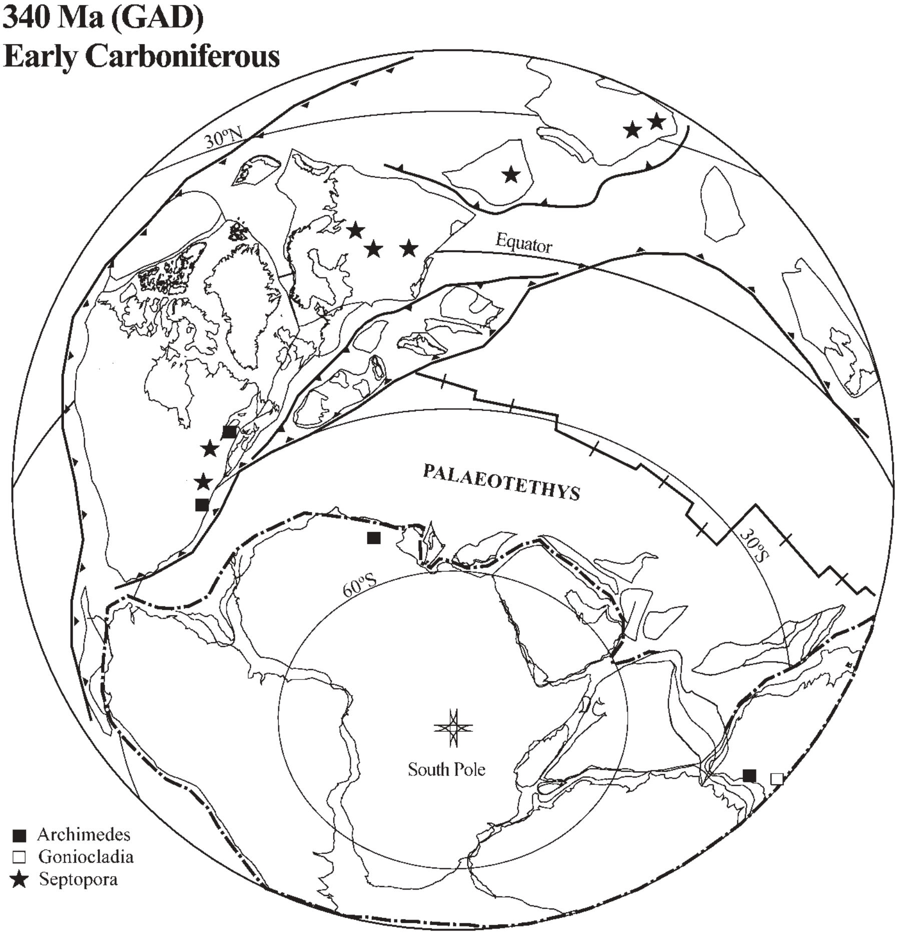

Fig. 8. Reconstruction for early Carboniferous (340 Ma) times. Terrane names are as shown in Figures 3 and 5. Annamia and South China and are missing, as they were located in the other hemisphere. The outline of Kazakhstania is arbitrary: the collage was in process of amalgamation (Sengor & Natalin 1996), but the terrane is shown as smaller than in Figures 9–11. Selected distribution data for some bryozoan genera are taken from Ross (1981).

closed by that time (McKerrow *et al*. 2000). Gondwana collided with Laurussia and intervening terranes, and the Variscan belt of Europe became part of a *c*. 8000 km belt that stretched from the Caucasus to the Appalachian and Quachita mountains (Matte 2001). For the first time, and in particular contrast to the Devonian, the Tarim Terrane and South Tien-Shan area of the Kazakh Terrane carry the same marine brachiopod faunas, indicating closer proximity to each other than hitherto. The conjoined Annamia–South China Terrane does not carry the glacial deposits and colder-water marine faunas characteristic of much of Gondwana and also Sibumasu, confirming the lower latitudes for South China–Annamia suggested by the published palaeomagnetism.

