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Gondwana from top to base in space and time

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ABSTRACT. Gondwana is reviewed from the unification of its several cratons in the Late Neoproterozoic, through its combination with Laurussia in the Carboniferous to form Pangea and up to its progressive fragmentation in the Mesozoic. For much of that time it was the largest continental unit on Earth, covering almost 100 million km^2, and its remnants constitute 64% of all land areas today. New palaeogeographical reconstructions are presented, ranging from the Early Cambrian (540 Ma) through to just before the final Pangea breakup at 200 Ma, which show the distributions of land, shallow and deep shelves, oceans, reefs and other features at nine selected Palaeozoic intervals. The South Pole was within Gondwana and the Gondwanan sector of Pangea for nearly all of the Palaeozoic, and thus the deposition of significant glaciogenic rocks in the brief Late Ordovician (Hirnantian) and the much longer Permo-Carboniferous ice ages help in determining where their ice caps lay, and plotting the evaporites in the superterrane area indicates the positions of the subtropics through time. Reefs are also plotted and selected faunal provinces shown, particularly at times such as the Early Devonian (Emsian), when high climatic gradients are reflected in the provincialisation of shallow-marine benthic faunas, such as brachiopods.

In Late Palaeozoic and Early Mesozoic times, Gondwana (with Africa at its core) lay over the African large low shear-wave velocity province (LLSVP), one of two major thermochemical piles covering ca. 10% of the core-mantle boundary. The edges of the LLSVPs (Africa and its Pacific antipode) are the plume generation zones (PGZs) and the source regions of kimberlite intrusions and large igneous provinces (LIPs). Our palaeomagnetic reconstructions constrain the configuration of Gondwana and adjacent continents relative to the spin axis, but in order to relate deep mantle processes to surface processes in a palaeomagnetic reference frame, we have also rotated the PGZs to account for true polar wander. In this way, we visualize how the surface distribution of LIPs and kimberlites relate to Gondwana’s passage over the PGZs.

There are only two LIPs in the Palaeozoic (510 and 289 Ma) that directly affected Gondwanan continental crust, and kimberlites are rare (83 in total). This is because Gondwana was mostly located between the two LLSVPs. The majority of Palaeozoic kimberlites are Cambrian in age and most were derived from the African PGZ. Sixty-six Early Mesozoic kimberlites are also linked to the African LLSVP. All known LIPs (Kalkarindji, Panjal Traps, Central Atlantic Magmatic Province and Karoo) from 510 to 183 Ma (the lifetime of Gondwana) were derived from plumes associated with the African LLSVP, and three of them probably assisted the breakup of Gondwana and Pangea.

Keywords: Gondwana, palaeogeography, Phanerozoic, Pangea assembly and breakup, large low shear-wave velocity provinces, plume generation zones, large igneous provinces, kimberlites.

Contents

1. Introduction

From its unification in the Late Neoproterozoic to its amalgamation with Laurussia in the Carboniferous to form Pangea, Gondwana was the largest unit of continental crust on Earth for more than two hundred million years. The superterrane of core Gondwana included the modern continents of South America, Africa, and most of Antarctica and Australia, as well as Madagascar and the Indian Subcontinent, which is 64% of all land areas today and 19% of the total Earth surface. In addition, Florida and most of Central America, southern Europe, and much of south-central and south-eastern Asia all formed parts of Gondwana at different times, and, as discussed below, the continents of North China, South China, Tarim and Annamia (Indochina) might also have been integral parts of Gondwana during the latest Precambrian. Even the large continents of Baltica and Siberia were very close to the superterrane in Late Neoproterozoic and Early Palaeozoic times.

The name Gondwana (or Gondwanaland as it is also often called, but we prefer the shorter version) was originally coined by H.B. Medlicott and H.F. Blanford of the Indian Geological Survey in 1879 for a sedimentary sequence of non-marine rocks in India, but became much more widely known after its use by Suess (1885) for the regions, chiefly in India, which hosted the distinctive Late Palaeozoic *Glossopteris* Flora. Suess imagined that the various floral provinces had flourished on continents which had always been in their present positions, but that they had been linked by land bridges in the Late Palaeozoic which had been subsequently drowned beneath oceans through isostatic readjustments. However, the concept of Gondwana was much changed and enlarged by Wegener (e.g., 1915), who postulated for the first time that the major components of what we here recognise as Gondwana had been united as a single superterrane during the Late Palaeozoic, as characterised both by the *Glossopteris* Flora and also by the presence of glacial deposits that could only have been formed in a polar region; and that the different sectors of Gondwana had subsequently travelled apart across the oceans. There was much opposition to Wegener's ideas on continental drift and the concept of a previously-united Gondwana, largely due to the lack of a plausible mechanism for the necessary continental movements; although some authors, for example in the substantial book by Du Toit (1937), continued to promote continental drift. That scepticism continued among most of the geological community until the advent of the plate tectonic theory in the 1960s, as reviewed by Torsvik and Cocks (2012).

In the past three-quarters of a century there has been an avalanche of publications on Gondwana; for example, the volumes edited by Vaughan et al. (2005) and van Hinsbergen et al. (2011), as well as the numerous papers in this journal and elsewhere, and only a small proportion of them are included in the present review. De Wit et al. (1988) constructed a magnificent map of the entire Gondwanan area on a large scale. Cocks and Fortey (1988) offered palaeogeographical maps of Gondwana at several intervals in the Lower Palaeozoic, and we have also previously published together global maps for the whole Palaeozoic (Cocks and Torsvik, 2002; Torsvik and Cocks, 2004) in which Gondwana is conspicuous due to its size; but all of those papers are now outdated, particularly in the accuracy of their progressive positioning of Gondwana through time. We have more recently considered two sectors of Gondwana, the north-eastern margin (Torsvik and Cocks, 2009) and the central sector (Torsvik and Cocks, 2011), but those papers only covered parts of the superterrane and for restricted time periods. Thus we feel that it is now timely to pen a relatively brief overview of the superterrane as a whole, from its original Late Neoproterozoic amalgamation, through its Carboniferous merger with Laurussia to form Pangea, and continuing on to the subsequent history of its principal components. Another important factor is that it is only during the past few years that we have been able to understand much better the relationships between Earth's crust and its underlying mantle, and realise the direct influences heterogeneities at the core-mantle boundary have played and continue to play on Earth surface processes; in particular since they constrain the sites of initiation of large igneous provinces (LIPs), kimberlites and hotspots (Torsvik et al., 2006; 2008a; 2010a). Although many people have used the term 'supercontinent' for Gondwana, we prefer to call it a superterrane, so as to distinguish Gondwana from the true supercontinents of Rodinia and Pangea. Gondwana became a part of the latter during the Carboniferous.

Our maps are combinations of the myriad small polygons into which the modern Earth has been divided (Torsvik et al., 2010b; 2012), and which are redistributed according to their individual progressive movements through geological time using the GPlates software (Boyden et al., 2011) with kinematic continuity. The disadvantage of that method is that only a few palinspastic and therefore subjective extensions to continental crust are shown; for example, the extension of today's northern margin of India prior to its collision with Asia in the Himalayan Orogeny has been added manually. In contrast, the elements of the Armorican terranes prior to the Variscan Orogeny, for example, are not shown with their original pre-Carboniferous shapes. However, the overwhelming advantage of using GPlates is that, unlike so many previously published palaeogeographical reconstructions, it is objective. In addition, it is chiefly the outlines of the smaller terranes which suffer most from the lack of palinspastic additions and subtractions; however, they form only a small proportion of our large-scale maps: the bulk of the superterrane of Gondwana and its component cratons have been relatively undistorted by Phanerozoic tectonics. To aid the recognition of terranes, we have included the outlines of modern coastlines where applicable.

The following sections firstly survey the palaeomagnetic data available (Section 2), and then there is a description of Gondwana's crust and its relationship with the underlying mantle (Section 3). We then go on to consider the individual Gondwanan components. Most authors, for example Vaughan and Pankhurst (2008), have divided the core of the superterrane into 'West' and 'East' Gondwana, and we follow them: those two major sectors are briefly characterised in Sections 4 and 5. That is followed by a brief listing of the many marginal terranes and microcontinents (Sections 6 and 7), after which there is an outline history of the whole superterrane area (Section 8).

2. Palaeomagnetic summary

Despite the enormous size of the superterrane, almost 100 million km^2, and the consequent potential availability of palaeomagnetic data and reasonable constrained Gondwana plate circuits, apparent polar wander (APW) paths for the combined core-Gondwana continents differ widely in the published literature. From Gondwana assembly at around 550 Ma (Meert and Van der Voo, 1997) to the Jurassic separation of West and East Gondwana at around 170 Ma (Gaina et al., 2013), Torsvik et al. (2012) included only 124 palaeomagnetic poles. Their data-selection are shown on a Gondwana reconstruction (Fig. 1) with palaeomagnetic sampling sites in Australia (West and East Australia), East Antarctica (including Dronning Maud Land), India, Madagascar, Arabia, Africa (Northeast and Northeast Africa, Somalia, South Africa) and South America (Amazonia, Paraná, Colorado and Patagonia). 48 out of 124 Gondwana poles are detrital sedimentary poles corrected for inclination shallowing using a standard flattening (*f*) value of 0.6; and the spherical spline Gondwana APW path of Torsvik et al. (2012) is reproduced in Figure 2. We also indicate when a mean pole in the APW path (shown in 10 Ma intervals) is of high, medium (based on one single pole) or low (interpolated) quality. The Late Neoproterozoic and Early Cambrian South Pole (keeping southern Africa fixed) was located in South America (Amazonia), and it migrated to NW Africa during the Lower Palaeozoic, followed by SE motion and a distinct Silurian-Devonian cusp. By the Carboniferous, the South Pole was located within East

Antarctica (Fig. 2). This south polar path differs radically from that used by Stampfli et al. (2013, fig. 5), which is mainly based on unverifiable industrial sources.

An APW path is a sequence of palaeomagnetic poles in time and space that can be inverted to represent plate motion relative to a fixed rotation axis, and we can therefore easily calculate ancient latitudes and plate velocities for a given location. A central Gondwana location in Southern Africa demonstrates southern hemisphere latitudes throughout the Palaeozoic and Early-Mid Mesozoic (Fig. 3a), but from the Devonian to Triassic there was a systematic drift from high southerly latitudes to the subtropics. Plate velocities peaked at 17 cm/yr between 550 and 540 Ma (Fig. 3b) at the height of the Pan-African Orogeny and the final assembly of Gondwana, and averaged down to 5.0 ± 3.8 cm/yr for the 550-170 Ma interval. These are minimum velocities (latitudinal velocities) because east-west longitudinal motions are unknown, but, in addition, true polar wander (TPW), which is caused by rotation of the planet relative to the spin axis, affects velocity estimates since, by definition, APW equals ‘continental drift’ + TPW. Our latest model, with velocities that only describe ‘continental drift’ for a central Gondwana location, is shown in Fig. 3c. This is an absolute plate model, longitude-calibrated (Torsvik et al., 2008a) and corrected for TPW (Torsvik et al., 2013a), and absolute velocities average to 7.0 ± 3.3 cm/yr, with peak velocities of about 12 cm/yr in Late Devonian and Late Carboniferous times. The latter coincides with the amalgamation of Gondwana and Laurussia to become part of Pangea. ‘Gondwana’ velocities — continuing as an integral part of Pangea — averaged 5.1 ± 2.4 cm/yr from the Late Carboniferous to the breakup of Gondwana (and Pangea) by the Jurassic. Fig. 4 shows the difference for the Early Cambrian at 540 Ma, where the upper reconstruction has taken account of TPW, and the lower one has not. Torsvik et al. (2013a) identified six phases of Palaeozoic TPW, but TPW is rather slow ($<1^{o}$/Ma), and there is no evidences for fast 90^{o} inertial interchange TPW, which has been postulated to have occured in Cambrian (Kirschvink et al., 1997) or Devonian (Piper, 2006) times. Although TPW is slow and oscillatory in nature, net TPW can be large in the Palaeozoic, and at 540 Ma (Fig. 4) net TPW is $\sim40^{o}$ around an axis located at 11^{o} East and 0^{o}N.

