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Notes

The Lower Palaeozoic palaeogeographical evolution of the northeastern and eastern peri-Gondwanan margin from Turkey to New Zealand

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Abstract: In Lower Palaeozoic times, Gondwana was by far the largest tectonic entity, stretching from the South Pole to north of the Equator, and is termed a superterrane. We consider the northeastern sector of the Gondwanan and peri-Gondwanan margin, from Turkey through the Middle East, the north of the Indian subcontinent, southern China and SE Asia, to Australia and New Zealand. There was progressive tectonic activity along some of its margins during the period, with areas such as southeastern Australia undergoing enlargement through the accretion of island arcs as that part of Gondwana rotated. However, most of the area, from the Taurides of Turkey to at least east of India, represented a passive margin for the whole of the Lower Palaeozoic. Other adjacent areas, such as the Pontides of Turkey and Annamia (Indochina), were separate from the main Gondwanan craton as independent terranes. The quality and quantity of available data on Lower Palaeozoic rocks and faunas varies enormously over different parts of this substantial area, and there are few or no detailed palaeomagnetic data available for most of it. Some workers have considered the string of terranes from Armorica to the Malaysia Peninsula as having left Gondwana together in the late Cambrian as a Hun superterrane, leaving a widening Palaeotethys Ocean between it and Gondwana. However, we consider that the Palaeotethys opened no earlier than in late Silurian time (with Armorica and other terranes to its north), and that the Hun superterrane was not a cohesive unity. Other researchers vary in presenting many substantial Central Asian and Far Eastern terranes, including North China, South China, Tarim, Annamia and others, as integral parts of core Gondwana and not leaving it until Devonian and later times. We conclude that North China, Tarim and Annamia, among others, were probably not attached to core Gondwana in the Lower Palaeozoic, that South China was close to Gondwana (but not an integral part of it), and that Sibumasu was probably part of Gondwana. We try to reconcile the very varied published geological data and opinions, and present new palaeogeographical maps for that sector of Gondwana and surrounding areas for the Cambrian (500 Ma), Ordovician (480 Ma) and Silurian (425 Ma).

Gondwana was by far the largest terrane during the whole of Lower Palaeozoic time, and comprised all of South America, Africa, Madagascar, Arabia, India, East Antarctica and Australia, totalling *c.* 95×10^6 km^2; that is, 64% of all landmasses today or 19% of the total Earth surface. However, surrounding it were a whole series of much smaller terranes, many of which originally formed part of the Gondwanan superterrane, and which became separated from it at various times during the Phanerozoic (Fig. 1 shows the modern geography and old terrane boundaries for the western part of the area, and Fig. 2 shows core Gondwana). It is the prime purpose of this review, first, to identify the boundaries of these marginal terranes in the northeastern sector of this superterrane in terms of today's geography, using a digitized database, and, second, to construct palaeogeographical maps of this very substantial area at successive times during the Lower Palaeozoic (Figs 3–5). We have already provisionally attempted this task as part of a global survey (Cocks & Torsvik 2002), but it

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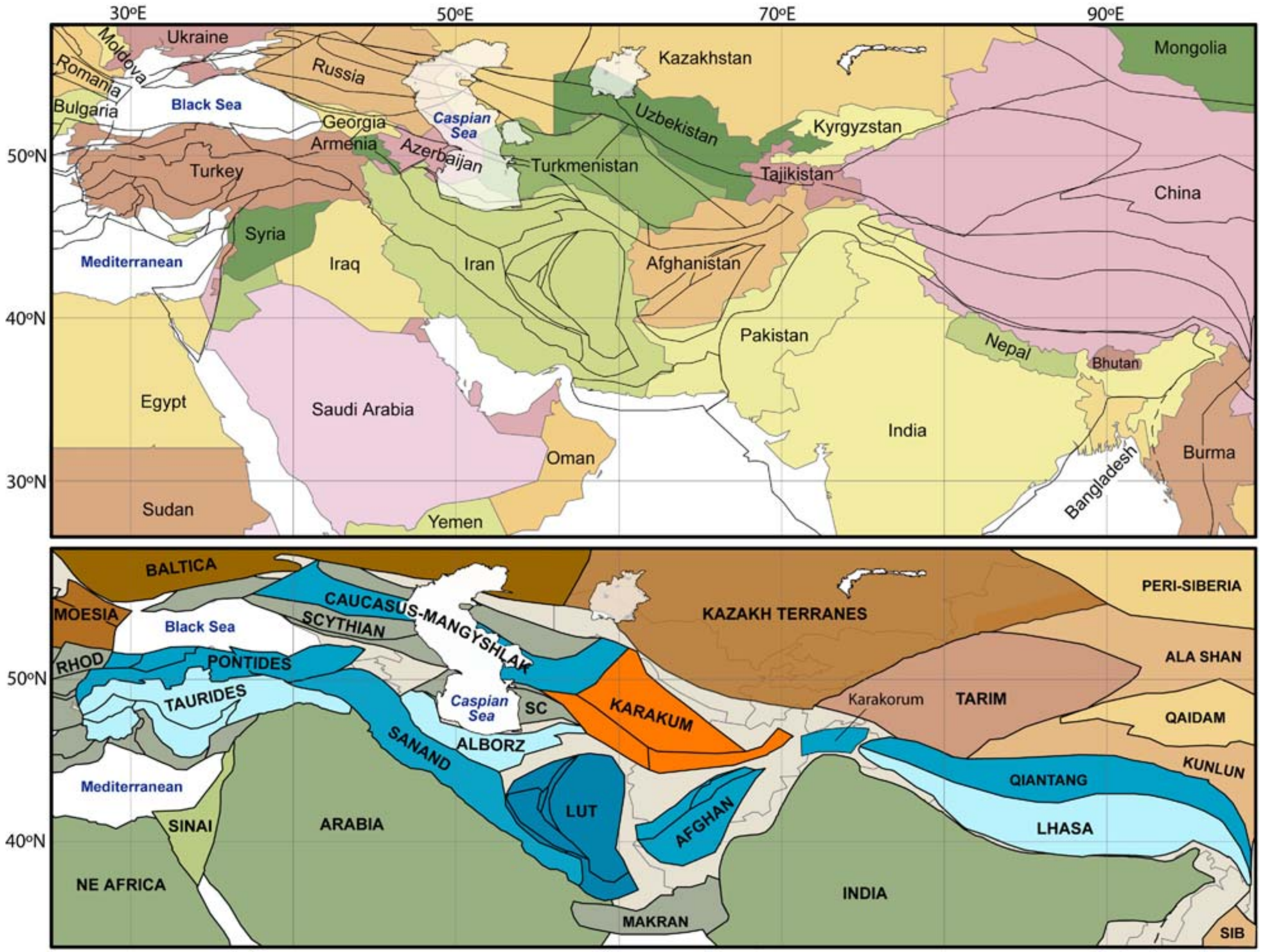

Fig. 1. (**a**) Map of the area from Turkey to Tibet, showing some modern country names and the boundaries of the terranes along the northeastern Gondwanan margin. (**b**) Map of most of the same area as in (a), but with country names deleted and indicating the names of the Palaeozoic terranes, which we discuss here. The light grey areas are Mesozoic to Recent accretionary belts, and the substantial brown area indicates the many Kazakh terranes, which are undifferentiated here. Rhod, Rhodope; SC, South Caspian; Sib, Sibumasu.

seems timely to review the area again in more detail, incorporating some of the large amount of new tectonic, palaeomagnetic and faunal data that have emerged since our previous work. That paper in turn was partially developed from an earlier review of the whole Gondwanan and peri-Gondwanan area in the Lower Palaeozoic by Cocks & Fortey (1988). However, the terrane margins were much more subjectively portrayed in those earlier papers than now, as were also therefore the consequent palaeogeographical reconstructions, and the Far Eastern sector in particular is much revised here.

We have identified two key questions to be considered. They are, first, whether or not many of these peri-Gondwanan marginal terranes were combined in the so-called Hun (or Hunic or Hunia) superterrane, as postulated by von Raumer, Stampfli and their co-authors (e.g. von Raumer *et al.* 2002; Stampfli & Borel 2002, 2004). There is clear consensus on the existence of rifting between core Gondwana and some of its marginal terranes over much of the area to form a widening Palaeotethys Ocean, but when that rifting initiated, and to what extent the peri-Gondwanan marginal terranes were coherent with each other to form a superterrane, is contentious. However, it is agreed by all researchers that the earlier rifting was a clearly distinct series of tectonic events from the subsequent and well-documented late Carboniferous rifting that separated many of the terranes away from core Gondwana to form the Neotethys Ocean in Permian times (Stampfli *et al.* 2001). The second difficult question is the reality or otherwise of the views published by various Australasian workers, particularly Metcalfe (e.g. Metcalfe 2002*a*), concerning the Central and SE Asian parts of the region. They have postulated that an enormous area, including North China, South China, Tarim, Qaidam, Sibumasu, Annamia and others, were unified as an integral part of equatorial core Gondwana throughout the whole of the Lower Palaeozoic, and remained so until the Palaeotethys Ocean opened in (according to them) Devonian times, or even, in the case of some terranes, until the Neotethys Ocean opened in the Permian.