Figure 9 shows the very widespread glacial deposits present in the late Carboniferous, and also the coal deposits, which were at their Phanerozoic maximum at that time (Trappe 2000). The coals were deposited in the two separate hemispheres in belts at temperate palaeolatitudes (Witzke 1990), most notably in the northern hemisphere, which must also have had humid and wet climates at the time, as well as in the equatorial wet belt. Evaporite deposits, whose peak abundances are normally found in the subtropical arid belts at 20–30 degrees north and south of the Equator, are also shown, and their Carboniferous distributions parallel those of today (Scotese & Barrett 1990) except for some low-latitude evaporite occurrences in SW Laurentia. The Variscan Orogeny caused crustal loading and widespread basin formation (Ziegler 1989); the main collision phase ended by the Late Carboniferous and most metamorphic terranes were unroofed before the deposition of late Carboniferous–early Permian strata.

There is considerable uncertainty; for example, few workers agree on the areas of the terranes that formed land above sea level at this time. Many reconstructions show relatively little land; but in contrast Lethiers & Crasquin-Soleau (1995) showed considerably more, and in particular a completely emergent palaeocontinent stretching from northern Canada to the south of South America and Africa, which they interpreted as a barrier for ostracode migration from the diverse and prolific tropical faunas of western North America to central Europe.

Geography at 280 Ma (early Permian)

This interval (Fig. 10) includes the Asselian (beginning at 290 Ma) and the Sakmarian (beginning at 282 Ma, ending at 269 Ma). The southern glaciation continued during the early part of this period. Rees *et al*. (2002) have described the phytogeographical patterns of the Sakmarian and compared them with climatic models derived from synthesis of the distribution of coals, evaporites and aeolian sands, and have identified climatic gradients that changed with time. They estimate the northward movement of Pangaea during the Permian as about 15°; our estimate is rather less, about 10°, but still broadly in agreement. Mei & Henderson (2001) have analysed the distribution of conodonts at five levels through the Permian. Apparently no