3. Gondwana’s crust and underlying mantle

Two antipodal Large Low Shear-wave Velocity Provinces (LLSVPs; Garnero et al., 2007) on the core-mantle boundary (CMB) beneath Africa and the Pacific Ocean are recognized in all shear-wave tomographic models (e.g., Ritsema et al., 1999; 2011; Masters et al., 2000; Mégnin and Romanowicz, 2000; Grand, 2002; Gu et al., 2001; Montelli et al., 2006; Simmons et al., 2007; Torsvik et al., 2008a; Dziewonski et al., 2010; Lay and Garnero, 2011), and coincide with residual geoid highs (Burke et al., 2008). The edges of these thermochemical bodies are the plume generation zones (PGZs; Burke et al., 2008; Burke, 2011), which are the likely source regions of the vast majority of global kimberlite intrusions (Fig. 5) and Large Igneous Provinces (LIPs), shown on Fig. 6. This surface-to-CMB correlation has been established by plate models as far back as the formation of Pangea (ca. 320 Ma) and is potentially valid back to the dawn of the Phanerozoic (Torsvik et al., 2010; 2013a), attesting the long-term stability of the LLSVPs. Many active hotspots, e.g. Hawaii and Reunion (but not all of them, for example Yellowstone), also project radially down to the PGZs (Fig. 7).

The African LLSVP (Figs. 7, 8) covers around 16 million km^2 (~10%) of the CMB, the centre of mass (~16°S, 13.0°E; Burke et al., 2008) is located beneath Angola (Southern Africa), and shear-wave velocity anomalies reach about minus 3% in the *SMEAN* tomographic model (Becker and Boschi, 2002). The African LLSVP is overlain by ~20 active hotspots, of which seven have been considered to have a deep source, based on several varied criteria (Fig. 8). Interestingly, practically all the ‘African’ hotspots project radially down to the edges of the African LLSVP (irrespective of whether plume advection is considered or not), and in no case are they close to the central parts of the LLSVP. Reconstructed LIPs and kimberlites (Figs. 6, 9) linked to Gondwana’s passage over the LLSVPs are discussed in the sections below.

4. West Gondwana (largely South America, Africa, and Arabia)

Nearly all of South America (apart from the western strip) was included within the core of Palaeozoic Gondwana. That core includes the Amazonia, Sao Francisco and Rio de la Plata cratonic blocks (Fig. 5), all of which have Archean and Palaeoproterozoic rocks, and which all originally formed continents separate from each other (Meert and Torsvik, 2003; Bogdanova et al., 2008; Fuck et al., 2008; Li et al., 2008). The geology of Chile was reviewed by Moreno and Gibbons (2007) and Argentina by many authors, for example Benedetto (2003) for the Ordovician. Tankard et al. (1995) edited a useful book which reviewed all the South American basins, many of which have yielded substantial hydrocarbon deposits; and Milani and Filho (2000) have also reviewed the same basins. Palaeozoic palaeogeographical maps of South America were published by Baldis (1992) and França et al. (1995). The intracontinental basins were caused by sag down-warping of the Gondwana Craton, one of the most substantial of which was between the Guyana and main sectors of the old Amazonia Craton, approximately in the centre of today’s Amazon basin, and that downwarp contained both the Solimões and the Amazonas basins during all of the Palaeozoic, in which there were deposited a mixture of marine and non-marine sediments. Further to the south, the Paraná and neighbouring Chaco-Paraná basins were intermittently separate or linked to each other. The varied sediments in all those basins indicate the presence of both shallow epeiric marine seas and also large intra-continental lakes at different times. At the north-west margin of the Amazon Craton, there was substantial Early Ordovician magmatism in the Eastern Cordillera of Columbia (Figuero et al., 2012).

Rapela et al. (2007) described the history of the Rio de la Plata Craton, largely in Argentina, which is known through boreholes to be much more extensive than is suggested by its present outcrop, and dated the basement there as largely Palaeoproterozoic (2.2 to 2.1 Ga). They also postulated that the craton reached its present position by large-scale dextral strike-slip movement against fore-arc sedimentary sequences that had developed on the southern and western margins of the Kalahari Craton of Africa in the earliest Cambrian. To the west of the Rio de la Plata Craton in north-eastern Argentina there is the Pampia unit, which includes many Neoproterozoic rocks which we group here with the Rio de la Plata Craton. From the Late Ordovician to the Middle Silurian, and from the Late Devonian to the early Permian, many glaciogenic rocks were deposited, which reflect the polar ice present during those times (Caputo et al., 2008).

There are differing published opinions on Patagonia, today’s southernmost sector of the South American continent. Whilst its small Neoproterozoic craton is comparable with others in Gondwana, and its faunas were undoubtedly of general Gondwanan affinity throughout its Phanerozoic history, as reviewed by Pankhurst et al. (2006); nevertheless, its independence from Gondwana (or lack of it) is controversial. However, we consider that it appears to have been an independent microcontinent until the Late Palaeozoic, as discussed in Section 6.6 below.

Bordering the Amazonia and Rio de la Plata Cratons to their west and south, the whole western coast of today’s South American continent from Patagonia (the southern areas of Argentina and Chile), through western Argentina and adjacent parts of Chile, extending northwards to Bolivia, southern Peru, and continuing on to the much-displaced Mexican terranes, consists of the remains of microcontinents (such as the substantial Arequipa-

Antofallo Block in the northern sector) and island arcs. Most of those units were newly accreted to core Gondwana at various different times from the Late Neoproterozoic to the Early Silurian. However, some of the blocks are marginal parts of the original Gondwanan Craton which were tectonically displaced and then reamalgamated at various times in the Phanerozoic (Sections 6.6 and 6.7). The whole area is generally termed the Proto-Andean Orogen (Vaughan and Pankhurst, 2008).

In addition, what were to become Florida and other terranes now in North America, as well as the independent microcontinent of Avalonia (reviewed in Section 6.8), and probably the Meguma Terrane of Eastern Canada, were all originally integral parts of core Gondwana near the Amazonian Craton. They left the superterrane during rifting events which were probably interlinked but may or may not have been at slightly different times, mostly near the Cambro-Ordovician boundary at around 490 Ma, when Avalonia rifted away from the Gondwana Craton (Fig. 10) and the Rheic Ocean opened between the two (Cocks and Fortey, 2009).

Aspects of Africa were reviewed in the many papers within van Hinsbergen et al. (2011). Africa, which was at the very centre of Gondwana (Fig. 4) and subsequently Pangea, is formed of several originally separate cratons with Archean and Palaeoproterozoic cores, which are named the West African, Congo, and Kalahari cratons (Fig. 5), as well as the smaller Lake Victoria Block, and they united progressively in the Neoproterozoic. As chiefly deduced from both the palaeomagnetic data, and supported by the distribution of icecaps and glaciogenic rocks deposited during the Late Ordovician Hirnantian (443 Ma) and the Permo-Carboniferous (315 to 295 Ma in Africa) glaciations, the South Pole lay beneath Africa for most of the Palaeozoic. Gondwana moved over the pole, so that it lay off the north-western coast in the Cambrian to beneath the southeast of South Africa in the Permian (Torsvik and Cocks, 2011, and Fig. 2). A large proportion of Africa was land for nearly all of the Palaeozoic, together with adjacent Madagascar, which also had Archaean and Palaeoproterozoic cratonic rocks, and which did not rift away from Africa until Mesozoic times.

Although Arabia does not have a craton older than Proterozoic, nevertheless it also formed an integral part of the core Gondwana area until the Red Sea opened in Late Tertiary times. That is very clearly shown in the marine benthic invertebrates found in the Lower Palaeozoic rocks there, which include the typically Gondwanan higher-latitude *Neseuretus* trilobite faunas originally documented from Early and Middle Ordovician rocks in Saudi Arabia (Fortey and Morris, 1982; El-Khayal and Romano, 1985).

In nearly all of northern Africa there are extremely well-exposed and impressive glaciogenic rocks deposited during the Late Ordovician ice age, originally described by Beuf et al. (1971) and revised by Ghienne et al. (2007). There were substantial freshwater lakes in both southern and south-central Africa in the Late Palaeozoic, and their sediments are inclusively termed the Karoo Supergroup over the whole area; although that group is laterally discontinuous and includes many unconformities. The Karoo Supergroup has yielded large quantities of important Permo-Carboniferous fossil amphibians and reptiles (Rubidge et al., 2013).

Thus the rocks seen today in most of West Gondwana represent a unified Late Precambrian to Permo-Triassic craton. Following the Mesozoic opening of the Atlantic Ocean, Late Jurassic and later marine rocks were deposited in the areas marginal to both oceans, and are well developed in both eastern and western Africa. Those strata include the hydrocarbon source rocks found today in western and offshore Angola and neighbouring countries, as well as in the Rift Valley of Uganda and elsewhere.

5. East Gondwana (Antarctica, Australasia, India, and Madagascar)

Veevers (e.g., 2004) and Li and Powell (2001) have described and reviewed the evolution of Gondwana with particular emphasis on Australia and Antarctica. The bulk of those two continents today consist of Precambrian cratonic rocks, but there are Palaeozoic island arcs adjoining both the Antarctic and Australian cratons which make up much of the modern continents. The cratonic area of the western two-thirds of Australia can be divided into the North Australian Craton and the Pilbara-Yilgarn Craton: in contrast, the eastern third is comprised of the marginal Tasman Fold Belt, which is itself divided into a northern Thompson Fold Belt and a southern Lachlan Fold Belt, both of which include several originally separate Palaeozoic accreted terranes (Section 6.4). The Kalkarindji Large Igneous Province flood basalts were intruded into the northern part of the western Australian craton (Figs. 4, 6, 10) during the Cambrian at 512 Ma (Glass and Phillips, 2006), and have provided a valuable data point for the estimation of the palaeolongitude of the Australian sector of Gondwana at that time (Torsvik et al., 2008a).

In a comparable way to Western Australia, only East Antarctica has an Archaean and Palaeoproterozoic craton. That was an integral part of Gondwana throughout its existence, and the cratonic margin during the Palaeozoic ran along the Transantarctic and Ellsworth-Whitmore Mountains. The latter underwent intracontinental extension during the Cambrian (Storey and Macdonald, 1987). In their northern sector, in northern Victoria Land, they incorporate Cambrian and Ordovician terranes which amalgamated both with each other and with the Gondwana Craton during the Lower Palaeozoic Ross Orogeny (Stump, 1995; Tessensohn and Henjes-Kunst, 2005). Laird (in Holland, 1981) reviewed the Lower Palaeozoic rocks of Antarctica, and Antarctic rocks of many Phanerozoic ages were covered in the volume edited by Vaughan et al. (2005); in particular, Leat et al. (2005) summarized the different tectonic histories of the constituents of the continent through time.

In contrast, the western half of today’s Antarctic continent is made up of several volcanic arcs considered in Section 6.5 below, as well as Dronning Maud Land. The latter had been a substantial separate microcontinent in the Neoproterozoic and consists of a Proterozoic basement unconformably overlain by Lower Cambrian sediments in the west and Middle to Upper Cambrian sediments in the east (references in Veevers, 2004). Dronning Maud Land became an intrinsic part of the main Gondwana Craton before the Cambrian, and it may have been linked to the Kalahari Craton of Africa in the Neoproterozoic (Torsvik et al., 2008b). Dronning Maud Land underwent extension in the Early Cambrian, leading to the emplacement of substantial charnockites in the Middle Cambrian at about 520 Ma (Jacobs et al., 2003).