We will first review the relevant parts of core Gondwana, and then each peri-Gondwanan terrane briefly in turn, and then present a short unified outline geological history of the area, accompanied by new palaeogeographical maps for the Cambrian, Ordovician and Silurian. As in our previous papers, we have combined our experience on faunal provinces and palaeomagnetism, together with some consideration of distinctive sedimentary facies, to produce our maps. We must also stress that knowledge and data from the various areas differ enormously, from excellent to pathetic, and the maps we present can only be regarded as provisional.

A note on the terminology of Lower Palaeozoic oceans is relevant. The Panthalassic Ocean was by far the largest, but lay a long way to the north of the area considered here and on the far side of the substantial Siberian terrane (Cocks & Torsvik 2002, 2007). All researchers seem agreed on the term Iapetus for the ocean between Laurentia and Baltica–Avalonia; most are agreed on Tornquist (originally named as a sea) for the pre-Caledonide ocean between Avalonia and Baltica, and Rheic for the widening ocean between Avalonia as it left Gondwana (although different workers have estimated opening and initial spreading times for that ocean varying between late Precambrian and mid-Ordovician), but again all these are topics outside the scope of this paper. For the ocean between Baltica and Gondwana we (Cocks & Torsvik 2005) have used the term Ran (Hartz & Torsvik 2002) from the Cambrian to early Ordovician times (before the rapid rotation of Baltica was complete), although this appears to be a similar oceanic concept to the Prototethys Ocean used by others in a comparable area from the Cambrian to the Silurian (e.g. Stampfli & Borel 2002, 2004). Palaeotethys seems to be consistently used by authors as the name for the ocean spreading from possibly Ordovician, but more probably late Silurian, times onward into the early Mesozoic, between the European and Middle Eastern peri-Gondwanan terranes and core Gondwana itself. However, further eastwards, a rather different concept of the Palaeotethys Ocean is portrayed by other workers, summarized by Metcalfe (e.g. Metcalfe 2002*a*). Also in this Central Asian and Far Eastern region, and adjoining Gondwana and peri-Gondwana to their north, the terms Asiatic and Palaeoasian (or Palaeo-Asian) have been used by various workers, particularly from the Former Soviet Union, for different oceanic areas at various Palaeozoic times. Many of these usages of Palaeoasian Ocean are for eastward extensions of the Ran, Prototethys or Palaeotethys. However, the reconstructions and palaeogeography of the complex area between Siberia and Gondwana, which include the many separate Kazakh terranes (Fig. 1b), are even further from being widely agreed than the region considered here, and will not be discussed further.

Comparably, considering the terminology of orogenies, the terms Caledonide and Hercynian (or Variscide) have been applied by many previous workers to various tectonic events in parts of Asia, both in the Middle and Far East, but those terms should be used only in Western Europe and eastern North America, where they apply to particular orogenic phases in the collision and assembly of terranes there; and thus we do not use them for the eastern and northeastern Gondwana areas discussed in this paper.

The Gondwanan core

All palaeogeographical reconstructions agree that the continents of Africa, Antarctica and Australia and the subcontinent of India were parts of our sector of Gondwana in the Lower Palaeozoic, and most workers also include Arabia. To put the area in larger context, we show the progressive palaeogeographical positions for the whole of core Gondwana in Figure 2. Other regions within the area, which may or may not have been parts of core Gondwana or peri-Gondwana, and whose positions and biogeographical relationships have often been contentious, are treated in the subsequent section. Gondwana is characterized by a series of terrane-distinctive faunal provinces very different from those found in other large contemporary areas such as Laurentia, Baltica and Siberia (documented and reviewed by Fortey & Cocks 2003). Because the old oceans were at their widest in the early Ordovician, those terrane-linked faunas are discussed in the Ordovician section below.

Reviewing the area (Fig. 1) from west to east, although the Sinai area of Egypt and Israel has undergone some Mesozoic to Recent movements, in the Lower Palaeozoic it was unquestionably part of Africa. The Arabia area shown as such in Figure 1, including Saudi Arabia, Yemen, Oman, Lebanon, Jordan and the southern parts of Syria and Iran, as well as the Sinai area, was an integral part of core Gondwana from earliest Cambrian times onwards (Allen 2007). The rest of Iran, particularly the Sanand terrane, is more contentious and is discussed below under 'Iranian terranes'. Sharland *et al.* (2001) have described the sequence stratigraphy of what they termed the Arabian plate; Millson *et al.* (1996) also reviewed the integrity of the various tectonic components of the area, as did Ruban *et al.* (2007). Fortey (1994) described typically Gondwanan trilobites from the late Cambrian of Oman, as did Fortey & Morris (1982) equally typical Gondwanan *Neseuretus* Fauna trilobites from the early Ordovician (Arenig) of Saudi Arabia, and El-Khayal & Romano (1985) from the middle Ordovician (Llanvirn) of Saudi Arabia. In the Silurian of Saudi Arabia, Al-Hajri & Paris (1998) described widespread deltaic sequences. The main part of the Indian subcontinent was certainly part of core Gondwana, but has relatively few Lower Palaeozoic rocks preserved upon it apart from at the northern margin, which is discussed under 'Himalayan area' below.

Between India and Australia today, the Lower Palaeozoic core Gondwana margin has either been subducted or lies beneath the Indian Ocean, and is also complicated by the Mesozoic tectonics of the Sibumasu area (see below). However, it is well exposed in Australia, whose Cambrian, Ordovician and Silurian faunas and biogeography have been reviewed by Wright *et al.* (2000), Webby *et al.* (2000) and Pickett *et al.* (2000), respectively. Li & Powell (2001) described the palaeogeographical evolution of Australasia from the Neoproterozoic onwards, but without many references to the faunas; and Metcalfe, in many papers (e.g. Metcalfe 2002*a*), has also described the Palaeozoic palaeogeography of that area as it developed.

The overall movements of the Gondwanan superterrane during the Lower Palaeozoic (Fig. 2) deserve comment. In the middle Cambrian (510 Ma) the South Pole lay under NW Africa, and Gondwana drifted to the NE in that polar area between then and the early Ordovician (480 Ma). In contrast, between 480 Ma and the middle Silurian (425 Ma), that part of Gondwana drifted to the SW, as can be seen by the Brazilian pole position at 425 Ma. However, the Australian part of Gondwana remained in an equatorial position throughout the entire Lower Palaeozoic; therefore these movements all indicate that the superterrane was in fact slowly rotating during this period, with active margins in the Australian–New Zealand–South American sectors and a passive margin from NW Africa to somewhere east of India.

Terrane review

We now review the areas considered here, progressing from Turkey clockwise round Gondwana to New Zealand. Many (but not all, as discussed separately below) of them were independent terranes at some time in the Phanerozoic. As a starting point we have used modern-day terrane boundaries in a digital form and given by Stampfli & Borel (2004) for the terranes as far east as Afghanistan. The boundaries of the more westerly terranes that we analyse, stretching from Turkey to SW China (Tibet), are shown in newly constructed diagrams (Fig. 1). The remainder, from Burma (Myanmar) to New Zealand, are not shown as a new figure here, but we largely follow Cocks & Torsvik (2002, 2007) and Torsvik & Cocks (2004) in their boundaries.