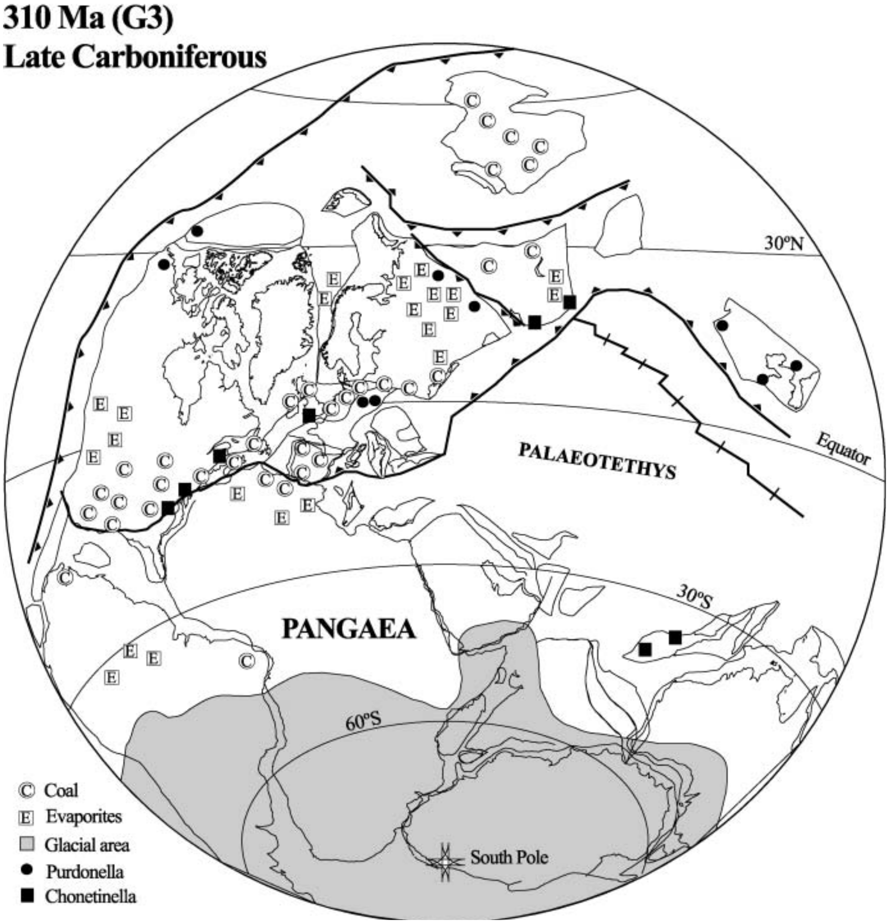

Fig. 9. Reconstruction for late Carboniferous (310 Ma) times. Terrane names are as shown in Figures 3 and 5, except that Laurussia and Gondwana had combined to form Pangaea. Also shown are the glacial deposits (shaded), coal deposits (C), and evaporites (E): data taken from Witzke (1990). Annamia and South China are missing, as they were located in the other hemisphere. The chonetid brachiopod distributions shown are modified from Yanagida (1976).

conodonts existed at higher latitudes than 50°, both north and south of the Equator, but between these palaeolatitudes between two and four provincial zonations can be defined at each level, which are entirely temperature (rather than terrane) related. However, their latitudinal plots very well reflect our overall palaeogeography for both the 280 and 250 Ma reconstructions (Figs 10 and 11). We show in our reconstruction (Fig. 10) the distribution of the various floral provinces, which have been known in general for many years (references in Rees *et al*. 2002). The combined Annamia–South China Terrane carries the flora of the Cathaysian Province (Metcalfe 2002), separating it from Gondwana and also emphasizing the links with North China at that time. The Cathaysian flora found in the eastern part of the west Malaysian peninsula (Hutchison 1989) links it unquestionably to Annamia–South China.

Angiolini (2001) has reviewed the brachiopod provincialization in central and southern Asia, and concluded that there were two provinces in the Roadian–Wordian of the Cimmerian region: the Transhimalayan Province of the Afghan and Karakum terranes, and the more southerly Sibumasu Province, which she extended to include Oman and the Salt Range of India as well as the Sibumasu Terrane itself. In the other hemisphere, Belasky *et al*. (2002) analysed brachiopods, fusulinids and corals to establish the relative positions (from north to south) of the small Wrangellia, Stikinia and Eastern Klamath terranes off the NW margin of the North American part of Pangaea: for lack of data at other times, these latter terranes are shown only on our 280 Ma map (Fig. 10).

The prolonged glacial interval, which had commenced in the preceding Westphalian, lasted for about 50 Ma; and we have plotted the distribution of tillites and other glacial deposits, as well as coals and evaporites for the Early Permian following Ziegler *et al*. (1997) in our new reconstruction. Thus the sedimentological data indicating palaeolatitudes confirm the palaeomagnetic conclusions, in particular in the positioning of the South Pole under the Antarctic part of Gondwana.

Geography at 250 Ma (mid- and late Permian)

This interval (Fig. 11) includes the Artinskian–Kungurian (beginning at 269 Ma), the Uffimian–Kazanian (beginning at 256 Ma), and the Tartarian (beginning at 252 Ma, ending at 248–251 Ma). The Kazanian correlates in general with the Roadian and Wordian. Some workers place the Artinskian and Kungurian into the Early, rather than the Mid-, Permian, but that would make the subdivision of the Permian very unequal in time: the Asselian and Sakmarian total 21 Ma, and from the Artinkian to the top of the Permian is 18–21 Ma. We show the outcrop areas of the widespread volcanic outpourings of the Siberian Traps in Figure 11 and also the very substantial Emeishan Traps of South China, both of which occurred at the same time at about 251 Ma, a date that may eventually prove to be better for the Permo-Triassic boundary than 248 Ma. The Neotethys Ocean between Gondwana and the Arabian and other terranes had opened at about 265 Ma, and was well developed by 250 Ma (Stampfli & Borel 2002). The northern part of Tibet, the Qiangtang Terrane and