Between East Antarctica and India lies the Kuungan orogenic belt, which represents another orogeny within Gondwanan assembly during the Late Neoproterozoic and earliest Cambrian. India, including the surrounding countries of Pakistan, Sri Lanka, and Bangladesh, as well as the smaller nations in the southern Himalaya, largely consists of a single Precambrian craton, unconformably overlain only by a few Early Cambrian marine rocks, and Permian non-marine rocks which were the origin of the name ‘Gondwana’ and which yielded the first known *Glossopteris* Flora (Medlicott and Blanford, 1879). That is apart from the Himalayan region, where there are varied Palaeozoic rocks which were laid down at the edge of Gondwana. As well as the Kuungan Orogen, which finished soon after the start of the Cambrian, there was also orogeny at that margin in the Late Cambrian and early Ordovician (Section 6.2). In the Salt Range of Pakistan there are substantial glaciogenic deposits of latest Carboniferous to Early Permian (Gizhelian to Asselian: 304 – 294 Ma) ages. Adjacent to Africa, Antarctica and India lay Madagascar, which also has an Archean and Neoproterozoic Precambrian craton intruded by many plutons, the latest dated to Lower Cambrian at 520 Ma

(Key et al., 2011), but there are no later Palaeozoic rocks there. Near Madagascar must have laid the now-vanished microcontinent of Mauritia, whose former existence is known only from its derived Precambrian zircons in Tertiary lava flows offshore from Mauritius (Torsvik et al., 2013b). The Seychelles Islands, today near the centre of the Indian Ocean, largely consist of 800 to 700 Ma Precambrian granites (Tucker et al., 2001; Ashwal et al., 2002), presumably originally a part of the Africa or Madagascar cratons; and the Seychelles Terrane also formed part of core Gondwana until the Mesozoic.

The microcontinent of Sibumasu, which stretches from Burma to Sumatra in Indonesia to the south, has long been identified as a fault-bounded and separate tectonic identity today (see Section 6.3 below). However, it is now generally accepted that it too formed an integral part of the core eastern Gondwana craton offboard from Australia (Metcalfe, 2011; Cocks and Torsvik, 2013) until the opening of the Neotethys Ocean during the Permian. That is further confirmed through the analysis of Devonian and other zircons in Sibumasu indicating Gondwanan affinities and origins (Dopieralska et al., 2012).

6. Marginal microcontinents and terranes

In addition to the varied areas mentioned below, there are many more which did or did not interact with core Gondwana over its long history as a superterrane, most of which are shown on the global map at 540 Ma (Fig. 4). However, not shown on Fig. 4 are many of the numerous Palaeozoic terranes and microcontinents, many with Precambrian cores, which now make up central Asia and are often referred to collectively as the ‘Kazakh terranes’ and the ‘Mongolian’ terranes, even though their boundaries extend well beyond Kazakhstan and Mongolia respectively in several instances. As reviewed in many papers (e.g., Şengor and Natalin, 1996; Fortey and Cocks, 2003), those Kazakh terranes merged progressively with each other, so that by the end of the Silurian some had united to form a big enough entity to be termed the Kazakhstania continent, and none were independent at the end of the Palaeozoic. But whether or not some of the Kazakh terranes originally formed sectors of peri-Gondwana during the Neoproterozoic, and perhaps even Early Cambrian, is very poorly constrained and thus uncertain; however, that will not be discussed further in the present paper and those terranes are not shown on our maps. Comparably, neither the Karakum Terrane, which straddles the border between Iran and Afghanistan and which could have formed part of either peri-Gondwana or the Kazakh terrane group (Torsvik and Cocks, 2009), nor the Pontides Terrane of Turkey (Section 6.2) are shown.

6.1. Southern Europe

Many authors over more than two centuries have described the geology of most of France (Armorica), southern Germany, the Iberian Peninsula, Italy, the Czech Republic (Bohemia), the Balkans, and adjacent areas. The different identities, extents of the terranes within them and the timings of their rifting away from Gondwana have been disputed. Various authors, for example Matte (2001), followed by Cocks and Torsvik (2002), had identified an 'Armorican microplate' (often termed ATA, the Armorican Terrane Assemblage) to accommodate many of these terranes as present in the Lower Palaeozoic following the Late Neoproterozoic to Early Cambrian Cadomian Orogeny in the area. However, there is now little doubt that those southern European terranes all continued to form integral parts of peri-Gondwana throughout the Lower Palaeozoic, or some even parts of core Gondwana, as can be concluded from analysis of their sedimentology and their contained provincial benthic faunas. Thus we now follow, for example Robardet (2003), in considering that the Armorican terranes left the Gondwana superterrane only with the opening of the Palaeotethys Ocean, whose timing is itself controversial but seems most probably to have occurred early in the Devonian. Nance et al. (2010) have reviewed the complex evolution of the Rheic Ocean, which lay immediately north of the Gondwanan margin at the ocean's origin in the earliest Ordovician, but to the north of the Armorican and associated terranes after the latter became independent from Gondwana in the Early Devonian. A widening Palaeotethys Ocean opened to the south of the Armorican Terrane Assemblage.

The Iberian Peninsula is today roughly square-shaped, but largely consists of a convolute structure which various authors, for example Shaw et al. (2012), have interpreted as an orocline which formed at around Carboniferous-Permian boundary time as part of the Variscan Orogeny. The earlier rocks there have been reconstructed as having formed an essentially straight belt about 1,400 km long which had previously been part of the Gondwanan margin, with the inner margin of the orocline representing the oceanwards part of that margin prior to their detachment and the creation of that orocline in the Middle Carboniferous. However, since the original palinspastic situations of the rocks which form the Iberian Peninsula are open to many interpretations, we have simply drawn it as a lozenge similar to its shape today on the small scale of our pre-Carboniferous maps. That those Iberian rocks were probably previously an integral part of core Gondwana is supported by the varied

Precambrian zircon analyses from the Ossa-Morena Zone of Iberia, which are complex and very comparable with those from the West African Craton (Pereira et al., 2012).

6.2. South-central and eastern Asia

The long margin of Gondwana running from Turkey to north-eastern India had a variety of adjacent terranes which chiefly remained parts of Gondwana until the opening of the Neotethys Ocean in the early Permian, as reviewed for the Lower Palaeozoic by Torsvik and Cocks (2009), although many suffered significant subsequent deformation in the Himalayan Orogeny, which is still continuing today. Those terranes include the Taurides of southern Turkey, the Lesser Caucasus Terrane of Georgia, the Sanand, Alborz and Lut terranes of Iran, the Mangyshlak Terrane (which spans the Caspian Sea, and is termed the Kopetdag Terrane by some authors), the Afghan Terrane (which may itself consist of several terranes), the Karakorum Terrane in the northwest of Pakistan, and the Tibetan Lhasa and Qiangtang terranes of the Himalaya, both largely in southern China. Some other authors, for example von Raumer et al. (2003), have recognized even more individual terrane units. In addition, although the relatively small Pontides Terrane in the northwest of Turkey was certainly close to Gondwana, as can be deduced from its faunas (for example the Lower Ordovician trilobites described by Dean et al., 2000), it does not appear to have formed an integral part of the superterrane during the Lower Palaeozoic. The Pontides seems to have lain further to today’s west, perhaps near Avalonia (Sayar and Cocks, 2013), and was displaced to its present position in the later stages of the Variscan Orogeny; however, its Palaeozoic positions are unknown and it is therefore omitted from our maps.

Most of the long northern margin of Gondwana was passive for much of the Palaeozoic. For example, the facies on either side of the substantial Zagros Suture, which today separates the Arabian sector of the craton from the Sanand to the Lut terranes, are essentially similar from Turkey to Pakistan (Zanchi et al., 2009). The same authors also noted that the Devonian to Middle Triassic rocks in the Alborz Terrane are all shallow-marine ramp carbonates without angular unconformities, endorsing the passive margin there throughout that long period. However, in the western Alborz Mountains of Iran, Zanchetta et al. (2009) have described Late Carboniferous eclogite formation in the Shanderman Complex at around 315 Ma, probably indicating that, like the Pontides Terrane, that western sector of Alborz was probably not part of the core Gondwanan margin in those times. Ramezani and Tucker (2003) described and dated extensive andesitic and trondhjemitic igneous activity near the western margin of the Lut Terrane as occurring from the latest Neoproterozoic (547 Ma) well in to Cambrian times (525 Ma).

In the Himalaya it is very difficult to disentangle formerly discrete Palaeozoic terranes from within today's very complex orogenic belt. That is why there is a gap shown between India and the Tethyan Himalaya (TH on Fig. 4) on the global early Cambrian map, a gap which was filled at that time by the northwards extension of India now subducted beneath Tibet, and which we have drawn subjectively on the later maps. Various authors, most recently McQuarrie et al. (2013) and Zhu et al. (2013) have assessed and reviewed the Palaeozoic rocks there, but the number and extent of the possible palaeogeographic units are not well characterised, and anyway would be too small to show on the scale of our maps. After the Neoproterozoic to Early Cambrian sector of the Kuungan Orogeny, there was a relatively short period of quiescence, when Lower and Middle Cambrian sediments in the Lesser and Tethyan Himalaya, for example at Spiti, represent parts of the northward-prograding, fluvial-deltaic depositional system of the main Indian Craton (Myrow et al., 2006). Subsequently there were probably Late Cambrian to Early Ordovician tectonic events in the central part of the Himalaya, termed the Greater Himalayan Orogeny by McQuarrie et al. (2013), with granite intruded there from 530 to 470 Ma and also at 496 Ma into the adjacent Lhasa Terrane, perhaps representing a retro-arc foreland basin some distance away from the main Gondwana Craton. Late Devonian granitoids in the southern margin of the Lhasa Terrane may represent an extensional magmatic event associated with rifting which may have been the precursor of the much later Neotethys opening (Zhu et al., 2013).

In the Permian and Triassic many of the terranes on the northern Gondwanan margin left it, following the rifting and subsequent widening of the Neotethys Ocean. From the distribution of Permian trilobites, Lerosey-Aubril (2012) deduced that what Torsvik and Cocks (2009) classified as the Alborz and Lut terranes stayed together as a single biological (and thus probably geographical) unit to the north of the Neotethys after its opening.

The Qiangtang Terrane of Tibet can be divided into two separate northern (sometimes termed 'eastern') and southern (sometimes termed 'western') sectors, separated by the Longmu Co-Shuanghu Suture Zone, as reviewed by Pan et al. (2010) and Metcalfe (2013), and largely consist of several formerly discrete island arcs, each with complex histories. Granites were intruded between the Late Devonian (Famennian: 370 Ma) and the Early Carboniferous (Visean: 350 Ma) into the Qiangtang Terrane (Zhu et al., 2013). In the Lower Permian of southern Qiangtang, as in the Lhasa Terrane and Sibumasu to its south, marine diamictites of glacial origin were laid down. In contrast, in the northern part of the Qiangtang Terrane, glaciogenic rocks are absent and the shelly faunas and Cathaysian Flora also present there appear to indicate warmer environments.

6.3. Sibumasu

A long ribbon-shaped microcontinent, which today stretches from Burma and south-western China (Yunnan Province), through western Thailand, much of Malaysia, and southwards down to Sumatra, Indonesia, has been termed Sibumasu by many authors (e.g., Metcalfe, 2011). In our earlier papers (e.g. Cocks and Torsvik, 2002) we had considered Sibumasu as an independent identity in the Lower Palaeozoic, but we have since accepted that there is no good evidence that it left core Gondwana before the Permian opening of the Neotethys Ocean (Cocks and Torsvik, 2013). Metcalfe (e.g. 2011, 2013) has described the changing palaeogeography of the region. Cocks et al. (2005) reviewed the Early and Middle Palaeozoic faunas of Sibumasu, and concluded that they were essentially of tropical Gondwanan provincial affinities throughout that period. In particular, the Late Ordovician (Sandbian) trilobite fauna described by Fortey (1997) from southern Thailand (then within Sibumasu) is essentially identical, even at the specific level, to faunas of the same age in the famous Pagoda Limestone of South China, indicating that the two areas were at similar latitudes and that the combined Annamia-South China continent (see Section 7.1 below) could not have been far from the Sibumasu sector of Gondwana at that time (Cocks and Torsvik, 2013). The Sibumasu Microcontinent is much distorted, both by Early Mesozoic tectonism and also by the intrusion of very substantial Triassic granites into its central and southern sectors, and was probably both larger and of a different shape in the Palaeozoic than is shown on our maps (Figs. 10 to 18).