Pontides terrane

The northern part of Turkey, from just west of the Bosphorus to just south of the border with Georgia, is considered as a single terrane (normally termed the Pontides) by some workers (e.g. Cocks & Torsvik 2002; Ruban *et al.* 2007) and as two or three separate terranes (Istanbul, Zonguldak and East Pontides) by some others (e.g. Stampfli &

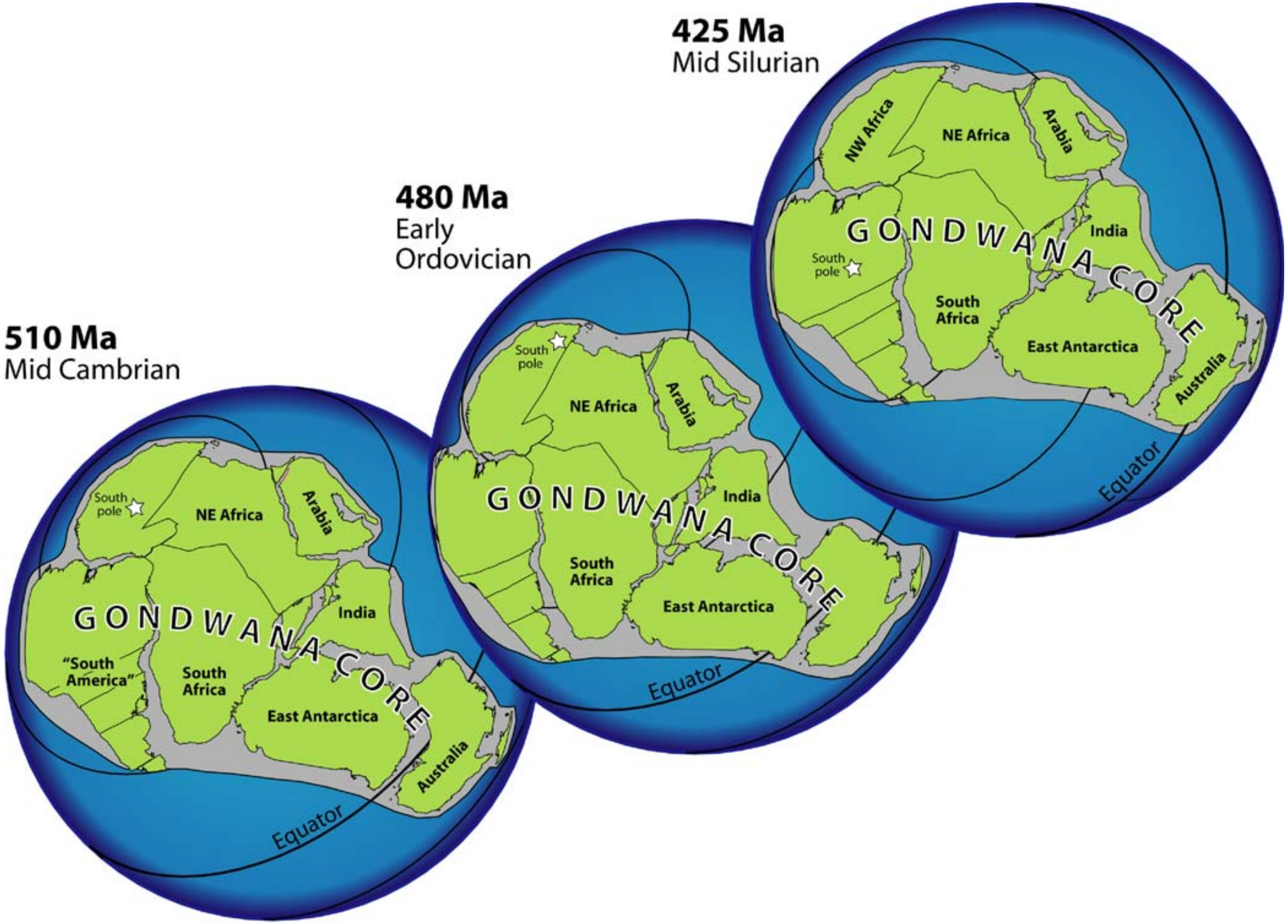

Fig. 2. Reconstructions for the middle Cambrian (510 Ma), early Ordovician (480 Ma) and middle Silurian (425 Ma), showing the palaeomagnetically constrained progressive positions of core Gondwana (Table 1). Many of the peri-Gondwanan terranes discussed in this paper were also probably parts of core Gondwana at these times, but, because their positions are not definitively constrained, they are not included in this figure; neither are the other contemporary terranes around the world.

Borel 2004). Adjoining it to the west lies the Rhodope terrane, which consists entirely of Mesozoic and later rocks, and to its north the Moesia terrane, which has been considered by various workers to have formed part of either peri-Gondwana or Baltica in the Lower Palaeozoic, but whose positioning is outside the scope of this paper.

Dean *et al.* (2000) have described a key early Ordovician trilobite fauna from the Pontus Mountains of northern Turkey, which indicates that the area is of undoubted Gondwanan affinity, as the terrane-specific faunas are very different from those in the substantial Baltica terrane (Cocks & Torsvik 2005), which adjoins the Pontides today. Those Pontide Mountain Ordovician rocks and trilobites, and also the Silurian rocks and brachiopods we have seen in the Istanbul area, contain no substantial carbonates and are, rather surprisingly, very reminiscent of those in the Welsh Borderland, then part of the distant Avalonian sector of peri-Gondwana. Thus we have omitted the Pontides from our maps (Figs 3–5) as its Lower Palaeozoic position is so uncertain.

Taurides terrane

Most of the southern part of Turkey and the NW part of Syria formed a single terrane in the Lower Palaeozoic, although some workers (e.g. Stampfli *et al.* 2001) have divided the area into two separate terranes, the Western Taurides and the Menderas Taurus terrane. Between the Pontides and the Taurides there is a large area within central Turkey that has no Palaeozoic rocks but that we have arbitrarily included within the Taurides in Figure 1b. From the differences between the apparently higher-latitude faunas of the now-adjacent Pontides terrane and the different and apparently intermediate-latitude faunas of the Taurides terrane, we conclude that the Pontides and the Taurides were probably not close to each other in the Lower Palaeozoic, as we also showed earlier (Cocks & Torsvik 2002). The Tauride Ordovician trilobite faunas have been extensively monographed by W. T. Dean (summarized by Dean & Monod 1997), and have been demonstrated to be typically core Gondwanan. However, in Cambrian and earliest Ordovician times, that part of Gondwana was not too far from the Baltica terrane, which lay on the opposite side of a relatively narrow Ran Ocean (Cocks & Torsvik 2005), thus allowing some normally diagnostic Baltic faunal elements, such as the trilobite *Asaphus*, to migrate to the Taurides as rare components of the fauna. In contrast, whereas Baltica carries no trace of the latest Ordovician Hirnantian glaciation, this is well developed in the Taurides (Monod *et al.* 2003). Thus the Taurides terrane is shown as part of core Gondwana on our reconstructions (Figs 3–5) and its later tectonic history was outlined by Okay *et al.* (2006).

Mangyshlak, Caucasus and Scythian terranes

The Caucasus Mountain area of Georgia and adjacent countries has been divided into a northern Greater Caucasus terrane and a southern Lesser Caucasus terrane, both of which lie to the west of the Caspian Sea and are also termed by some the Transcaucasus terrane. To the east of them, and on the eastern side of the Caspian, lies the Mangyshlak terrane, termed by some workers the Kopetdag terrane. Cocks (2000, fig. 6) used the term Mangyshlak terrane (which today adjoins Baltica to its north) to include both the Caucasus terranes and the Mangyshlak terrane. The Lower Palaeozoic faunal signals from these terranes are very inconclusive: there are no rocks older than middle Devonian on the eastern side of the Caspian, and the Silurian cephalopods recorded from the Caucasus are not terrane-specific. There is considerable middle and late Devonian volcanism in the Greater Caucasus terrane; however, Ruban *et al.* (2007), after a review of the published evidence, concluded that the Lesser Caucasus terrane did not leave Gondwana until the Permian, during the opening of the Neotethys Ocean. To the south of the Caucasus terrane lies the Scythian terrane, which was formed only in Mesozoic times by the creation of a Jurassic volcanic arc, and to the south of the eastern part of the Mangyshlak terrane area there is the South Caspian terrane, which is again of Mesozoic origin. Because of the lack of early Palaeozoic palaeogeographical evidence, all these terranes are omitted from our reconstructions (Figs 3–5).

The Kazakh terranes

To the north and NE of the Mangyshlak, Karakum, Karakorum and Tarim terranes lie the many, and as yet poorly defined, terranes, largely today within Kazakhstan, which are termed the Kazakh terrane assemblage. Most did not unite to form a much larger Kazakh (or Kazakhstania) terrane until the Late Palaeozoic. Many of those terranes have Precambrian cores and important and distinctive Lower Palaeozoic successions and faunas, some reviewed by Popov & Cocks (2006) and Fortey & Cocks (2003); but, although some carry faunas that may loosely defined as having some affinities with Gondwana and also with the lower-latitude areas of South China and elsewhere, their history and palaeogeography are outside the scope of this paper. There is no firm proof that any of the

Kazakh terranes lay within the boundaries of our Lower Palaeozoic palaeogeographical maps: some may have done so, but they are not shown in Figures 3–5.