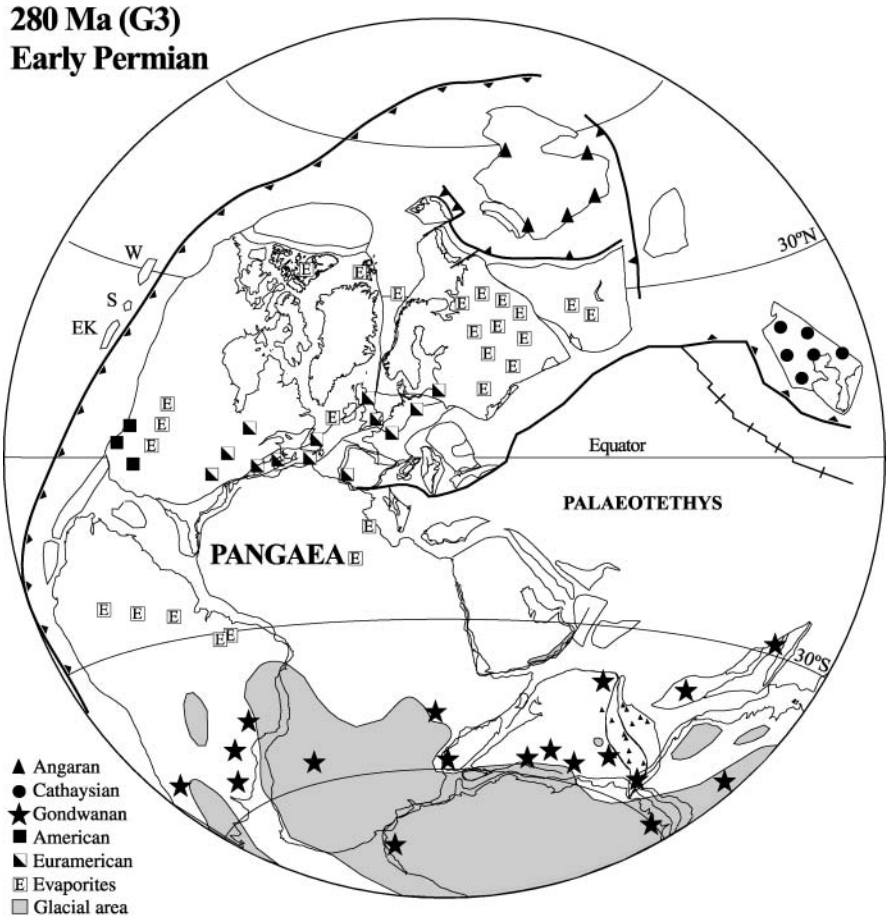

Fig. 10. Reconstruction for early Permian (280 Ma) times. Terrane names are as shown in Figures 3 and 5. W, Wrangellia–Alexander; S, Stikinia; EK, Eastern Klamath terranes. Glacial deposits (shaded) and evaporites (E) are plotted from Ziegler *et al*. (1997). Floral provinces are plotted from various sources (references given by Metcalfe 2002; Rees *et al*. 2002). Annamia and South China are missing, as they were located in the other hemisphere. ▲, sites of glacial diamictites in SE Asia, plotted fromMetcalfe (2002, fig. 4).

Sibumasu, also separated from Gondwana at about the same time and also formed part of the Neotethys rifting event; rather than part of the earlier Devonian–Carboniferous Palaeotethys rifting as preferred by Stampfli & Borel (2002) and (by implication) by Ziegler *et al*. (1997). That later movement is clearly supported by the distribution in Qiangtang of Lower Permian glacial-marine diamictites and cold-water marine faunas shown by Metcalfe (2002, fig. 4). The amalgamation of North China and South China–Annamia commenced during this period (Yin & Nie 1996), but was not complete until the Jurassic. Rees *et al*. (2002) have once again plotted the plant geography and integrated it with the climatic patterns, and showed that the superterrane of Pangaea is at the palaeolatitudes that broadly agree with our independent palaeomagnetic data.