6.4. Australasian Arcs

The eastern Gondwanan margin has been and remains very active for much of the Phanerozoic. This is best seen in the eastern parts of Australia (eastern Queensland, New South Wales, Victoria and Tasmania), often termed the Tasman Orogenic Belt. That belt consists of a variety of island arcs which progressively accreted to the main North Australian Craton of western and central Australia at many different times in the Palaeozoic, as reviewed, for example, by Glen (2005) and Percival and Glen (2007). Glen identified several cycles of tectonic activity, the first the Neoproterozoic to earliest Ordovician Delamerian cycle, which started by initial rifting, followed by convergent margin tectonism and accretion of some island arcs in the Middle to Late Cambrian. The second, the Ordovician Benambran Cycle, included further new island arc formation and transform margin movement, ending with latest Ordovician-earliest Silurian terrane accretion to core Gondwana. The subsequent Middle Silurian to Middle Devonian Tabberabberan cycle included the development of a large back arc basin system, the intrusion of granite batholiths and the accretion to the superterrane of a previously independent Ordovician to Early Devonian island arc terrane in the Middle Devonian. The Middle Devonian to Carboniferous Kanimblan cycle began by rifting, followed by substantial terrestrial sedimentation inboard of a convergent margin, and which continued on into the Late Devonian to Triassic Hunter-Bowen series of events, which included the accretion of yet more island arcs.

Although New Zealand consists mostly of Mesozoic and later rocks, there are some tectonised areas there containing Palaeozoic strata, a few of which have yielded distorted fossils. Cooper (1989) described the Early Palaeozoic terranes there, the most important of which is the Takaka Terrane in South Island. All were formed within volcanic arc settings (Münker and Cooper, 1999). For example, there are sparse Cambrian trilobite and other faunas found in limestones fringing the volcanic islands; brachiopods of the widely-dispersed Late Ordovician *Hirnantia* Fauna (Cocks and Cooper, 2004), and Devonian brachiopods in the classic Reefton Complex (Boucot et al., 1969). However, since New Zealand is almost entirely made up of deep water volcanics and sediments deposited on oceanic crust well offshore from core Gondwana, it has been difficult to place those island arcs with any degree of confidence, since enormous amounts of strike-slip movements appear to have occurred in that area during and since the Palaeozoic, and thus they are shown only diagrammatically on our maps. It is uncertain whether or not New Zealand was a westward extension of the successive arcs which fringed eastern Australia.

6.5. Antarctic microcontinents and arcs

Off the main Antarctica craton there were several small terranes and microcontinents, notably the Antarctic Peninsula, Marie Byrd Land, Thurston Island and the Ellsworth-Whitmore Mountains, all of which were independent in the Palaeozoic and continuing the very extensive archipelago between Patagonia to their west and New Zealand to their east (Torsvik et al., 2008b). The Antarctic Peninsula is a Mesozoic to Cenozoic continental arc system which includes remnants of Ordovician turbidites and Silurian to Permian magmatism in the Eastern Domain, which appear to have been of oceanic origin (Millar et al., 2002), and thus it is not shown on our maps before the Permian. In contrast, two separate tectonic units are present in Marie Byrd Land, termed ‘provinces’ by Pankhurst et al. (1998), who summarized the geology. The Ross Province, near the Ross Sea, has metamorphosed turbidites over 5 km thick, the Swanson Formation, which is of uncertain but probably Late Cambrian to earliest Ordovician age (listed with a maximum age of 514 Ma by Leat et al., 2005), and which was intruded by the 380-370 Ma (Late Devonian) Ford granodiorite and a smaller Early Carboniferous granite at about 340 Ma. The Amundsen Province, near the Amundsen Sea, has no well-characterised Palaeozoic succession, but contains calc-alkali granitoids of Ordovician to Silurian (450 to 420 Ma) and Permian (276 Ma) ages. Thus Marie Byrd Land is shown mostly as deeper shelf on Fig. 11, the Early Ordovician (480 Ma), and later maps. Thurston Island was also an independent unit during the later Palaeozoic, with the oldest rocks there dated at about 300 Ma (Late Carboniferous to Early Permian) by Leat et al. (2005), although they also contain crustal elements dating to 348 Ma (Tournaisian), and thus it is shown in our Early Carboniferous (340 Ma) and later maps as a deeper-water extension of Marie Byrd Land, although there is no solid evidence that the two units were physically linked in the Late Palaeozoic.

The Trans-Antarctic Mountains and Ellsworth-Whitmore Mountains run right across today’s Antarctic continent and formed the margin of the eastern Antarctica sector of the Palaeozoic Gondwana Craton during most of the Palaeozoic. In northern Victoria Land, in a sector of the Ellsworth-Whitmore Mountains, Tessensohn and Henjes-Kunst (2005) described the three adjacent fault-bounded units within the Ross Orogen there. These are, firstly, the Wilson Terrane, which formed part of the Neoproterozoic crystalline basement near the Cambrian passive margin of Gondwana; and secondly, the Bowers Terrane, which was originally an offshore arc with Middle Cambrian (up to 500 Ma) volcanics overlain by the Middle to Late Cambrian Mariner Group of shallow-water marine rocks and the Latest Cambrian quartzites of the Leap Year Group, which are lithologically comparable to the Grès Armoricain of North Africa and southern Europe. The third unit in northern Victoria Land is the Robertson Bay Terrane, which consists of turbidites intruded by a Middle Cambrian (511 Ma) granite followed upwards by a warmer-water limestone of Early Ordovician (Tremadocian) age. That region also represents a typical picture of Lower Palaeozoic tectonic activity, which has made our maps very difficult to construct with much degree of realism. However, although the ages of their accretion to form parts of the Gondwana Craton are poorly constrained in detail, all must have been in place before the Late Devonian, since they are stitched to the craton by the Devonian-Carboniferous Admiralty Granites and the subaerial Gallipoli Volcanic Group, which straddle the terrane boundaries (Tessensohn and Henjes-Kunst, 2005).

6.6. South American microcontinents and arcs

The southern tip of South America today formed the Palaeozoic Patagonia Microcontinent, which is separated from the main South American Craton by a major active E-W strike slip fault. Patagonia probably merged with the rest of South America at some time in the Permian (Pankhurst et al., 2006; Ramos, 2008). However, it has a Neoproterozoic core which was affected by the latest Precambrian-early Cambrian Brasiliano orogeny (Tankard et al., 1995), and so it cannot have been too far away from the core Gondwana Craton then.

The whole Proto-Andean south-western coast of today’s continent from Patagonia (the southern areas of Argentina and Chile), through western Argentina and adjacent parts of Chile and extending northwards to Bolivia and southern Peru, consist of the remains of microcontinents (such as the substantial Arequipa-Antofallo Block in the northern sector) and island arcs, which accreted to core Gondwana at various different times from the Late Neoproterozoic to the early Silurian. They are shown in Rapalini (2005). Important terranes include the Famatina Arc and the Chilenia Terrane. The Famatina Arc (with which we have grouped the adjacent East Puna unit of some authors) progressively accreted to the Pampean Complex to its east during latest Neoproterozoic to Early Ordovician times, accompanied by voluminous calc-alkaline volcanism, ending with 484 to 463 Ma (Tremadocian to Darriwilian) granites (Dahlquist et al., 2013). As reviewed by Miller and Sölner (2005), because of the inherited components within the Famatina metasediments and granitoids, it seems more probable that there was autochthonous arc-continent convergence between Famatina and core Gondwana, rather than believing that Famatina had earlier been an exotic terrane. The sediments within Famatina are well dated through their Early Ordovician (Tremadocian to Darriwilian) faunas reviewed by Astini (2003). The collision between Famatina and the main craton was accompanied by a succession of Middle to Late Ordovician granitoids near St Luis, Argentina, which date from about 470 to 450 Ma (Dapingian to Katian), although some post-collisional granitoid intrusion continued on in that area to Devonian times (379-369 Ma: Famennian), including the huge Achala batholith (Quenardelle and Ramos, 1999). The Chilenia Terrane today lies on the Pacific Ocean side of the Arequipa-

Antofallo Craton in northern and central Chile and also the Famatina and Precordillera terranes in Argentina, but, although it is somewhat sporadically exposed, includes some Late Ordovician ophiolites and MORB basalts. The terrane must obviously have docked onto the Gondwana Craton at some time after the others, but the bulk of the tectonism was in the Devonian, including the start of the development of a large accretionary prism along its western margin (Álvarez et al., 2011).

There is an intriguing exception to the other terranes in South America in the relatively small Precordillera Terrane (sometimes termed the Cuyania Terrane) in the northwest of Argentina, whose Cambrian and Earliest Ordovician faunas of trilobites, brachiopods and other benthic forms are clearly of warmer-water North American (Laurentian) equatorial affinity and probable origin (Astini et al., 1995; Benedetto et al., 1999). A minority of authors (e.g. Finney et al., 2003) have explained that faunal distribution as due to extraordinary ocean current patterns which affected that terrane, which they regarded as having been a peri-Gondwanan terrane from the Neoproterozoic onwards throughout the Palaeozoic. However, we follow the majority of authors in agreeing that it is most likely that the Precordillera Terrane drifted across the ocean between Gondwana and Laurentia during the middle part of the Lower Palaeozoic, although the tectonic mechanisms for that are not yet resolved. The benthic faunas, particular the trilobites and brachiopods, have the highest proportion of endemic taxa (those not found in either Laurentia or Gondwana) in the Middle Ordovician (Darriwilian to Sandbian), indicating that the Precordillera was most probably the furthest distance away from both superterranes at that time. The terrane accreted to the Argentine sector of Gondwana before the end of the Devonian, as evidenced from zircon provenance in units of subsequent ages within the Precordillera (Abre et al., 2013). However, it had clearly arrived in higher latitudes near the Gondwana margin before the end of the Silurian, since it was host then to the very distinctive Late Silurian Malvinokaffric *Clarkeia* brachiopod Fauna. That fauna was restricted to higher-latitudes and presumably cooler-water seas and is only found at many sites in South America and western Africa (Cocks, 1972). The same areas, which later included the Falkland Islands, subsequently formed the colder-water Malvinokaffric Realm, which continued on at least until the Emsian (Boucot et al., 1969) in the same high latitudes (Fig. 13).

6.7. Central American terranes

As reviewed by Cocks and Torsvik (2011), it is very difficult to identify the true identitities and reconstruct the positions of the individual elements within that substantial area with confidence during the Palaeozoic. That is chiefly because there has been so much tectonic activity over the past 300 My (activity which was at its height when Gondwana and Laurussia were uniting in the Carboniferous to form Pangea), as well as the masking of the Palaeozoic terranes by the subsequent deposition of many Mesozoic and later rocks in Central America. However, there are various inliers within the general cover of Cretaceous and later rocks which apparently represent Palaeozoic terranes, although analysis of how many and which were united in the Palaeozoic has varied in different papers. Keppie in various reviews (e.g. 2004; Keppie et al., 2008) has concluded that all those terranes originally formed parts of peri-Gondwana, apart from the Caborca and Chihuahua terranes in north-western Mexico, whose stratigraphies were summarized by Sánchez-Zavala et al. (1999), and which formed part of peri-Laurentia. The Sierra Madre, Cortez, Mixteca, Oaxaquia, Yucatan, Chortez, and Taraumara terranes have all been identified as peri-Gondwanan units in the region, but whether or not some or which ones were united into a ‘Middle American Continent’ during the Palaeozoic is not well constrained. Keppie et al. (2010) reported that the basement of the Oaxaquia Terrane is of Proterozoic age (1.3 to 0.9 Ga) and may have originally extended along the Gondwana border as far as Florida (the Suwanee Terrane), although, unlike Florida, they suggested that the Oaxaquia Terrane may have left Gondwana with the initial rifting of the Rheic Ocean, in the same extensional event as Avalonia, at about Cambrian-Ordovician boundary time. Nance et al. (2009) and Dickinson and Lawton (2001) also described the tectonic evolution of the various Mexican terranes. However, the overall Palaeozoic scenario and the true palinspastically realistic distributions of facies in those times, are not yet well resolved. In this paper, we have generally followed the reconstructions presented in Cocks and Torsvik (2011), debatable though they are; however, most of the terranes are rather small on the large scale of our maps. The terrane shapes and margins which we show are particularly unrealistic, due to the subsequent tectonic upheavals in that region.