Iranian terranes

In our previous review (Cocks & Torsvik 2002), we treated the Sanand (or Sanandaj–Sirjan), Lut (Central Iran) and Alborz terranes together, although as separate from the main Arabian plate (of which the Zagros Mountains formed part, although these are sometimes represented as a terrane independent from Arabia), following the review of terranes in the area by Millson *et al.* (1996) and Sharland *et al.* (2001). Gondwanan faunas have been reported from the centre of Iran: brachiopods by Bassett *et al.* (1999) for the late Cambrian and early Ordovician, and ostracodes by Ghobadipour *et al.* (2006) for the middle Ordovician and by Schallreuter *et al.* (2006) for the late Ordovician. However, there was some Lower Palaeozoic tectonic activity near that Gondwanan margin; for example, Ramezani & Tucker (2003) have described and dated extensive andesitic and trondhjemitic igneous activity near the western margin of the Lut terrane as occurring from 547 to 525 Ma in early Cambrian times, which is inconsistent with the rest of the neighbouring parts of Gondwana, which apparently formed a passive margin.

Data from the Late Palaeozoic, for example, those given in the paper by Brock & Yazdi (2000), which deals with the palaeobiogeographical affinities of Devonian brachiopods from Iran, indicate close faunal relationships between the Alborz terrane and adjacent parts of the north Gondwanan margin in Afghanistan, Armenia and Pakistan, as well as the Gondwanan cratonic core in northeastern Africa (Libya). Thus we consider these united units as continuing to be an integral part of core Gondwana at that time, and most workers appear to conclude that the Iranian terranes remained part of core Gondwana until the opening of the Neotethys Ocean in the late Palaeozoic, which was the same presumption as that held by us earlier (Cocks & Torsvik 2002). Along the suture zone between the Sanand terrane and the Arabian plate there is an ophiolite of Permian age, indicating their separation as part of the Neotethys opening event. However, Angiolini & Stephenson (2008), after an analysis of terrane-diagnostic Permian (Asselian–Sakmarian) brachiopods and palynomorphs, have concluded that by that later time the faunas in the Alborz Mountains of Iran were more similar to the Uralian sector of southeastern Laurussia (previously Baltica), and bore no resemblance to those from Gondwana, which carried faunas similar to the other parts of the Iranian terrane assemblage. There are few Lower Palaeozoic palaeomagnetic data from this large area, but, as far as can be determined from an analysis of published faunas, all these units were close to each other in Cambrian to Silurian times and formed parts of the Gondwanan passive margin.

The Afghan terrane assemblage

Lower Palaeozoic faunal and palaeomagnetic data are generally rather weak from this substantial area, but these data have been summarized by Talent & Bhargava (2003) and do not appear to include terrane-specific faunas. In contrast, however, there is much more information from Devonian times onwards. Afghanistan and immediately adjacent areas can be divided between a southern Helmand terrane and a northern Farah terrane. To the south of the Helmand terrane is the Makran terrane (Fig. 1b), which is a Mesozoic to Tertiary accretionary wedge, and from which no Lower Palaeozoic rocks are known, and which therefore receives no further mention here. Most workers have concluded that these Afghan terranes remained part of Gondwana until the Neotethys Ocean opened in the late Palaeozoic (mid-Permian), and we follow them.

Karakum terrane

The southern margin of this terrane (sometimes termed the Karaku or Karakum–Turan terrane) is adjacent to and north of the Iranian and Afghan terrane collages. There are no terrane-diagnostic Lower Palaeozoic faunas known from the terrane, and its palaeogeographical positioning is therefore uncertain: it could be either peri-Gondwanan or part of the Kazakh Terrane Assemblage and is thus omitted from the palaeogeographical reconstructions below.

Karakorum terrane

Gaetani (1997) has reviewed this terrane, which lies largely in the NW of Pakistan, from the Ordovician to the Cretaceous. Above a pre-Ordovician crystalline massif of uncertain age lies a succession containing early to middle Ordovician acritarchs and chitinozoans (Quintavalle *et al.* 2000), and Talent *et al.* (1999) have described early Ordovician conodonts from the western Karakorum and the adjacent Hindu Kush area. None of these biota are terrane-specific, and so we simply show the terrane as an outboard part of the core Gondwana passive margin on our reconstructions. The Karakorum terrane was stitched by lavas to the Pamirs to its north by middle Devonian time, but the Lower

Palaeozoic northern Gondwanan margin is difficult to resolve in detail in these areas.

Himalayan area

To what extent any separate and independent terranes fringed the Himalayan part of the Gondwana superterrane in Pakistan and northern India is uncertain, as the northern margin of the Indian plate is considered to have been much foreshortened by its Tertiary collision with China in the Himalayan orogeny, when many Lower Palaeozoic rocks were probably subducted. However, Myrow, Hughes and their colleagues (e.g. Myrow *et al.* 2006*a*, *b*) have ably documented the Himalayan area in the Cambrian and earliest Ordovician, and concluded that the various sections there, many of which have been relocated by subsequent tectonics, represent the Lower Palaeozoic passive margin of the main Gondwana superterrane. The area has been revised for the Ordovician by Torsvik *et al.* (2009*b*). Parcha (1996) has described the Cambrian of Spiti, which is adjacent to the Niti area from which Salter & Blanford (1865) described early Ordovician and other faunas in the pioneering days of the Indian Geological Survey. Those faunas, some of which were revised by Cocks & Rong (1989), are an interesting mix of endemic genera and species and those from elsewhere. There are few data from the succeeding mid- to late Ordovician, as a major unconformity covers much of the area, extending up to the middle Devonian in many places. Talent & Bhargava (2003) have summarized the Silurian data, and concluded that all the preserved rocks and fossils lay on the Indian plate and were thus within core Gondwana when they were deposited: we concur with that assessment.

Tarim, Kunlun, Qaidam, Ala Shan, North China and peri-Siberia

This group of terranes are partly shown in the NE of Figure 1b. We have included the area of the probably independent Gurvanshayan terrane of Mongolia within the Ala Shan terrane in that figure. Some of these terranes, the Qaidam, Kunlun and Ala Shan terranes, have been shown as connected to the Qiangtang and Lhasa terranes in the Lower Palaeozoic; for example, by Metcalfe (2002*a*), who concluded that the large terranes of Tarim and North China were also welded to Gondwana near Australia until the Devonian. However, chiefly from faunal analysis, some summarized by Fortey & Cocks (2003), we do not think that any of them are likely to have formed part of peri-Gondwana, although it must be admitted that their Lower Palaeozoic positions and relations to each other are not well constrained. There are some palaeomagnetic and a great deal of palaeontological data for Tarim, many of these summarized by Zhou & Chen (1992), and also for North China (Zhou & Dean 1996). We have elsewhere reviewed the peri-Siberian terranes (Cocks & Torsvik 2007), and concluded that they rotated with the main Siberian craton in the Palaeozoic, so that the area of peri-Siberia shown in Figure 1b lay on the far side of Siberia from Gondwana in the Lower Palaeozoic.

Tibetan terranes

The modern margins of the various terranes that make up Tibet and immediately adjacent areas in China are shown in Figure 1b; the principal peri-Gondwanan areas of this region are the Qiangtang terrane in the north and the Lhasa terrane in the south. Because the whole Tibetan area was strongly involved in the Himalayan orogeny, there are no good Lower Palaeozoic palaeomagnetic data, and there is some possibility that the Qiangtang terrane might not have formed a single unity in those times. However, there are some useful Lower Palaeozoic shelly faunas, such as the brachiopods described from the early Ordovician by Liu (1976) from near Mount Everest (Mount Jolmo Lungma), which, although many are endemic, nevertheless show some affinity with those in South China. Hughes *et al.* (2002) reviewed a small Middle Cambrian trilobite fauna from the Yunlung collage of the eastern Himalaya and concluded that it represents the most southeastward part of the Qiantang terrane, and that both it and the Lhasa terrane formed parts of the passive margin of core Gondwana in the Lower Palaeozoic.

South China terrane

It is a matter of controversy whether or not the substantial South China terrane area (which is sometimes termed the Yangtze terrane, and which is off the diagram to the NE of Fig. 1b) was an integral part of the core Gondwanan craton in the Lower Palaeozoic, although it has been shown as such by several workers (e.g. Cocks & Fortey 1988; Metcalfe 2002*a*). We did not show it as united with Gondwana in our earlier study (Cocks & Torsvik 2002, figs 3–7).