The map (Fig. 11) shows late Permian brachiopods of the Kazanian Stage (the approximate equivalent of the Murgabian and Midian in some terminologies). The localities shown are gleaned from many papers, but the provinces shown follow those in various papers by Archbold and Shi (e.g. Shi *et al*. 1995; Shi & Archbold 1998). These workers have divided the three somewhat generalized faunal realms of many researchers into a number of provinces: the northern part of the Gondwana Realm into the West Arctic and Verkolyma provinces; the lower-latitude Tethyan Realm into the Texas, West Tethyan and Cathaysian provinces; and the more southern part of the Gondwana Realm into the Paratinan/Andean, Westralian and Austrazean provinces. We have included the Trans-Himalayan Province of some workers (e.g. Angiolini 2001) within the West Tethyan Province. However, the boundaries between these provinces were by no means sharp, and Shi *et al*. (1995) have documented 'transitional zones' between some of them. We have shown the distribution of the Sibumasu Zone of Shi & Archbold (1998) in Figure 11. However, the latter was at its most distinctive somewhat earlier, in the late Sakmarian and Early Midian, and by the Kazanian was in the process of coalescing with the Cathaysian Province to its north.

There are no glacial deposits known from this period. The climate was extraordinarily arid, as can be seen from the distribution of the evaporites shown in Figure 11, and the humid wet belts indicated by the coal deposits stretched into the highest palaeolatitudes: both coals and evaporites shown in our figure are taken from Ziegler *et al*. (1997). It is noteworthy that low-latitude coal deposits are missing within Pangaea (arid equator) whereas a wet equator is indicated for terranes in the eastern Palaeotethys (South and North China), which was not part of Pangaea at this time. The end of the Permian marked the largest biotic crisis of the Phanerozoic, with an associated massive series of extinction events, but its causes are outside the scope of this paper.

Resolution of the Pangaea problem

Figure 1 shows comparisons of rather crude maps of Pangaea in which many smaller elements (e.g. the Mediterranean, Tethyan and Mexican terranes and micro-blocks) are not included. This is the case for nearly all previously published papers in which Pangaea A, B and C reconstructions have been discussed. However, in our analysis we now proceed to include all the major