6.8. North American terranes and Avalonia

There are several terranes today within North America which once formed parts of Gondwana in the Palaeozoic. From south to north, the chief units are Florida, the Carolinia, Ganderia and Meguma terranes, and today’s western portion of the more substantial microcontinent of Avalonia. Although there are no Palaeozoic rocks exposed at the surface in

Florida, they are known in boreholes, some of which contain Ordovician trilobites, such as the *Plaesiocomia* recorded by Whittington (1953), which is of undoubted Gondwanan affinity. The Carolinia Terrane was described by Ingle et al. (2003), who concluded that the patterns within its contained zircons indicated a Gondwanan origin near the Amazonia Craton, although the fossils found there are largely graptolites of no particular provincial significance. The definition and Palaeozoic placements of the Ganderia Terrane have varied between different authors; for example, van Staal et al. (2012) placed that elongate ribbon-shaped area to the west of Avalonia in their Cambrian and Ordovician reconstructions, but on the Laurentian margin of Avalonia in the Permian after Pangean assembly. However, Florida did not leave the Gondwanan margin until the Mesozoic opening of the Atlantic Ocean (Torsvik et al., 2009a).

There are further suspect terrane areas, such as the Late Ordovician island arcs of probable peri-Gondwanan origin in Alabama described by Tull et al. (e.g., 2007), which now consist of metamorphic rocks which were thrust on to the Laurentian margin during the Alleghanian Orogeny in the Late Palaeozoic. There is also the Smith-River Allochthon which straddles the Virginia-North Carolina boundary and which may also be of Gondwanan origin, based on U-Pb monzonite and staurolite ages from the rocks there which are apparently incompatible with a Laurentian origin, despite Smith-River being surrounded by undoubted Laurentian strata (Hibberd et al., 2005).

The old microcontinent of Avalonia, today lies on both sides of the Atlantic Ocean, stretching from New York State through the Maritime Provinces and Newfoundland in Canada, south-eastern Ireland, England and Wales to Belgium and beyond (Cocks and Fortey, 2009). Avalonia was an integral part of Gondwana until about Cambrian-Ordovician boundary time, when substantial rifting started and a widening Rheic Ocean opened between it and Gondwana. Both prior to that separation and also during the Early Ordovician, the benthic faunas of all these terranes in that peri-Gondwanan region, chiefly trilobites and brachiopods, formed part of the higher-latitude, lower-diversity Mediterranean faunal Province, as reviewed by Fortey and Cocks (2003). That province contrasts in both diversity and generic diversity with the Ordovican equatorial faunas of Laurentia (Cocks and Fortey, 1982). However, due to the relatively fast movement of Avalonia across the Rheic Ocean, by the end of the Ordovician its contained benthic faunas had more in common with Baltica and Laurentia than with Gondwana.

7. Continents outside Phanerozoic Gondwana

7.1. North China, South China, Annamia and Tarim

There is no firm evidence that any of these four substantial continents formed integral parts of Gondwana during the Palaeozoic, even though they are depicted as such in Lower Palaeozoic reconstructions by some authors, for example Metcalfe (2013) and Usuki et al. (2013). However, the zircons in all of them show complex variation which appears to indicate that they were probably derived from a much larger continental landmass than any of the four possess today, of which Gondwana is the obvious candidate. To prevent the supposition of more than the minimal numbers of subduction zones and spreading centres, we have suggested that South China and Annamia (Indochina) were adjacent sectors of the same continent during the Lower Palaeozoic until they separated during the Devonian rifting which heralded the start of the Palaeotethys Ocean (Cocks and Torsvik, 2013). We also think that, prior to the Late Cambrian, the combined Annamia-South China continent lay in temperate southern palaeolatitudes off the north-western Indian sector of Gondwana, as suggested by Torsvik et al. (2009b), particularly because of the distributions of Middle and Late Cambrian trilobites. The continent subsequently moved northward along the superterrane by substantial strike-slip faulting until, by the Silurian the combined continent was at equatorial latitudes off northern Australia. However, McKenzie et al. (2011) postulated that, because of the patterns of zircon distribution, South China was physically attached to the north-western Indian sector of Gondwana in the Cambrian and North China to the north-eastern Indian sector, although they did not suggest a placing for Annamia even though it also has comparably complex zircons in its Precambrian craton. Nevertheless, despite some faunal provincial similarities, particularly the Middle and Late Cambrian trilobites listed by McKenzie et al. (2011), the somewhat limited palaeomagnetic data and the associated APW paths from North China and South China published by Cocks and Torsvik (2013), both indicate that the two continents were connected neither to each other nor with the bulk of core Gondwana during the Palaeozoic. However, questions on their Palaeozoic origins and situations remain open, as does their original Proterozoic position near or attached to one of the cratons which later became Gondwana and the timing of their separations from those cratons.

In addition, Tarim was a substantial palaeocontinent, largely today in western China, whose geology is summarised, for example, in the book edited by Zhou and Dean (1996) and its tectonic framework and evolution was described by Zhang et al. (2013). It too has a complex pattern of Precambrian zircons, and it appears to have been originally part of one of the Gondwana cratons, but probably left it in the Neoproterozoic. However, there is no useful palaeomagnetic data from Tarim until the Middle Devonian and later, and it seems unlikely from its contained Early Palaeozoic benthic faunas to have been within core Gondwana then. Thus Tarim is not considered further in this paper, apart from appearing on some of our maps as peripheral to the superterrane. The geology and palaeogeography of the western parts of the Altaids, between Tarim, Baltica, and Siberia has been discussed by many authors, for example Xiao et al. (2010), but, although some of the many terranes and microcontinents within the Altaids have Precambrian cores with multiple zircons (which suggest origins from Gondwanan component cratons), it does not seem likely that any of them formed part of Gondwana during the Phanerozoic.

7.2. Baltica and Laurentia

Both these substantial continents were separate from Gondwana during the whole of the Palaeozoic prior to the assembly of Pangea in the Carboniferous; however, both form important sectors within our reconstructions at various times. In particular, Baltica appears to have been very close to the northwestern Africa sector of the Gondwanan margin during Cambrian times (Fig. 5). As reviewed by Cocks and Torsvik (2005; 2011), they were independent continents until their combination in the Silurian Caledonide Orogeny, just prior to which, at about Ordovician-Silurian boundary time at 443 Ma, Baltica had merged with the microcontinent of Avalonia, which had itself left Gondwana at the start of the Ordovician.

8. History of the Gondwana Superterrane

We present now a narrative whose chief purpose is to illuminate key features of the new palaeogeographical reconstructions drawn at selected intervals from 550 to 200 Ma. As noted above, Gondwana was an independent superterrane from the Late Neoproterozoic at about 550 Ma to the Carboniferous at about 320 Ma, but we also describe the subsequent history of the very substantial Gondwanan sector of the Pangea supercontinent until the end of the Palaeozoic, and end by briefly reviewing the area until after Pangea’s progressive breakup in Mesozoic times. It must be acknowledged that the palaeomagnetic data from the Early Carboniferous (350 and 340 Ma) are poor (Fig. 2), which makes our maps more subjective in that critical period for the final formation of Pangea. There is also poor palaeomagnetic coverage from Mid-Silurian to Early Devonian times.

We have used a very great number of papers for the various sedimentary, faunal, igneous, and other geological data to produce our maps (Figures 10 to 19); however, only a proportion is explicitly acknowledged here, but many more are cited in our earlier papers (Torsvik and Cocks, 2009; 2011). Unlike those previous papers, because Gondwana is so large, we have not been able to show volcanoes and igneous intrusions on our maps, and thus the Palaeozoic volcanic island arcs are only shown diagrammatically. The continental shelves are divided between 'shallow' and 'deeper' chiefly so that the areas of continental craton which were flooded can be clearly distinguished from the deeper shelves off the margins of the continents.

The reconstructions in Figures 10 to 19 are centred around a fixed Africa in Mollweide projections. The South Pole and lines of latitude (grid) at the appropriate reconstruction times were subsequently draped onto the reconstructions. This method has the advantage of keeping core Gondwana in the same place on the maps, enabling visualization of the rifting and collisions along its margins. The latitude grid is calculated from a palaeomagnetic model which constrains configurations of continents relative to the spin axis (Fig. 4b), which should always be used in classical palaeogeographic and palaeoclimate reconstructions. Plate reconstructions corrected for TPW (Fig. 4) reflect plate motions relative to the Earth's mantle and are useful for exploring links between surface volcanism (e.g., LIPs and kimberlites) and the LLSVP margins near the core-mantle boundary. Our reconstructions are absolute in the sense that both latitude and longitude is determined (Torsvik et al., 2013a), and, in order to relate deep mantle processes to surface processes in a palaeomagnetic reference frame, we have also rotated the plume generation zones (PGZs) to account for TPW (stippled red lines in Figs. 11-22). In this way, one can see how well the surface distribution of LIPs and kimberlites relate to the deep mantle in the Torsvik et al. (2013a) model. Net TPW angles (around a pole located at 11°E at the equator) were as high as 62^{o} during the Palaeozoic, and palaeomagnetic and TPW-corrected (Fig. 4) reconstructions therefore differ radically in the Early Palaeozoic. For example, Southern Norway (part of Baltica) plots at intermediate to high southerly latitudes in a palaeomagnetic frame, but corrected for TPW, southern Norway would plot on the Equator.

8.1. Precambrian unification of the superterrane

The Archean and earlier Proterozoic histories of the various cratons which make up the vast region of Gondwana are outside the main scope of this review, but most geologists now accept that at about a billion years ago there was an earlier supercontinent termed Rodinia, which subsequently broke up from about 800 Ma onwards (Torsvik, 2003; Li et al., 2008). The individual identities and margins of the many and various continental blocks which include cratons older than 1 Ga (Fig. 4), and which were probably formerly parts of Rodinia and later made up Gondwana, are variably constrained, as are their positions relative to each other during the Precambrian. The unification through the subsequent subduction in the now-vanished oceans which must have separated the many sectors which make up Gondwana probably took place over a considerable period. However, the superterrane appears to have only finally been unified very close to the end of the Latest Precambrian in the Pan-African Orogeny, which was largely contemporaneous with the Brasiliano and Pampean orogenies in South America, the Cadomian Orogeny in southern Europe and North Africa, and the Kuungan Orogeny between India and East Antarctica (Fig. 4).

Meert and Liebermann (2008) presented a 565 Ma reconstruction in which the individual sectors of Gondwana were still not united, although the Iapetus Ocean between Laurentia and the Amazonia and Rio Plata parts of Gondwana was already quite wide. However, by 550 Ma, most of Gondwana had assembled, as suggested by Meert and Van der Voo (1997). For example, even though the majority of post-collisional granitoids within the north-eastern Brazilian sector of the Amazonia Craton were chiefly intruded in two major phases, the first Late Neoproterozoic at about 580 Ma and the second Early to Middle Cambrian at about 530 Ma, nevertheless granitoid intrusion extended as late as Middle Ordovician times at 460 Ma there (Castro et al., 2012). There were comparable Lower Palaeozoic granitoids and other plutonic intrusions near many other individual margins of the various cratons which had united to form the Gondwana superterrane.

8.2. Cambrian

The Cambrian lasted from 542 to 490 Ma, and we present a new global map for the Early Cambrian at 540 Ma (Fig. 4), and the first of our maps showing facies in the Gondwanan region at 510 Ma, the late Middle Cambrian (Fig. 10). Meert and Liebermann (2003) also published a map for the Lower Cambrian at 530 Ma.

8.2.1. Tectonics and igneous activity

The various Pan-African and coeval orogenies, which all began in the Late Neoproterozoic, were still continuing to unite Gondwana in many sectors during at least the earlier part of the Cambrian and they did not finish at the same time. Rowell et al. (2001), from isotopic and stratigraphic evidence, were able to assess that the various phases of deformation in the Transantarctic Mountains lasted from the latest Neoproterozoic up to the late Middle Cambrian.