Blieck & Janvier (1999) have documented the distinctive South Chinese Devonian fish faunas, which were endemic to the area and terrane-diagnostic, and which indicate separation that was probably substantial from both North China and Gondwana. However, in South China, many of the Lower Palaeozoic faunas found there are of the same faunal provinces as those in peri-Gondwana

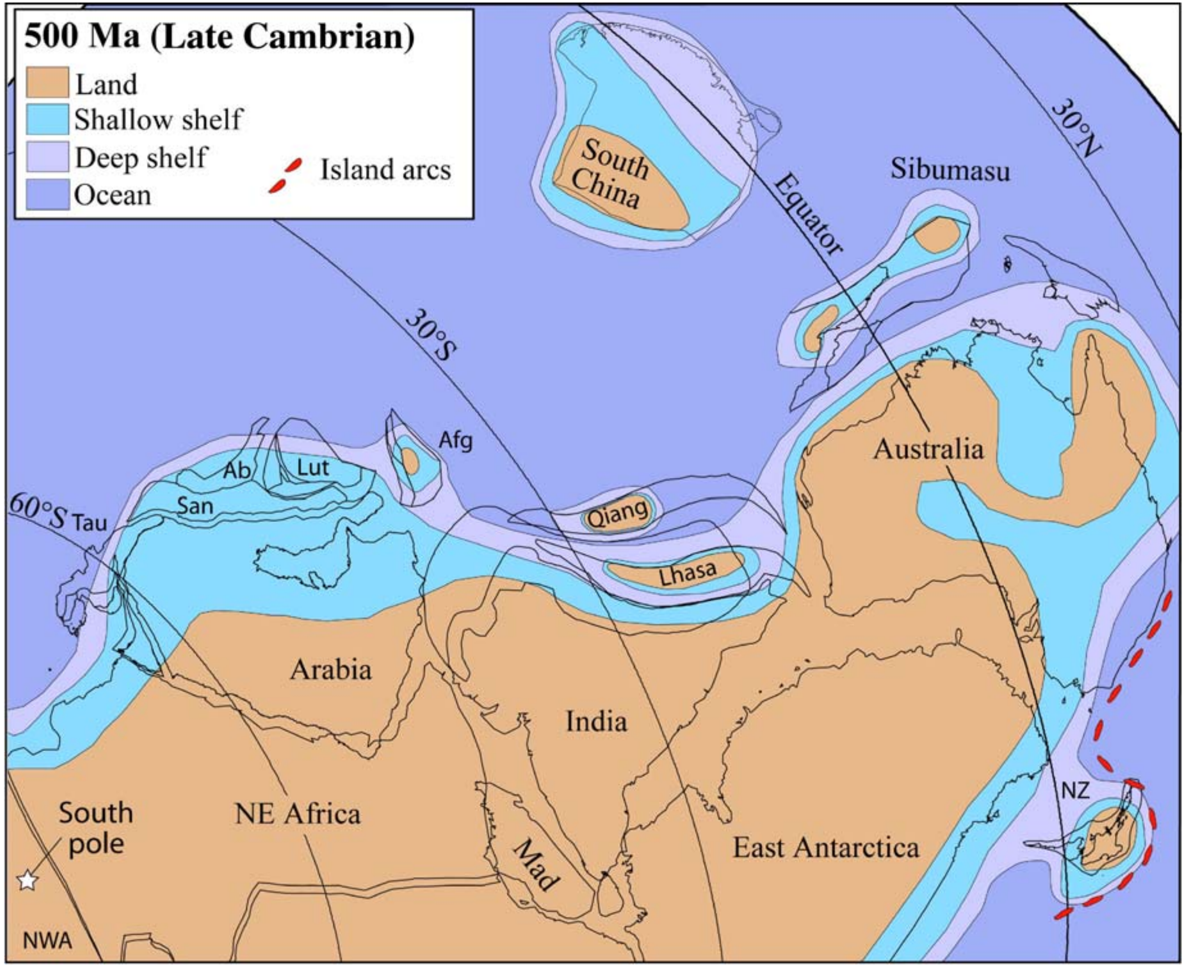

Fig. 3. Palaeogeography of the northeastern and eastern Gondwanan and peri-Gondwanan area in middle Cambrian times at 500 Ma. Ab, Alborz terrane; Afg, Afghan terranes; Mad, Madagascar; NWA, NW Africa; NZ, New Zealand; Qiang, Qiantang terrane; San, Sanand terrane; Tau, Taurides terrane.

and Gondwana. An outstanding example of this is the analysis by Fortey (1997) in which he established that the trilobites found in the late Ordovician Pa Kae Formation of southern Thailand, and the adjacent Kaki Bukit Formation of NW Malaysia, both in the Sibumasu terrane, were identical, even down to the species level, with those from the Pagoda Limestone, which lies in the central part of the South China terrane. In contrast, the South China terrane was probably at a substantial distance from the now-adjacent North China terrane in the Lower Palaeozoic, as the contemporary shelly faunas have little in common, as can be seen from the global provincial analysis of Cambrian trilobites by Shergold (1988). North and South China did not accrete to each other until early Mesozoic times; however, South China had merged with the neighbouring Annamia terrane by the end of the Carboniferous. Unlike most of the other peri-Gondwanan terranes discussed in this paper, South China does have palaeomagnetic data for the Lower Palaeozoic, some of which were summarized by Cocks & Torsvik (2002, table 1). However, since then, Yang *et al.* (2004) have published an important paper with new Cambrian palaeomagnetic data indicating that South China was probably then in the equatorial position that we show in Figure 3, and that agrees with the evidence from the dikelokephalinid trilobites found in both South China and Australia in the Early Ordovician. Yang *et al.* (2004) concluded that South China was attached to core Gondwana, but their new palaeomagnetic data do not constrain that, and we have not followed that part of their conclusions. The late Ordovician and Silurian palaeogeographies (Figs 4 & 5) within the South China terrane follow Rong *et al.* (2003).

Thus we conclude that, although South China appears to have been close to, and in substantial faunal communication with, core Gondwana during the whole of the Lower Palaeozoic, on balance it was more probably a terrane separate from the core. That is supported by an independent tectonic and sedimentary analysis by Allen (2007), which concluded that, whereas South China formed an integral part of Gondwana in the late Neoproterozoic and earliest Cambrian, the two plates evolved separately from early Cambrian times onwards.

Sibumasu terrane

There are diverse and abundant Cambrian to Devonian rocks and faunas in this well-known terrane (sometimes termed the Shan–Thai terrane), whose boundaries stretch today from Sumatra in the south, through the western part of the Malaysian Peninsula and Thailand, to the Shan States of Burma (Myanmar). Unfortunately, the substantial early Mesozoic granites through the spine of most of this terrane have badly distorted and fractured the older rocks, and it is thus difficult to present accurate Lower Palaeozoic palaeogeographical maps of the area. Cocks *et al.* (2005) reviewed the Cambrian to Devonian faunas in the more southerly parts of the terrane, in the NW Malaysian Peninsula and southern Thailand. There, there are extensive Cambrian to mid-Ordovician shallow-water sediments and faunas, which contrast with the turbidites and graptolitic shales of deeper-water, and presumably terrane-marginal, origin seen to the east and south of them in Perak in the Malaysian Peninsula and further southwards. In contrast, in the Silurian there are also thick carbonates of shallow-water origin (now largely dolomitized) in the Kuala Lumpur area in the central part of the peninsula. At the opposite end of the terrane, in the Shan States of Burma (Myanmar), there are extensive

Table 1. *Reconstruction fits for core Gondwana and peri-Gondwana terranes discussed in the text (relative to a fixed South Africa), and the basis for Figures 3–5*

	Euler latitude	Euler longitude	Euler angle
NW Africa	16.5	6.7	−1.15
NE Africa	40.4	−61.4	−0.7
Arabia	30.9	17.5	−6.32
Madagascar	14.8	137.5	−15.4
India, Lhasa	29.8	42.1	−60.5
East Antarctica	10.5	148.8	−58.2
Australia	19.6	117.8	−56.2
Taurides	30.8	17.5	−6.3
Sanand, Alborz, Lut	27.2	18.3	−5.4
Afghanistan	15.8	99.7	16.9
Qiang	32.3	33.2	−52.1
Sibumasu	7.5	91.8	−110.8
North New Zealand	12.9	120.1	−73.5

Based on Torsvik *et al.* (2009*a*) and this study.