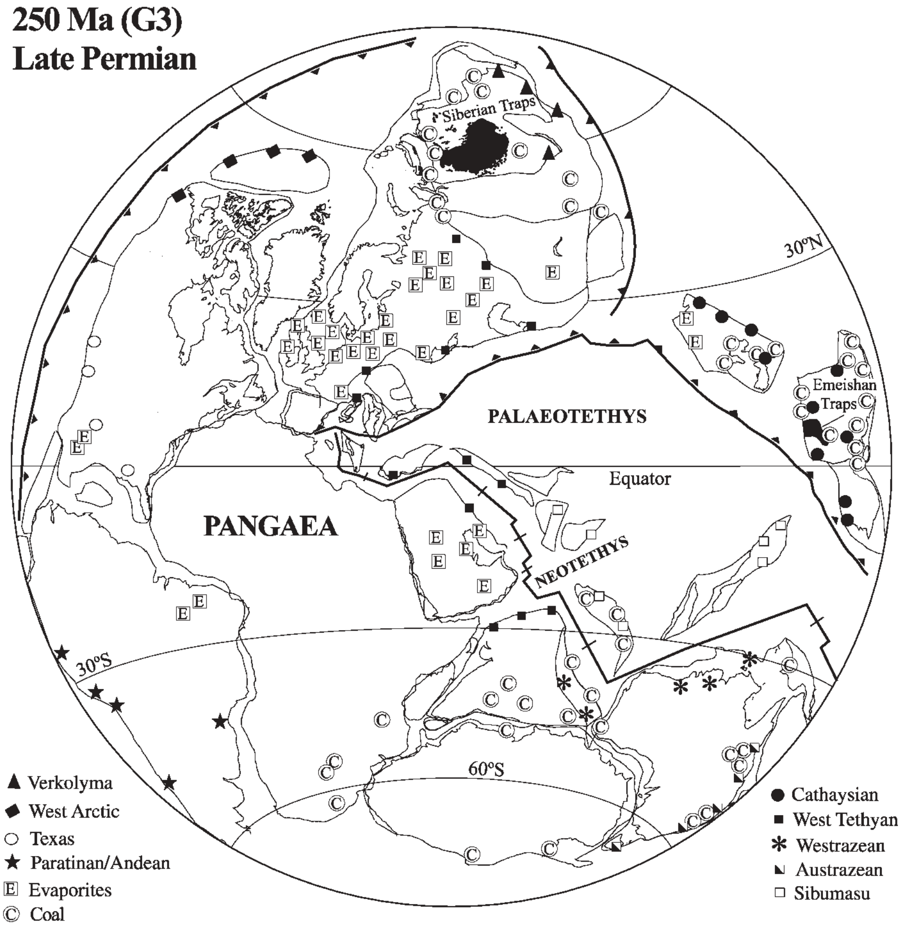

Fig. 11. Reconstruction for late Permian and earliest Triassic times (250 Ma). Terrane names are as shown in Figures 3 and 5. Sibumasu was in the opposite hemisphere. Coal deposits (C) and evaporites (E) are taken from Ziegler *et al.* (1997). The opening of the Neotethys Ocean, which had commenced shortly before this time, should be noted. Brachiopod provinces follow Shi & Archbold (1998) (for further discussion see text).

terranes known to have been present in the late Permian. Thus in our Figures 9–11 we have reconciled palaeomagnetic and geological data by incorporating non-dipole field contributions, with the overall result that our new reconstructions are similar in general to Pangaea A. They also make geological sense, as they explain the developing Variscan belt with peak metamorphism at around 300 Ma, and maintain kinematic continuity over the whole 150 Ma period. In Figure 12 we show the consequences of reconstructing the continents in three different ways.

The Pangaea A part of the diagram is a reduced and simplified version of our Figure 11. The Pangaea B reconstruction (based on a GAD model) is untenable because of the substantial terrane overlap involved: there is no room for parts of the Armorican Terrane Assemblage (e.g. Sardinia and Corsica), Adria, the Hellenic Terrane (including Moesia) and the Pontides of Turkey, unless they were detached from Laurussia and placed further east in the Palaeotethys. The latter, except perhaps for Adria (Muttoni *et al.* 2001), is a most unlikely scenario, as it would imply that the Palaeotethys Ocean never existed and makes the Variscan Orogeny hard to explain. It would also imply the presence of an undetected ocean between Iberia and Sardinia–Corsica, unless it was concluded that it was Florida that collided with the Avalonia–Baltica part of Laurussia; a conclusion that does not seem tenable. Florida would have had to have been detached from Gondwana during the Carboniferous to avoid total overlap with Iberia, which does not agree with the overall geology there either. In addition, the NW part of South America would overlap with the eastern seaboard of North America, and the positioning of the Mexican terranes would be very problematic (the Gondwanan blocks of Mexico were probably accreted to Laurentia during the Carboniferous).

Pangaea C is also reached by assuming a GAD model. That reconstruction resolves the problems of overlaps discussed above, but would also involve a dextral strike-slip east–west movement of *c.* 8000 km between the northern and southern halves of Pangaea during the Triassic and Early Jurassic (>11 cm a^{-1} if we assume that Pangaea A came into existence in the Jurassic): the geology along the potential movement zone does not reflect the sense of movement required (see, e.g. Weil *et al.* 2001). Pangaea C also leaves the Alleghenian mountain belt totally unexplained (nothing collided with Laurentia along that margin). Pangaea B and C reconstructions also necessitate that the Asian blocks must have been further displaced from Laurussia during the Late Permian, which would imply a totally different evolution for the whole Tethyan region than the one normally accepted. Both Pangaea B and C reconstructions must therefore be rejected on geological grounds, leaving Pangaea A as the only viable reconstruction. The latter can be constructed from the palaeomagnetic data with integrity only by incorporating a 15% octupole component into the calculations (Torsvik & Van der Voo 2002), as can be seen from our Late Permian example (Fig. 11). Admittedly, incorporation of non-dipole fields is controversial and the Pangaea problem could partly be caused by sedimentary inclination shallowing (e.g. Rochette & Vandamme 2001), or simply by our palaeomagnetic database being flawed.