In the South American sector, even though there was no major continent offshore to the west of Gondwana, there was a considerable amount of Cambrian tectonic activity, with an active subduction zone to the southwest of the continent near which various island arcs originated which eventually merged into terrane blocks such as Chilenia. The Punoviscana Ocean closed in the Early Cambrian, thus causing the substantial and elongate Arequipa-Antofalla Block to its west to unite with the main Gondwanan Craton (Escayola et al., 2011). Just to the south of that, the previously independent Pampean Terrane also accreted to the craton at about the same time, approximately 530 Ma, presumably because of the activity of the same subduction zone, and that accretion was followed by the intrusion of substantial highly peraluminous granites at about 520 Ma, all termed the Pampean Orogeny (Rapela et al., 1998; Sims et al., 1998). However, that subduction zone off the South American margin was apparently subsequently quiescent until the start of the Famatinian Orogeny at 495 Ma in the latest Cambrian Furongian Stage. Aceñolaza et al. (2002) showed the distribution of volcanoes along the entire western margin of South America in latest Cambrian and early Ordovician times. In similar latest Cambrian to earliest Ordovician times there was rifting in today’s north-western margin of Gondwana, where some of the Mexican terranes left the core craton area (Keppie et al., 2012).

After the Cadomian Orogeny in the northwest, the northern Gondwanan margin seems to have been passive and tectonically quiescent, apart from a Middle Cambrian to Early Ordovician (530 to 490 Ma) event in the Himalayan area, and Tibetan Plateau (Zhu et al., 2013). The event was termed the Bimphedian Orogeny by Cawood et al. (2007), who considered it as representing an Andean-type orogenic event with island arc andesitic and basaltic magmatism which may have been related to the final assembly of Gondwana. McQuarrie et al. (2013) interpreted those Late Cambrian to Early Ordovician events in the Himalaya as a switch from an open-ocean passive margin to an active margin in the region, and also concluded that there was a deep basin between an offshore volcanic island arc and the craton. However, further eastwards, rocks in the northern parts of the extensive Sibumasu and northern Australian sectors of the Gondwana Craton appear to represent a passive margin.

In contrast, the eastern Gondwanan margin was much more active throughout the Cambrian, and remained so for nearly the entire Palaeozoic. This is best seen in eastern

Australia, where, for example, Glen (2005) has reviewed what is generally termed the Tasmanides, which consists of a successive series of mostly originally oceanic island arcs being progressively accreted to the stable margin of western Australia. During the Cambrian that tectonic activity is best seen in the Delamerian Orogeny of western Tasmania, New South Wales, Victoria, and South Australia, where orogeny had started during the Neoproterozoic, and where it continued on into the earliest Ordovician (Glen, 2005). In Dronning Maud Land, Antarctica, Jacobs et al. (2003) documented the part of the Pan-African Orogeny termed the Ross Orogeny which represents the union of southern Africa and Antarctica. That orogeny had two major phases, an initial event starting before 560 Ma (their date for the earliest syntectonic leucogranite) and continuing on until just into earliest Cambrian time; and a second event, which started at about 530 Ma and continued until near the end of the Cambrian at about 490 Ma. A significant late Middle Cambrian (510 Ma) event was the massive basalt outpourings of the Kalkarindji Large Igneous Province (LIP), formerly known as the Antrim Plateau Basalts, over a large area of north-western Australia (Glass and Phillips, 2006). Kimberlites were intruded in South Africa from 510 to 500 Ma and in South China at around 510 Ma (Torsvik et al. 2013a). The kimberlites and the Kalkarindji LIP were all sourced from the plume generation zones (PGZs) associated with the African LLSVP (red stippled line in Fig. 10).

8.2.2. Facies and faunas

The contributions in the books edited by Holland (e.g. 1985) give detailed overviews of many of the Palaeozoic rocks in much of Gondwana. Álvaro et al. (2003) analysed the distributions of trilobites along the western Gondwanan margin at successive times in the Cambrian and presented maps. Brock et al. (2000), although chiefly characterising the Australasian faunas, also reviewed the provinciality of various key fossil groups, thus describing Gondwana’s place within a global framework. For example, benthic polymerid trilobites have been allocated between three realms over many years, termed the Redlichiid, Olenellid and Bigotinid realms, and all of the lower-latitude parts of Gondwana were within the Redlichiid Realm in the Cambrian, and the bigotinids in the higher latitudes, whilst the Olenellid Realm was centred on Laurentia, which was also tropical. The lower-latitude Australian Redlichiid Realm trilobites are notably diverse, with varied faunas, many described by Shergold (e.g., 1991), between the various shallow-marine basins there throughout the Cambrian. However, Brock et al. (2000) also pointed out that the archaeocyathids were broadly comparable between Australasia and Laurentia, as were the brachiopods; although, since the latter were mostly inarticulated, it has long been known that their larval stages lived longer than the articulated brachiopods which became more dominant from the Ordovician onwards (Cocks, 2011), and thus the Cambrian brachiopods were less likely to demonstrate provincial differentiation when compared with the trilobites. Streng et al. (2011) described inarticulated brachiopods of latest Cambrian and earliest Ordovician ages from the Oaxaquia Microcontinent of Mexico, and concluded that, although the brachiopods and their associated trilobites showed largely Gondwanan (and no Laurentian) affinities, there appear to be enough endemic taxa present there to suggest that there was some insularity between that microcontinent and the main Gondwanan Craton.

8.3. Ordovician

This system is now dated from 490 to 443 Ma, and we present two new reconstructions for the Gondwanan region, in the Early Ordovician at 480 Ma at about Tremadocian-Floian boundary time (Fig. 11), and in the Latest Ordovician at 445 Ma, the latter so that we can show the southern hemisphere during the brief Hirnantian glacial interval (Fig. 12).

8.3.1. *Tectonics and igneous activity*

A notable event at about Cambrian-Ordovician boundary time at 490 Ma was the rifting and subsequent origin and progressive widening of the Rheic Ocean which caused the relatively small but elongate continent of Avalonia, which had probably been situated offshore from Amazonia, Florida and NW Africa, to leave Gondwana (Cocks and Fortey, 2009). Further eastwards and slightly later, at about 478 Ma, a chain of tonalites and granodiorites was intruded within the Central Iberian Zone of Spain (Rubio-Ordóñez et al., 2012), indicating that all of that north-western margin was active in those times. Near the end of the Ordovician, at about 446 Ma, that activity extended as far east as Turkey, where metagranites are known from the Tavşanh Zone, just north of the Taurides (Özbey et al., 2013). On the opposite Gondwanan margin, in Australia, a string of peri-Gondwanan island arcs developed. However, between those two active areas the northern Gondwanan margin was largely passive and remained so until the Trias (Torsvik and Cocks, 2009), apart from the final phase of the Bhimphelian Orogeny in the Himalayas described by Cawood et al. (2007) and McQuarrie et al. (2013), which had peaked before the end of the Cambrian at about 490

Ma, but rumbled on into the Ordovician in the form of a granite emplaced as late as the Dapingian (470 Ma).

In South America, Bahlburg et al. (2011) have documented the south-western coastal area through the analysis of zircons. They identified an elongate basin along the Ordovician east coast where today is the transition zone between what they term the Sierra Subandinas on the site of the modern Andes. That basin was floored by continental crust and extended westwards to the Arequipa Massif, which had accreted to Gondwana in the Late Neoproterozoic to the Early Cambrian. There was also substantial plutonism, ranging from ultramafic intrusive rocks to calc-alkaline granitoids, as well as much associated metamorphism in the adjacent Pampean mobile belt which lasted from the Early Tremadocian at about 490 Ma up to the Late Ordovician at about 450 Ma, all termed the Famatinian Orogeny (Rapela et al., 1998; Sims et al., 1998; Dahlquist et al., 2013), although orogeny had started in that general area at about 495 Ma, just before the end of the Cambrian. Chernicoff et al. (2009) further analysed the metagabbros in the southern Pampean area, which they date from 474 to 452 Ma, and whose chemical signatures indicate that they were enriched MORB intrusions with a back-arc signature. Rapela et al. (1998) also recorded that, at the same time, in the adjacent Famatinian area, there were Early Ordovician gabbros and calc-alkaline volcanics, accompanied by extensive volcaniclastic turbidites from the Dapingian (Late Arenig) to the Sandbian (Early Caradoc). Inboard from them, extensive Famatinian granites were intruded in the proto-Andean area from 486 to 468 Ma (Tremadocian to Dapingian) times (Hervé et al., 2013).

In the central America region, Keppie et al. (2012) dated meta-granitoids in the Acatlán Complex of southern Mexico, part of the Oaxaquian Microcontinent (which include inherited zircons from the underlying Proterozoic basement) as about 452 Ma (Katian) age. There are also earliest Silurian (442 Ma) dykes intruding low-grade metamorphic rocks in the same region; all of which are interpreted as the final episode of a prolonged 480 to 440 Ma event associated with the rifting away of the Rheic Ocean from the Gondwana Craton there.

Gondwana’s eastern margin remained active throughout the Ordovician, where the Benambran Orogeny within the Lachlan Fold Belt of eastern Australia represented the further accretion of originally oceanic island arcs to the Gondwana Craton (Glen, 2005). For example, the Early Ordovician to earliest Silurian Macquarie Arc of New South Wales accreted to the craton in four phases during that period. The first phase, during the Tremadocian to Floian, consisted of emergent volcanic islands in the ocean which were fringed by shallow-water tropical carbonates. This was followed by a 9 Myr hiatus until the Darriwilian, when more volcanism occurred, much of it submarine, but some locally emergent, also with fringing carbonates. The third phase consisted largely of intrusives associated with regional uplift and a widespread carbonate platform, and the final phase, of Katian to Early Llandovery age, included the extrusion of lavas and the intrusion of porphyries with evolved shoshonite geochemistry (Percival and Glen, 2007). No Ordovician or Silurian kimberlites or LIPs are known within Gondwana, probably because most of the superterrane was located between the two LLSVPs (see Fig. 12).

8.3.2. *Facies and faunas*

There are many good faunal and palaeomagnetic data to help position Gondwana and its surrounding areas in the Ordovician. Because it stretched from the South Pole to well north of the Equator, there was plenty of space in which to develop temperature gradients in the seas bordering the superterrane, and thus the higher latitudes hosted the *Neseuretus* trilobite Fauna in the Early Ordovician (Cocks and Fortey, 1982) as well as the Mediterranean brachiopod fauna during most of the Ordovician, as reviewed by Havlíček et al. (1994). In contrast, the lower-latitude tropical benthic faunas were entirely different, and naturally much more diverse. However, there were clines between the two extremes. For example, the large and unmistakable Early Ordovician pentameride brachiopod *Yangzteella* was originally thought to be endemic to lower-latitude South China, but was subsequently found in the temperate-latitude Taurus Terrane of Turkey (Cocks and Fortey, 1988), and is now known from various medium to low latitudes in Gondwana and peri-Gondwana, but not from the higher-latitude regions, as reviewed by Cocks and Torsvik (2013). In the Himalayan sector, in for example Spiti, there were diverse shallow-marine faunas with many endemic genera and species, such as the Darriwilian brachiopods originally described by Salter and Blanford (1865), now preserved within the remnants of arcs which were separated by a deep basin from the main craton in the Ordovician (Zhu et al., 2013)

Land in the eastern Australian continental sector of Gondwana was separated from the main Gondwanan land area by the Larapintine Sea, a shallow-water and entirely intracratonic sea which stretched across Australia from north to south, and whose marine sediments are preserved in the Amadeus and Georgina basins of central Australia today. In the Later Ordovician, that sea was more intermittent, and extensive evaporites were deposited in the remnants of those basins. The Ordovician palaeogeography of the area, which was host to a great faunal diversity of many marine animal groups, was reviewed by Webby et al. (2000). Off eastern Australia, the island arcs were hosts to a variety of benthic faunas, such as the brachiopods monographed by Percival (1991), many of which are endemic and which reflect their tropical location.