Lower Palaeozoic deposits and substantially Gondwanan or peri-Gondwanan terrane-diagnostic faunas, particularly in the Ordovician (Cocks & Zhan 1998). On balance, we now consider that Sibumasu most probably formed part of core Gondwana, as shown by Metcalfe (e.g. Metcalfe 2002*a*) and other workers, in contrast to our previous preliminary conclusions (Cocks & Torsvik 2002).

Annamia terrane

Often termed Indochina, this terrane occupies most of the Indochina peninsula, a portion of adjacent political China, and the eastern part of the Malaysian Peninsula, where it is divided from the Sibumasu terrane by the substantial Bentong–Raub Suture Zone. To the north of Annamia there is a suture with South China, with which it merged before the late Carboniferous (Metcalfe 2002*b*). There are no good palaeomagnetic data, and the Lower Palaeozoic faunas of the former French colonies largely described over a century ago need substantial revision; however, in the Western Yunnan Province of China, Zhou *et al.* (2001) have reviewed the Ordovician (Darriwilian) colder-water trilobite faunas and differentiated between the Sibumasu, Annamian and South Chinese parts of that province, and concluded that the boundaries of Annamia today lie between the Nandinghe–Lanchanfiang Fault and the Honghe Fault in Yunnan. Metcalfe (2002*a*) showed Annamia as adjacent to Sibumasu and as part of core Gondwana in his Lower Palaeozoic reconstruction. However, as reviewed by Fortey & Cocks (2003) and (Cocks *et al.* 2005), although there are some fossils in common between Annamia (on the one hand) and South China and Sibumasu (on the other hand), the dominant impression is that there are rather different Lower Palaeozoic faunas in those terranes, and that Annamia may have been separate and somewhat distant from the other two and situated at higher palaeolatitudes: the shallow-water faunas were certainly very different in the better-documented Upper Palaeozoic. Thus we do not consider it probable that Annamia was part of core Gondwana in the Lower Palaeozoic, and it is omitted from Figures 3–5.

North Borneo

The boundaries of any possible independent Lower Palaeozoic terrane in this area are impossible to define as they are today inextricably involved in the more modern and very complex terrane collage around Indonesia and the South China Sea. However, Fortey & Cocks (1986) documented early Ordovician graptolites from the centre of North Borneo, and it seems probable that those deeper-water rocks represented part of the northern margin of Gondwana. Whether or not they formed a terrane separate from the main supercontinent, or perhaps an offshore mid-ocean basin, is difficult to assess and we do not show it as such in our reconstructions. Talent *et al.* (2003) reviewed more recent discoveries of Ordovician and Silurian rocks, including shallow-water mid- to late Silurian limestones containing corals and conodonts, although the latter have been found only in loose boulders in jungle streams.

Southeastern Australia

Largely today in the states of New South Wales, Victoria and Tasmania, there are the remains of several island arcs and microterrane belts that accreted to Gondwana in the Lower Palaeozoic, partly in the Cambrian but chiefly in the Ordovician. They form the southern part of what is known as the Tasman Orogenic Belt, the northern part of which, extending into Queensland (the New England orogen), is chiefly of Late Palaeozoic age. There is a large body of published data on the area, ably summarized by Gray & Foster (2005), and our palaeogeographical maps are largely drawn from the reconstructions of Metcalfe (e.g. Metcalfe 2002*a*) and Veevers (2004). Nearest the craton, the Delamerian orogen was active from the late Precambrian to the late Cambrian (about 650–500 Ma), and the more outboard Lachlan orogen, the largest in the belt, is largely of Ordovician age, but its final granites were intruded throughout the Silurian and into Early Devonian times. The Lachlan orogen has been revealed by geophysical investigations to continue northwards underneath the much younger surface rocks of the Great Artesian Basin, where it is locally termed the Thomson orogen. The Ordovician and Silurian faunas from both the craton and the arcs, and their palaeogeographical affinities, were summarized by Fortey & Cocks (2003, p. 261) and the correlation of the Lower Palaeozoic sedimentary basins on the adjacent Gondwanan craton was analysed by Jago *et al.* (2002).

New Zealand

Few Lower Palaeozoic faunas are known from this area, which is tectonically very active today; however, Cooper (1989) identified several terranes there. Münker & Cooper (1999) defined a Takaka terrane, cropping out in the Nelson area of northwestern South Island, which consists largely of a mid- to late Cambrian arc complex and which contains characteristic low-latitude Gondwanan Cambrian trilobites, indicating that the terrane may be confidently included within the active margin of

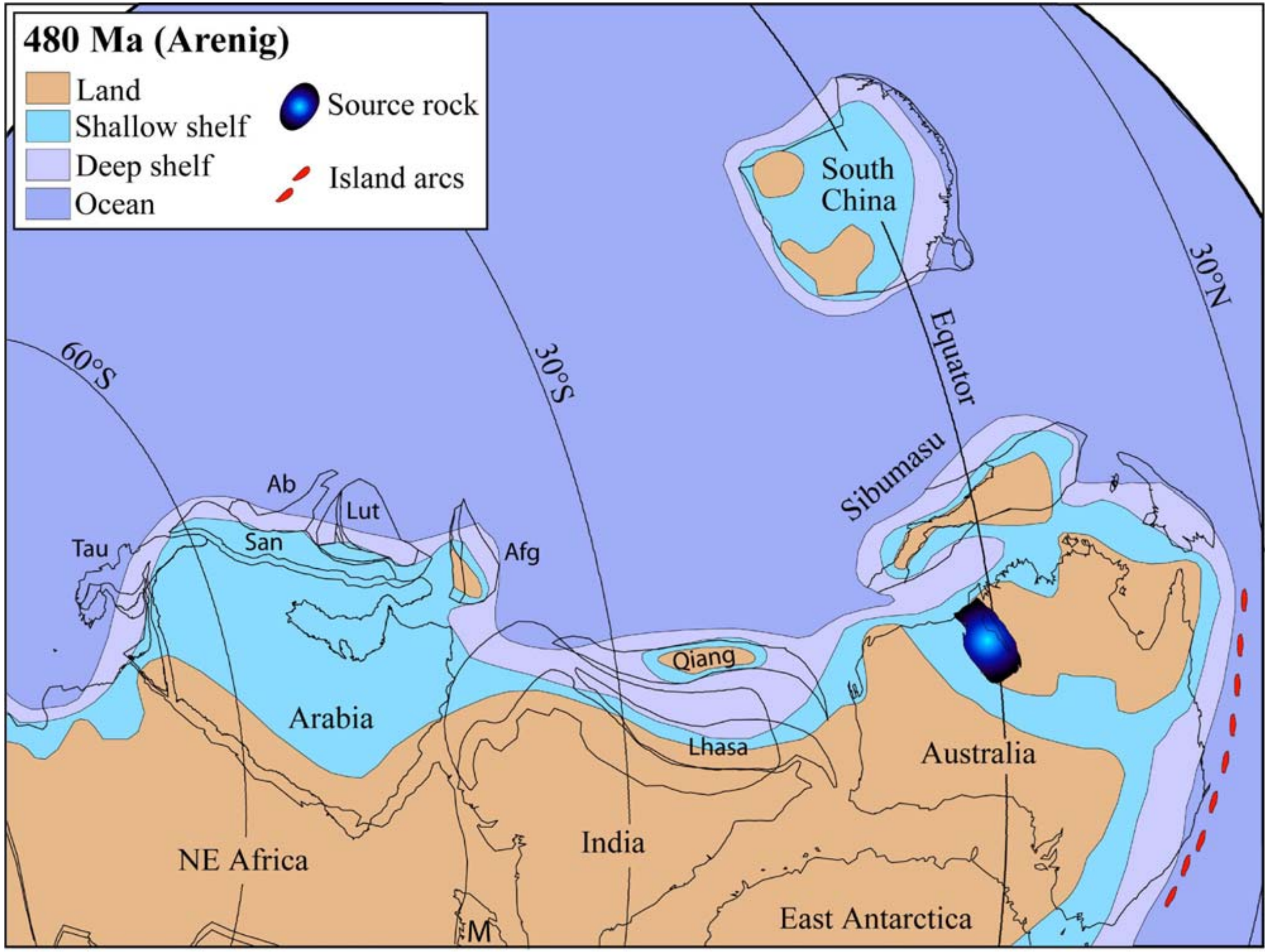

Fig. 4. Palaeogeography of the northeastern Gondwanan and adjacent peri-Gondwanan areas in early to mid-Ordovician (Arenig) times at 480 Ma. Abbreviations as in Figure 3, and M, Madagascar. Petroleum source rock areas are also shown.

peri-Gondwana. Cocks & Cooper (2004) documented a latest Ordovician *Hirnantia* brachiopod fauna within a dominantly graptolitic sequence, also near Nelson.