Climate modelling for the Permian has been plausibly represented in both Pangaea A and B reconstructions. Ziegler and his colleagues (e.g. Ziegler *et al.* 1998; Rees *et al.* 2002) have used what is essentially the Pangaea A reconstruction, whereas Fluteau *et al*. (2001) have used a model that is closely similar to the Pangaea B reconstruction. Thus the distribution of Permian climatic belts cannot alone differentiate between the validity of the Pangaea A, B and C reconstructions: we have plotted the sedimentological data on both Pangaea A (Fig. 11) and Pangaea B (Fig. 12) maps for comparison. These reconstructions show a rather broad arid belt with evaporites in Laurussia and parts of Gondwana, well-developed northern and southern humid wet belts with coal deposits, whereas equatorial coals are present only in South and North China. No polar glaciations are known during the Late Permian.

Conclusions

(1) Recalculation of palaeomagnetic data to include a non-dipole component (Torsvik & Van der Voo 2002) reconciles the differing palaeomagnetic results of many workers in forming reconstructions of the main Gondwanan and Laurussian parts of Pangaea with the data generated by most other geological disciplines, including structural geology, palaeontology and sedimentology. The so-called Pangaea A reconstruction, which reconciles all the varied data, is close to the reconstructions used here for 310 Ma and onwards.

(2) We have produced new palaeogeographical maps at 30 Ma intervals for the 150 Ma period that differ from previous published reconstructions in a number of ways. The collage of terranes that make up Armorica apparently remained attached to the main Gondwanan palaeocontinent for a longer period than previously thought. The opening of the Palaeotethys Ocean appears to have been only between the Armorican, Adrian, Pontides, Hellenic and Moesian terranes, on the one hand, and Gondwana on the other; and probably initially occurred in the Silurian. The opening of the Neotethys Ocean between Apulia, the Taurides, the Middle Eastern terranes and the Tibetan Qiangtang Terrane and Sibumasu on the one hand, and Gondwana on the other, did not occur until the Permian. Most previous workers have associated the Qiantang Terrane movement with the earlier Palaeotethys opening event rather than with the Neotethys.