The contrast between the warmer-water and cooler-water faunas is most dramatically seen in the Early Ordovician brachiopods from the now adjacent Precordillera and Famatina terranes of Argentina analysed by Benedetto (1998), the former being much more diverse (and similar to the tropical Laurentia), and the latter with many fewer species, reflecting their higher palaeolatitude. The decreasing percentages of Laurentian brachiopod genera in the Precordillera Terrane during the Ordovician (from 52% in the Floian, down to 32% in the Darriwilian, and their virtual absence by the Katian) is eloquent testimony of the relatively speedy movement of that terrane from peri-Laurentian to peri-Gondwanan between 475 and 450 Ma; although with the caveat that the detailed distribution of unknown oceanic currents and their included temperatures may also have played a role in those faunal changes, as well as the increase in the palaeolatitude.

Eustatic sea level rose and fell during the Ordovician, as well demonstrated in the flooding surfaces of various ages seen in the subsurface rocks of the entire Ordovician in Oman and the United Arab Emirates (Rickards et al., 2010), both of which were within the passive margins of the Arabian sector of the Gondwanan Craton and therefore little prone to tectonic upheaval in those times. In South America, Rubenstein et al. (2011) documented the Middle Ordovician (Dapingian to Darriwilian) sediments in the Sierras Subandinas of north-western Argentina, which represent the outermost exposures of the Central Andean Basin, and which are alternations of shallow-marine deltaic systems and estuarine environments, the latter of which have yielded spore-like fossils of probable non-marine origin.

The Late Ordovician South Pole lay under northwest Africa, and thus the surrounding areas were covered by a substantial icecap during the Latest Ordovician (Hirnantian) glaciation. The glacial and peri-glacial deposits were extensive, as depicted by Beuf et al. (1971), Ghienne et al. (2007), Torsvik and Cocks (2011, fig. 7), and Fig. 12 here. However, that Hirnantian glacial episode was relatively short, probably less than a million years (Villas et al., 2006), but it caused oxygenation within deeper levels in the oceans than before or after the cooling. That additional oxygenation enabled the extension of the colonisation of the *Hirnantia* brachiopod Fauna into the deeper parts of the continental shelves. That fauna extended far beyond the boundaries of Gondwana (Rong and Harper, 1988; Rong et al., 2002), and we show its distribution on Fig. 12. It is interesting to note that the *Hirnantia* Fauna stretched from high to low latitudes, and it might therefore be more correct not to interpret that fauna as 'cooler-water' as many authors (including ourselves) have done, but one whose generally lower diversity reflects the limited proportion of brachiopod taxa which were able to react quickly to the changing environments. Although there were substantial and well-documented faunal extinctions during and after the Hirnantian glaciation at the Ordovician-Silurian boundary, there were also an important number of benthic families and higher taxa, the so-called 'Lazarus taxa', which, although unknown from Hirnantian and Early Silurian rocks (as reported for the brachiopods by Cocks and Rong, 2008), are known from both older and younger rocks and thus clearly survived that extinction in as yet undiscovered refugia.

8.4. Silurian

The Silurian is a much shorter period than both the preceding Ordovician and the subsequent Devonian systems, lasting only from 443 to 418 Ma, and thus no specific map for that period is included here, although the earlier palaeogeography of the period was essentially the same as that shown on the latest Ordovician map at 445 Ma (Fig. 12).

8.4.1. Tectonics and igneous activity

Away from Gondwana, on the opposite side of the Rheic Ocean, there was the Caledonide Orogeny between Laurentia and Avalonia-Baltica which formed the other contemporary superterrane of Laurussia from the mid-Silurian to their combination in the Carboniferous. In addition, it seems likely that incipient rifting took place on the North African sector of the Gondwana margin before the end of the Silurian in advance of the subsequent opening of the Palaeotethys Ocean, but to what extent that activity might have been linked to the Caledonide Orogeny can only be speculative, since the Rheic Ocean between the two areas by then had become several thousand kilometres wide. The tectonic activity and propagation of new terranes in an island arc setting offshore of south-western South America, which had commenced in the Cambrian, continued throughout the Silurian.

As in the Ordovician, today's northern margin of Gondwana eastwards from Turkey was quiescent as far as northern Australia. However, Gondwana's eastern margin continued to be very active, with the Macquarie Arc of New South Wales and neighbouring parts of Australia, which was originally of oceanic origin and Early Ordovician to Llandovery in age, being accreted to the main Gondwanan Craton during the later Silurian (Glen, 2005). To what extent that active subduction zone extended southwestwards along the Antarctic and South African margins of the craton is uncertain: only oceanic rocks are known from Antarctica as Ordovician and Silurian fragments in the Antarctic Peninsula (Millar et al., 2002).

8.4.2. Facies and faunas

The Earth only warmed up slowly after the end-Ordovician glaciation, and glaciogenic rocks continued to be deposited in South America until well into Silurian times (Grahn and Caputo, 1992). When the icecap retreated in North Africa and Arabia, the transgressive sea incorporated many previously glaciogenic sediments and was poorly oxygenated, and that resulted in the extensive deposition of Early Silurian (Llandovery) ‘hot’ black shales there, which together form the world’s largest area of hydrocarbon source rocks. The post-glacial slow warming was reflected in the global distributions and gradually expanding diversity of Llandovery brachiopods, as reviewed by Cocks and Rong (2008). However, in contrast to most of the preceding Ordovician; since the major continental blocks were apparently close enough to each other to enable invertebrate larvae to cross the intervening oceans more easily, the benthic faunas were far more cosmopolitan in the Silurian than they had been earlier. The exceptions to that are the less diverse faunas which occupied the higher palaeolatitudes, such as the *Clarkeia* brachiopod fauna, which is known only from South America and the then adjoining parts of Africa within Gondwana (Cocks, 1972). Those faunas were the precursors of the Malvinokaffric Province which was even more distinctive in subsequent Devonian times. It is notable that the Late Silurian *Clarkeia* Fauna is found in the Precordillera Terrane of South America, indicating that that terrane had neared the end of its journey from peri-Laurentia to higher latitudes by then. However, although Rapela et al. (1998) considered that the Precordillera had obliquely docked with the Gondwana Craton at about the end of Silurian time, it seems more likely that that accretion occurred in the Devonian. The only other Silurian brachiopods which formed a distinctive province separate from the ‘cosmopolitan’ faunas of the rest of the world, lived in Siberia, which was then inverted and well away from Gondwana, and where the *Tuvaella* Fauna reflected the provincial isolation (Cocks and Torvik, 2007).

8.5. Devonian

This system is now dated from 418 to 359 Ma, and we present two new reconstructions for the Gondwanan region, in the Early Devonian at 400 Ma at Emsian time (Fig. 13), and in the Late Devonian (Famennian) at 370 Ma (Fig. 14).

8.5.1. Tectonics and igneous activity

The Early Devonian saw the opening of the Palaeotethys Ocean between Gondwana and the various terranes which now make up southern Europe (Torsvik and Cocks, 2011). However, it is uncertain whether or not that is the same rifting event which also caused oceanic opening much further away, in which both the combined Annamia-South China continent moved away from the margin of Gondwana and Annamia and South China separated from each other (Cocks and Torsvik, 2013), is open to question. Thus whether or not or not the seas in that south-eastern Asia area should properly be termed the Palaeotethys Ocean is also doubtful.

In south-western South America the Achalian Orogeny was essentially the prolonged collision between the Chilenia Terrane and the Precordillera Terrane, with much thrusting and sinistral strike-slip movements in the Sierras Pampeanas of Argentina (Sims et al., 1998), together with the intrusion of plutons from 403 to 382 Ma (Emsian to Frasnian) (Dahlquist et al., 2013). The tectonic activity and propagation of new terranes in an island arc setting offshore of south-western South America, which had commenced in the Cambrian, ceased in the Early Middle Devonian. For example, in central Chile, at around 39°S, there was an active margin until the Late Devonian (about 385 ma), but that margin was subsequently passive, although with much strike-slip faulting, until about 340 Ma (Early Carboniferous: Visean), after which there was the start of a subduction-related accretionary prism, which continued its activity until the end of the Permian (Hervé et al., 2013). In the Patagonian sector of the proto-Andes, there were substantial intrusions from the Middle to the Late Devonian (Emsian to Famennian: 401 to 371 Ma), as shown in the palaeogeographical maps of Hervé et al. (2013).

In central America, Keppie et al. (2012) documented a 35 Myr period of flat-slab subduction within the Acatlán Complex of southern Mexico which ended in the Late Devonian at about 365 Ma. During that period the rocks were taken to about 40 km below the surface and then back up again in a subduction erosion-intrusion cycle. The relative positions of Gondwana and the Laurentian sector of Laurussia do not appear have changed much between the Early and Late Devonian (compare Figs. 13 and 14), with the Rheic Ocean between them. However, subsequently, between the Late Devonian and the Middle Carboniferous, when the two superterranes united to form Pangea, there must have been an enormous amount of strike-slip faulting between the two so as to bring round today's southern Laurentia to face the northwestern sector of Gondwana. That faulting also helps to explain the fragmentary nature of the Mexican terranes.

The northern Gondwanan margin remained largely passive, although Latest Devonian (Famennian) to Early Carboniferous (Tournaisian) granitoids were intruded into the central Himalaya area and adjacent Tibetan terranes, which Zhu et al. (2013) interpreted as connected with rifting heralding the Permian opening of the Neotethys Ocean there. The eastern margin of Gondwana remained active, with the Tabberabberan Orogeny, which had started in the Middle Silurian continuing on until the Middle Devonian (430 to 380 Ma) in the New England and Thomson orogenic areas of eastern Australia, representing the accretion of yet more volcanic arc material to the Gondwana Craton, associated with the intrusion of more granites (Glen, 2005). The various tectonic units within Tasmania amalgamated in the Early Devonian at about 400 Ma (Veevers, 2004); and Moore et al. (2013) suggested that the Melbourne Zone of Victoria was much shortened along a décollement during the Tabberabberan Orogogeny. Kimberlites were intuded into Western Australia in the Late Devonian, between 382 and 367 Ma (Torsvik et al. 2013a), and sourced from the Pacific PGZ.

8.5.2. Facies and faunas

Global eustatic sea levels rose during the Early Devonian (Lochkovian to Emsian: 416 to 400 Ma), leading to transgressions over many Gondwanan cratonic areas, for example the substantial southward extension of the shallow sea over much of North Africa. At the opposite Gondwanan margin, in Antarctica, the shoreline passed the Ellsworth Mountains and Ohio Range and was backed by non-marine sandstone deposition in the Pensacola Mountains, Beardmore Glacier area, and South Victoria Land (Veevers, 2004). Those transgressions were probably one of the factors causing a notable increase in the provinciality in the shallow-marine benthic faunas over the same period, which was one of the greatest in the whole Palaeozoic, as documented by Boucot and Blodgett (2001) for the brachiopods. Those provinces are shown on our Fig. 13, which is updated from Cocks and Torsvik (2002, fig. 9). The higher latitudes of Gondwana (over 60°S) were occupied by the low-diversity Malvinokaffric Province, principally in the centre and south of South America and the southwestern parts of Africa. The period of maximum provinciality in the Emsian may have been partly enhanced by a global regression between the Late Pragian and the Early Emsian; for example, in the Paraná Basin of Brazil there were substantial faunal extinctions before the Late Emsian (Bosetti et al., 2012). Zabini et al. (2012) have documented the Pragian to Eifelian successions in the Paraná Basin and noted that the faunal diversity there was generally low or medium across successions ranging from shoreface to distal tempestites, and used lingulide brachiopods as indicators of regular transgressive and regressive phases throughout the period. However, the Paraná Basin remained at the inboard end of an epeiric sea throughout that period.

Young (1990) cladistically analysed the global distribution patterns shown by Early and Late Devonian fish, and demonstrated that those found around Gondwana differed substantially from those around Laurussia (which he termed Euro-America) in the Early Devonian, but, as the Rheic Odean narrowed, there was less faunal differentiation. McKerrow et al. (2000) plotted the fish faunas on maps showing northwest Gondwana and the whole of Laurussia, and noted that the Rheic Ocean was still wide enough in the Early Devonian (Lochkovian) at 415 Ma to divide the fish provinces, but that by Frasnian times (380 Ma) there was no substantial differences between the fishes found in the two superterranes.