Geological history

There now follows a series of palaeogeographical reconstructions for the northeastern and eastern parts of Gondwana and their adjacent marginal areas and terranes at three times in the Lower Palaeozoic (Figs 3–5). The reconstructions were made using the digitized modern terrane boundaries outlined above and shown for the more westerly part of the area in Figure 1b, and moving them with kinematic consistency using SPlates, a prototype of Gplates (www.GPlates.org) now being developed by the Geodynamics Group at Trondheim in collaboration with Sydney University and the California Institute of Technology. The palaeomagnetic data for core Gondwana (Table 2) used in the constructions of Figure 2 are largely taken from Torsvik & Van der Voo (2002). As in our previous papers on Baltica and Siberia (Cocks & Torsvik 2005, 2007), we differentiate ocean, deep shelf, shallow shelf and land areas on our maps; however, we do not show mountain ranges or other variations in the land areas. A paramount consideration in our construction of these maps is the need for kinematic continuity between successive reconstructions. There are few palaeomagnetic data for most of the peri-Gondwanan terranes, apart from South China, but the successive palaeolatitudes for core Gondwana are now relatively well constrained (Torsvik & Van der Voo 2002): they are as shown in Table 2. We have also used aspects of the palaeogeographical maps by Veevers (2004) for the whole Gondwanan and peri-Gondwanan region, particularly the Australasian parts, and by Metcalfe (2002*a*) for SE Asia, to assist us in the compilation of our new maps.

Table 2. *Palaeomagnetic South Poles for South Africa and South China*

Age (Ma)	South Africa		South China	
	Latitude	Longitude	Latitude	Longitude
425	−10.2	357.6	−18.4	19.8
480	32.8	6.1	33.2	359.2
510	17.8	1.1	51.3	346.0

For South Africa the mean spline poles of Torsvik & Van der Voo (2002) are used (geocentric axial dipole (GAD)-based model). The South pole for South China is based on a running mean path using the *c*. 510 Ma (Middle Cambrian) Douposi Formation (Yang *et al.* 2004), the *c*. 430 Ma Yangtze Block (Sichuan and Yunnan) pole of Opdyke *et al.* (1987), and the *c*. 422 Ma Daguab–Shiqian pole of Huang *et al*. (2000). The *c*. 478 Ma Yunnan Province pole of Fang *et al*. (1990), which indicates a high latitude for South China, has not been included.

Cambrian

Gondwana was vast, stretching from over the South Pole under NW Africa to as far as 30°N of the Equator in the Australian and North Borneo areas (Fig. 2). Its Precambrian history is largely outside the scope of this paper, but Meert (e.g. Meert 2003) concluded that the formation of the northeastern part of the superterrane was essentially completed during the late Neoproterozoic by about 580 Ma, and that Gondwanan assembly involved the largest known series of mountain-building events in Earth history. In contrast, Allen (2007) concluded that the process was not complete in the Arabian area until earliest Cambrian time, at about 540 Ma. In either case we can assume that the whole cratonic core of the area under review here, from North Africa through Arabia and India to Australia, was a single united terrane well before 520 Ma, still within the early Cambrian. We show a newly reconstructed palaeogeographical map (Fig. 3) of northeastern Gondwana and the peri-Gondwanan terranes there in mid-Cambrian times (500 Ma). Apart from a possible glacial interval near the start of the Cambrian, in general the palaeotemperature and consequently the sea-level stands appear to have been high for much of the period, leading to extensive shallow-water seas flooding many of the Gondwanan craton margins, and the varied niches in those seas probably helped to facilitate the Cambrian faunal radiations.

Allen (2007) has described the substantial belt of early Cambrian evaporites that stretched within the Gondwanan margin, certainly across Arabia and perhaps as far as India. Stump *et al.* (1995) and other workers have identified a ‘Supergroup’ extending from the Middle Cambrian to the Late Ordovician in Saudi Arabia and adjacent areas, which was deposited on a stable continental passive margin in fluvio-deltaic to mid-shelf settings. Comparably, Myrow *et al.* (2006*a*, *b*) have documented the Cambrian and early Ordovician palaeogeography of the Himalayan area and have identified and analysed a Gondwanan passive margin as exemplified in the Zanskar and Spiti valleys. Further eastwards, Cocks *et al.* (2005) have summarized and reviewed the faunas in Sibumasu, in which a thick middle to late Cambrian shallow-water succession in Taratao Island, southern Thailand, carries trilobite and other faunas characteristic of the low-latitude parts of the Gondwanan craton of Australia. In contrast to the reconstructions shown by Cocks & Torsvik (2002), we now show Sibumasu as part of core Gondwana, and South China, although probably a terrane independent of core Gondwana, has new palaeomagnetic data (Yang *et al.* 2004) suggesting an equatorial position, at least from the middle Cambrian onwards. However, to reach that conclusion we have had to discard the data from South China published by Fang *et al.* (1990), whose high-latitude Ordovician positioning of South China contradicts both the faunal evidence and the data of Yang *et al.* (2004).

In the Australian sector, the Delamerian Orogen represents orogenic activity that originated during the late Precambrian and continued through most of Cambrian time, as at least one (and perhaps more) island arcs accreted to the main Gondwanan craton margin. In Tasmania, well-dated mid-Cambrian ophiolite obduction occurred, indicating accretion of an island arc to the Gondwanan margin there (Crawford & Berry 1992). In addition, in the Uluru shelf of central Australia, there was a large igneous province (LIP) tholeiitic eruption at about 510 Ma, termed the Antrim Plateau Volcanics, presumably caused by passage over a hotspot and extending for *c.* 400 000 km^2 (Veevers 2004, p. 113). Wright *et al.* (2000) and Li & Powell (2001) have also presented Cambrian reconstructions of the Australasian area; we differ from the latter in that we do not include the Annamia (Indochina) terrane within the Australasian part of Gondwana. There was an active mid- to late Cambrian island arc complex in New Zealand (Münker & Cooper 1999).

Ordovician

Gondwana and its associated terranes had a series of distinctive shelly faunas in the early Ordovician, which were characterized in detail by Cocks & Fortey (1988) and Fortey & Cocks (2003). These consisted of the Calymenacean–Dalmanitacean trilobite province in the higher-latitude parts of northwestern Gondwana and associated areas such as Avalonia, Armorica and Perunica (Bohemia), which were mostly outside the area treated in this paper apart from the Saudi Arabian occurrence documented by Fortey & Morris (1982); and the Dikelokephalinid trilobite province in the northeastern parts of Gondwana exemplified by Australia and the comparably low-latitude South China terrane. Between these two extremes there stretched a faunal cline through the intervening latitudes of Gondwana, within which were the medium- to high-latitude shelly faunas described from Iran by Bassett *et al.* (1999) and the distinctive early Ordovician (Arenig) brachiopod *Yangzteella* in the Taurides terrane, which also occurs in the lower latitude South China terrane. Stampfli & Borel (2002) stated that their Hun superterrane left Gondwana near the beginning of Ordovician time. However, Robardet (2003) has convincingly demonstrated that the Armorican terrane assemblage (most of France and the Iberian peninsula), which formed the westerly part of the postulated superterrane, carries higher-latitude terrane-diagnostic faunas of many phyla (the Mediterranean Province) which are indistinguishable from those in the main Gondwanan craton in North Africa from the Cambrian until the beginning of Devonian time. These indicate that any possible spreading centre to the south of Armorica could only have opened at an extraordinarily slow rate in the hundred million years after the supposed early Ordovician opening, which we consider unlikely.

In Figure 4 we present a new palaeogeographical reconstruction of the NE parts of Gondwana and the peri-Gondwanan terranes at early to mid-Ordovician (Arenig) times at 480 Ma. Again, this is considerably changed from the palaeogeography published by Cocks & Torsvik (2002), as there is much more now known both on the faunas of South China and Sibumasu and also on the palaeomagnetism of South China, placing both those terranes on equatorial palaeolatitudes and Sibumasu as part of core Gondwana. Part of the main Gondwanan craton in Australia was flooded by the Larapintine Sea, leading to the substantial early Ordovican sequences preserved today in the Canning, Georgina and Amadeus basins of western and central Australia (Veevers 2004), and the island arcs that progressively accreted to Tasmania, Victoria and New South Wales in the Lachlan orogen accommodated a succession of distinctive endemic shelly faunas, including the late middle Ordovician (Caradoc) brachiopods described by Percival (1991). Global eustasy reached a high point in Caradoc times, contributing to marine flooding of many regions in Gondwana and elsewhere.