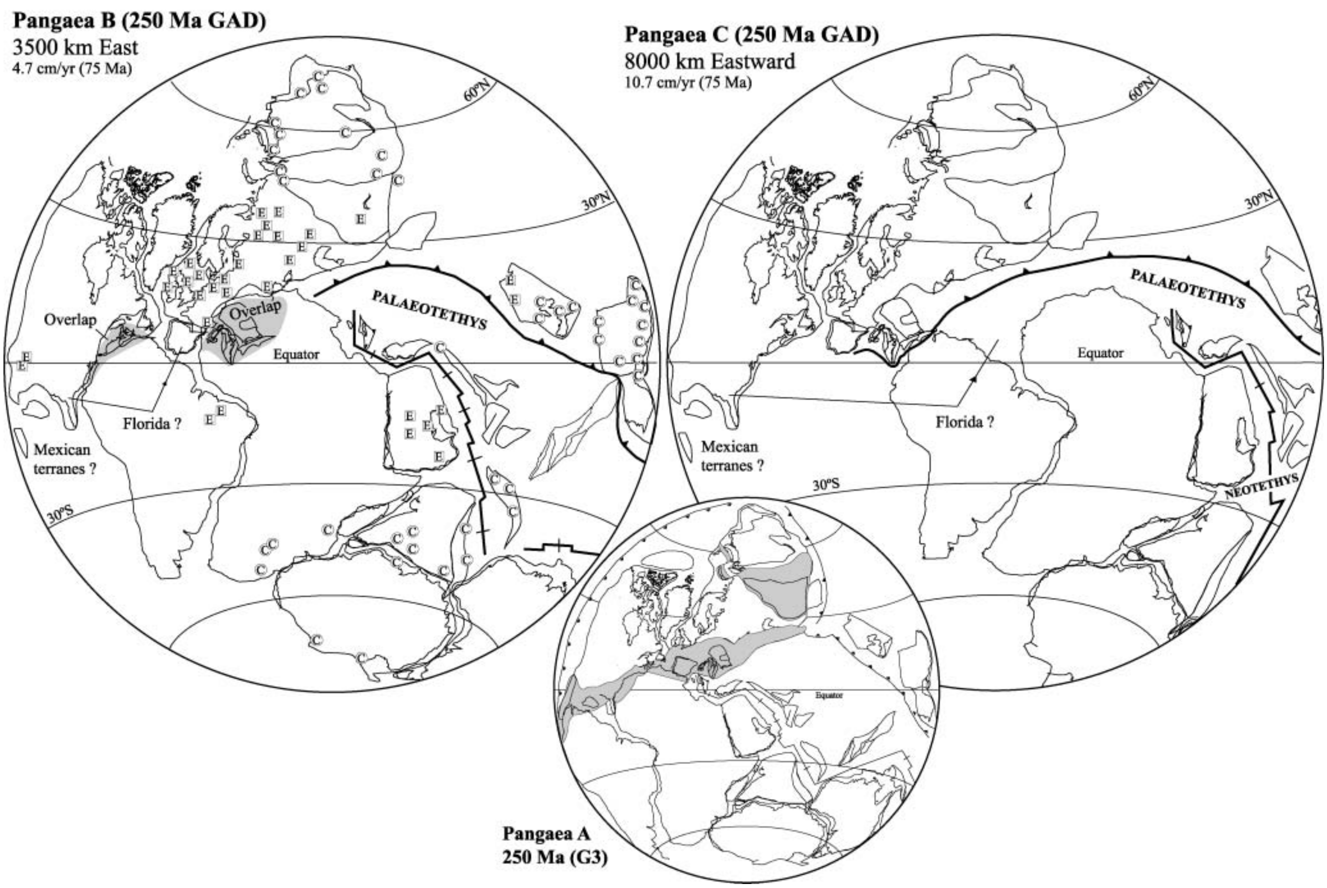

Fig. 12. Late Permian (250 Ma) reconstructions of Pangaea A, B and C (compare with Fig. 1). The Pangaea A reconstruction is a smaller version of Figure 11 with no sedimentological data but Variscan mobile belts are shaded (peak metamorphism *c*. 300 Ma). The Pangaea B map has the same sedimentological data as Figure 11, but is untenable because of the severe overlap problems caused by the southern European terranes of Armorica, Apulia, the Hellenic Terrane (and Moesia) and the Pontides. Pangaea C would involve 8000 km of lateral movement and would leave the Alleghenian belt totally unexplained (see discussion). Pangaea B and C use mean palaeomagnetic poles (calculated in the traditional fashion assuming a GAD field) of 50.4°N, 116.3°E (Laurussia, North American frame), 47.7°S, 72°E (Gondwana, South Africa frame), 50.4°N, 358.1°E (North China), 50.3°N, 226.7°E (South China), 68.7°N, 184°E (Tarim), and 34.6°N, 342.4°E (Sibumasu). It should be noted that the main difference between the two GAD-based reconstructions, and the partial G3 reconstruction (small diagram), is that the latter shows Gondwana *c*. 400 km more southward), and hence avoids the 'equatorial' overlap in Pangaea A reconstructions.

(3) Faunas and floras have again supplemented the palaeomagnetic data at many levels to determine terrane placing. For example, the late mid-Devonian fishes emphasize the longitudinal separation of Laurussia, the Kazakh terranes and Siberia at that time from North China, Annamia, South China and eastern Gondwana. The long-known distributions of the floral provinces in the Late Carboniferous and Permian also fit in very well with our reconstructions.

(4) The distribution of coals, evaporites and glacial deposits in the later Carboniferous and Permian is also very well documented by earlier workers, and, when plotted on our new reconstructions, reinforces the data from palaeomagnetism and fossils.

(5) In our time interval Pangaea reached its largest size in the latest Permian (250 Ma). The main growth occurred during the Carboniferous (Laurussia–Gondwana collision); some continents were subsequently added along the Pangaea margins (e.g. Siberia) whereas others rifted off during the supercontinent cycle. The formation of Pangaea had spectacular effects on both surficial and deep Earth processes: it radically changed the distribution of land and sea areas, widespread magmatic activity occurred, and one or several of these factors led to unusual climatic and biological conditions that culminated in the largest known extinction event ever known, at the Permo-Triassic boundary.

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