The very end of the Ordovician saw the well-documented Hirnantian glaciation, which has its maximum expression in the NW African sector of Gondwana near the South Pole, but is also represented by glacial and periglacial deposits in Saudi Arabia and elsewhere in the then more southerly parts of our region. It also contributed to much deeper oxygenation of the oceans than usual, leading to the presence of the coeval and globally widespread *Hirnantia* Brachiopod Fauna even at lower latitudes such as New Zealand, where it is the sole shelly fauna represented in a succession otherwise consisting only of graptolitic shales (Cocks & Cooper 2004).

Silurian

Because most of the major terranes, including much of Gondwana, were at low to intermediate latitudes during the Silurian, which ran from 443 to 416 Ma,

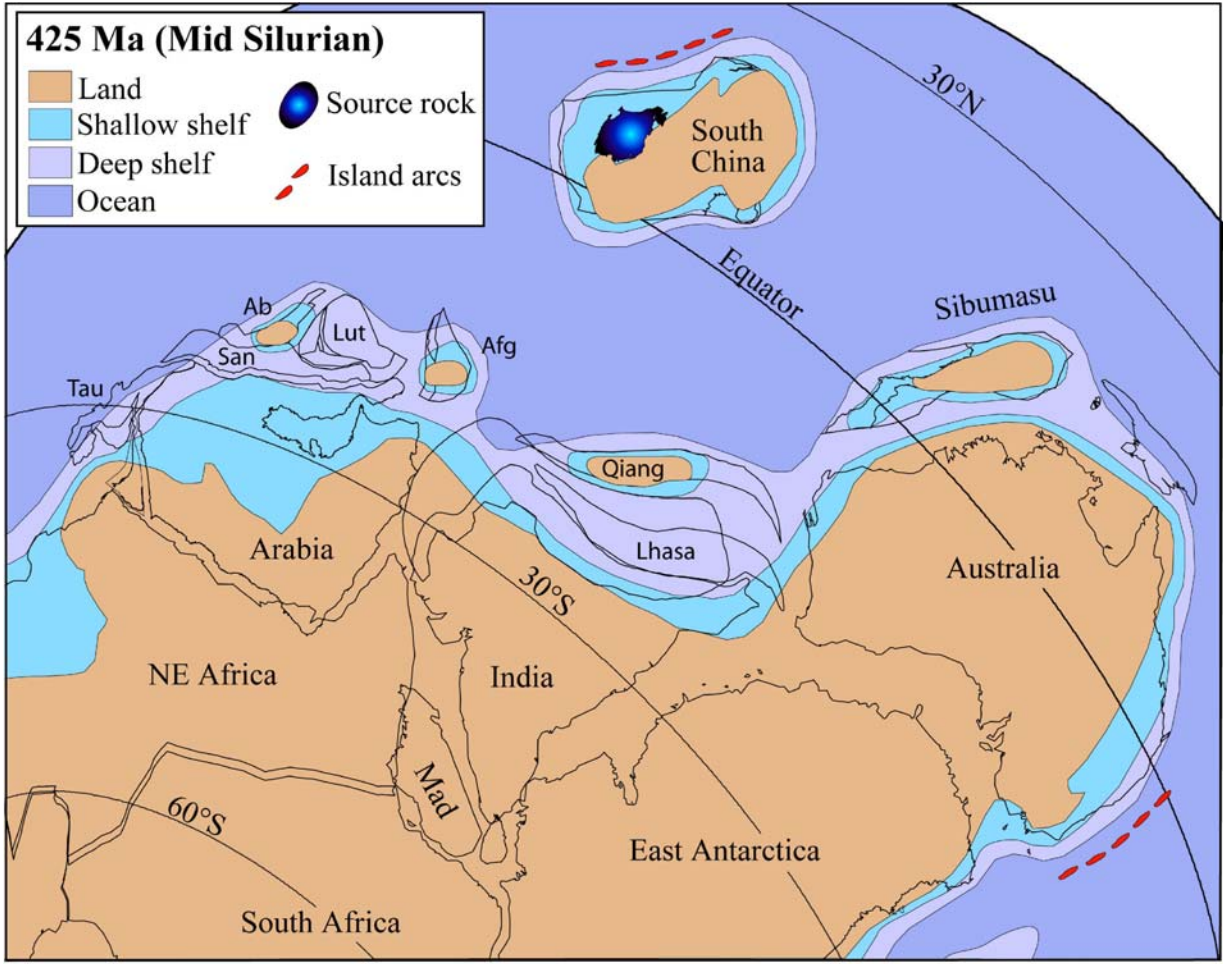

Fig. 5. Palaeogeography of the northeastern Gondwanan and adjacent peri-Gondwanan areas in middle Silurian times at 425 Ma. Abbreviations as in Figure 3.

and were not too far from each other, there were largely cosmopolitan shelly faunas over the whole of the area under consideration here, which are of little use in identifying separations of the various terranes from one another. Gondwana had drifted and rotated so that the South Pole lay under South America rather than NW Africa (Fig. 2). As in the Ordovician, there is a cline seen in the brachiopod and trilobite distributions along the Gondwanan margin, which has been documented for the late Silurian brachiopods by Rong *et al.* (1995). Our palaeogeographical map (Fig. 5) shows NE core Gondwana and the adjacent peri-Gondwanan terranes in mid-Silurian (Wenlock) times at 425 Ma. In contrast to Cocks & Torsvik (2002), and because of the new palaeomagnetic data of Yang *et al.* (2004), South China is shown in a more equatorial palaeolatitude. Sibumasu was a part of core Gondwana adjacent to Australia, as previously postulated by Metcalfe (e.g. Metcalfe 2002*a*).

There are differing opinions as to whether or not the main Australian part of the craton was still crossed by the Larapintine Sea (contrast the various maps of Metcalfe 2002*a*, Talent *et al.* 2003, and Veevers 2004), but we do not show it in Figure 5. In today's SE part of Australia there was substantial orogenic activity, represented by Silurian granites and other intrusions, after the Ordovician island arc terranes in the Lachlan orogen had completed their accretion to the main Gondwanan superterrane, indicating that that part of Gondwana was still an active margin.

Discussion and conclusions

The concept of a Hun (or Hunic or Hunia) superterrane, suggested chiefly by von Raumer, Stampfli and their co-authors (e.g. von Raumer *et al.* 2002; Stampfli & Borel 2002), consists of a large number of peri-Gondwanan terranes all shown as attached to each other in a very elongate ribbon stretching from Armorica to the Tibetan terranes, and all leaving the main Gondwanan cratonic area at the same early Ordovician time. This concept has attractions in that it invokes the parsimonious solution of postulating only a single spreading area within the underlying crust. However, the date of separation of such a superterrane from core Gondwana is contentious. Its western end is said to include the Armorican Terrane Assemblage (chiefly modern France and the Iberian peninsula), but various workers, particularly Robardet (2003), have clearly documented that the Armorican western end of the postulated 'Hun superterrane' remained with faunas identical to those of Gondwana until at least the early Devonian. Unless the sea-floor spreading rate of this Palaeotethys Ocean between the Gondwanan craton and the 'Hun superterrane' was exceptionally slow, it seems that the ocean was unlikely to have opened until, at the earliest, the late Silurian rather than the early Ordovician (Tremadocian) as stated by Stampfli & Borel (2002). Those workers also depicted the Hun superterrane as divided into two in some of their earlier reconstructions, a Cadomian terrane assemblage to the west and a Serindia terrane assemblage to the east; the two displaced from each other by a substantial north–south-trending strike-slip fault system for which we find little evidence.

In the eastern sector of Gondwana, the northeastward drift of the superterrane was fuelled by subduction at that Australian margin, so that consequently island arcs were accreted in the Cambrian Delamerian and the Ordovician Lachlan orogens there. In the northeastern peri-Gondwanan area our reconstructions (Figs 3–5) are different from those previously published (although not for the North Borneo to New Zealand sector), as we do not think that either North China or Annamia (Indochina) were attached to, or even near, core Gondwana during the Lower Palaeozoic. In addition, and with the help of newer and more plausible palaeomagnetic data (Yang *et al.* 2004) than those previously published, we consider South China to have been a terrane independent from core Gondwana but not far from it, and that South China apparently remained equatorial for the whole period. However, we now consider Sibumasu to have formed part of the main Gondwanan terrane in the Lower Palaeozoic, which follows the conclusions of Metcalfe (e.g. Metcalfe 2002*a*) rather than those shown in our previous paper (Cocks & Torsvik 2002).

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