The temperate and equatorial latitudes hosted many diverse warm-water faunas and sedimentary features, including the bioherms plotted by Copper (2002). Although the climates were relatively warm during nearly all of the period, the latest Devonian saw the first of the long-lasting but intermittent Upper Palaeozoic glaciations which continued on until the Early Permian; however, those earliest glaciogenic rocks are only found in the Famennian of South America (Caputo et al., 2008).

8.6. Carboniferous

The Carboniferous ranged from 359 to 299 Ma, and we present two new reconstructions for the Gondwanan region, in the Early Carboniferous at 340 Ma at Visean time (Fig. 15), and in the Late Carboniferous (Moscovian) at 310 Ma (Fig. 16).

8.6.1. Tectonics and igneous activity.

It was during the Carboniferous that Gondwana ceased to be an independent superterrane, since it merged with the other superterrane of Laurussia to form the true supercontinent of Pangea at around 320 Ma. The collision was heralded by the Early Carboniferous down-warping of the Ouichita Basin in the southern U.S.A., and the Ouichita Orogeny there is reflected directly in the compressional deformation first recorded in the Middle Carboniferous of Oklahoma. Orogenic activity peaked in the Late Carboniferous and the final phase was complete by the earliest Permian. The two large superterranes collided obliquely, as evidenced by the considerable evidence of strike-slip faulting in the Ouichita Mountains and nearby. The strike-slip can also be seen by comparing Fig. 14 (Late Devonian: 370 Ma) with Fig. 15 (Early Carboniferous: 340 Ma) and Fig. 16 (Late Carboniferous: 310 Ma), during which time Laurussia had moved a very long way by lateral strike-slip faulting and had also rotated considerably. Nevertheless, probably because of the sheer bulk of the two superterranes, the Gondwana-Laurussia union seems to have caused few large tectonic ripples both to the north of the Ouichita orogenic zone in Laurentia and far inboard within the old Gondwana. In contrast, in adjacent Mexico, there was substantial plutonic and other igneous activity in the Early Carboniferous, as well as faunal exchange between the Mexican terrane margin of Gondwana and Laurussia (Keppie et al., 2008), and there was also much disturbance subsequently as the two superterranes merged and the intervening much smaller Central American terranes became extremely tectonised.

In southern Europe and northern Africa, the Laurussia-Gondwana collision was the prime factor causing the very substantial and prolonged Variscan Orogeny. For example, the double orocline which forms the Iberian Peninsula today was formed at about Carboniferous-Permian boundary time and seems to have represented a 1,300 km-long sector of the Gondwanan margin which was completely distorted as a slow consequence of the Gondwana-Laurussia collision (Shaw et al., 2012). That collision was preceded in Iberia by deepening basins on both sides which were filled with turbidites with different zircons on their opposing sides, indicating that the Ossa-Morena Zone of central Iberia had originated on the Gondwana margin of the Rheic Ocean, but that the now adjacent South Portugese Zone had previously been on the Laurussian side (Pereira et al., 2012).

The south-central and eastern sectors of Gondwana were little affected by its union with Laurussia: the northern margin remained largely passive, and the eastern margin active. Although Zhu et al. (2013) depicted the Lhasa Terrane as leaving the Himalaya before the Visean, we have found no direct evidence that rifting and subsequent sea-floor spreading occurred there at that time, and the main Neotethys Ocean did not open in the region until the Early Permian. In eastern Australia, there was further arc accretion in the Yarrel and New England orogens, including Late Devonian to Carboniferous deformation (Glen, 2005). Late Carboniferous kimberlites were intruded in Australia at 305 Ma (Torsvik et al., 2013a) and are linked to the African PGZ. In Antarctica, the Devonian-Carboniferous Admiralty Granite was intruded and the subaerial Gallipoli Volcanics extruded, both of which straddle the boundaries between the Gondwana Craton and the Robertson Bay, Bowers and Wilson terranes, all within the Ross Orogen of North Victoria Land (Tessensohn and Henjes-Kunst, 2005).

In south-western South America, substantial molasse sediments were deposited in both the Precordillera and the adjacent Sierras Pampeanas (Rapela et al., 1998). There was emplacement of Early Carboniferous granites to the west of the Precordillera Terrane (Dahlquist et al., 2013), from 357 Ma (Tournaisian) to 322 Ma (Serpukhovian) times, which peaked at about 341 Ma (Visean), as well as the intrusion of the Achala granite, the largest batholith in the region, in the Sierras Pampeanas at 369 Ma (the Tournaisian), interpreted as a post-collisional/slab-breakoff A type granite inboard from the passive Gondwanan margin (M. Domeier, pers, comm., 2013). In the Late Carboniferous there was retroarc volcanism in the same western Gondwana marginal zone near Mendoza, Argentina, which was extruded under both subaerial and submarine facies (Koukharsky et al., 2009). In central Chile, the substantial Coastal Batholith there was intruded between 320 and 300 Ma (Hervé et al., 2013).

8.6.3. Facies and faunas

Although there are some rocks of glacial origin in the latest Devonian (Famennian) of South America, it was not until the Carboniferous that glaciogenic rocks were deposited in many areas; and that heralded the start of the total global icehouse period which lasted for over a very long time, continuing on into the Early Permian. That was by far the most long-lived series of glacial events and development of their associated icecaps known in the whole Phanerozoic, as described by many authors, for example Isbell et al. (2008). Rocha-Campos et al. (2008) described and mapped the extent of the Carboniferous glacial deposits of the Paraná and Sanfransicana basins of Brazil and northeast Argentina. Those glacial rocks range in age from the Serpukhovian to the Ghezelian (about 325 to 300 Ma), a span of more than 25 Myr, and that ice sheet may have extended over as far as Namibia in the Late Carboniferous, where it is termed the Windhoek Ice Sheet. However, in the adjacent Parnáiba, Solimões and Parecis basins of south America, the glacial diacmictites are earlier, ranging from the Tournaisian to the Late Visean (about 355 to 325 Ma). In the Alborz Mountains of Iran, Gaetani et al. (2009) described the glaciogenic rocks there as being confined to two episodes in the Carboniferous, the first in the Bashkirian, and the second across the Carboniferous - Permian boundary from the Ghezelian to the Sakmarian (305 to 290 Ma).

Although at the beginning of the Carboniferous the division of plants into floral realms is less obvious, by at least mid-Carboniferous times, four realms can be identified (Chaloner and Lacey, 1973), the most well-known of which is the Gondwanan Realm (formerly termed the *Glossopteris* Province), which was essentially characteristic of the higher latitudes in the Gondwanan sector of Pangea, and whose recognition was one of Wegener's chief planks when he originally characterised continental drift (1915). The others were the Angaran Realm (largely confined to Siberia), the Cathaysian Realm, which is best developed in China, but elements of which are known from neighbouring areas of Gondwana in the Late Carboniferous, and the Euramerian Realm, which was also widespread over Europe and North America, but extended to the temperate fringes of Gondwana.

In the Australasian sector of Gondwana and subsequently Pangea, separate as it was from most other tropical land masses in Carboniferous times, there were many diverse faunas and floras, as reviewed by Jones et al. (2000), with a high proportion of endemic genera in some groups, for example the corals and foraminifera; although the brachiopods, whilst also diverse in generic numbers, were more cosmopolitan than might be expected. However, the outcrops yielding brachiopods are relatively restricted, with no brachiopod faunas at all known in Australia from most of the Middle Carboniferous (Serpukhovian and Bashkirian).

8.7. Permian

The Permian ranged from 299 to 251 Ma, and we present two new reconstructions for the Gondwanan region, in the Early Permian at 280 Ma at Artinskian time (Fig. 17), and at around the Permo-Triassic boundary time at 250 Ma (Fig. 18). For the facies we have drawn to some extent on the global Permian maps of Ziegler et al. (1997).

8.7.1. Tectonics and igneous activity

Although the bulk of Pangea remained united throughout the period, there was break-up at some of its margins. The most significant was in the Gondwana sector, where the Neotethys Ocean opened in the Early Permian. As a consequence of that opening, a string of terranes, notably Sibumasu and the Tibetan terranes of Lhasa and Qiantang, as well as many smaller terranes from Turkey eastwards through Alburz, Iran, Lut and Sanand, Afghanistan, and Pakistan, all moved away from the previous Gondwanan craton. For example, in the

Himalayan area, Zhu et al. (2013) documented many Lower Permian volcanics, as well as granitoids which continued to be intruded into the Qiantang Terrane up to the close of the Permian. Whether or not those terranes were physically united in a single ribbon continent which has been termed Cimmeria by various authors (e.g. Sengor et al., 1984) is unknown, but it seems reasonable to suppose that at least some were joined to their neighbours.

On the western margin of Gondwana there was substantial volcanic and plutonic activity, as can be seen in the Mendoza area of Argentina, where the marine basin there closed in a tectonic phase in the Middle Permian between 284 and 276 Ma (Artinskian to Kungurian), as documented by Gregori and Benedini (2013). In central Chile, below 39° S, the subduction-related accretionary prism continued its activity, inboard of which there were plutons dated at 294 to 281 Ma (Sakmarian to Artinskian) in the North Patagonian Massif (Hervé et al., 2013). In Central America, by this time part of the unified western margin of Pangea, a Late Carboniferous to Middle Permian (300 to 263 Ma) volcanic island arc was active offshore from Guatemala to southern California (Kirsch et al., 2012).

In the Early Permian (Sakmarian: 289 Ma) a LIP, the Panjal Traps (also dubbed the Tethyan Plume), was extruded in the north-western Himalayas and has been correlated with fragments of flood-basalts in other parts of the Himalaya, the Lhasa Terrane and Oman (Lapierre et al., 2004; Chauvet et al., 2008, Shellnutt et al., 2011). The fragments of the Panjal Traps are allochthonous today, but they are shown as united on our Early Permian map (Fig. 17). If the Panjal Traps are a LIP sourced by a plume from the core-mantle boundary, we link it to the African PGZ. The Panjal Traps may have triggered the subsequent opening of the Neotethys Ocean (Fig. 18). At the end of Permian there occurred the vast outpourings of the Siberian Traps Large Igneous Province at 251 Ma, but there is no evidence that that major event directly affected the Gondwanan sector of Pangea.

8.7.2. Facies and faunas

As in the Late Carboniferous, the plants around the world were differentiated into four groups, of which the best known is the Gondwanan Realm (informally termed the *Glossopteris* Province), which was characteristic of the higher latitudes in the Gondwanan sector of Pangea. However, in the Tibetan terranes and the Sibumasu area, also in Gondwana at the start of the Permian, as well as the *Glossopteris* Flora, there were also elements of the Cathaysian Floral Realm in the Early Permian. That realm, which was reevaluated by Stevens et al. (2011), was originally described from China and spread into adjacent areas by the end of the Carboniferous, and expanded into even wider areas as the Permian progressed (Cocks and Torsvik, 2013). Comparably, the *Glossopteris* Flora had become absent from the Paraná Basin of Brazil by the latest Carboniferous and earliest Permian (Holz et al., 2010).

Widespread coals were formed over much of the Gondwanan sector of Pangea, particularly in the first two-thirds of the Permian. Inland, in eastern Brazil, a sequence of sediments, all deposited under arid climates in the intracratonic Recôncavo Basin, displays a regression during the Permian from shallow marine to isolated evaporitic, through continental sabkha to sporadic lacustrine deposits (Silva et al., 2012). In the Paraná Basin of Brazil there are a variety of rocks which are largely fluvial in origin, with some glaciogenic deposits in the Early Permian (Early Sakmarian to Middle Artinskian), and with a single marine incursion in the Paraguaçu Member of the Rio Bonito Formation. Those are followed by sediments of the Palermo and Tatui formations, which represent deposition within shallow marine shoreface embayments, which are followed in turn by the Late Artinskian to Kungurian Irati and Serra Alta formations, which have yielded many plants (including coals), fossil reptiles and fish in sediments which include evaporites, as well as thin layers representing possible marine incursions (Holz et al., 2010). In Africa, the non-marine Karoo Supergroup, which was also deposited within large intracontinental lakes, was host to a wide variety of tetrapods, together with interbedded volcanic ashes from which absolute ages have been measured in the Late Permian (Rubidge et al., 2013).

Permian brachiopods were also provincial (Shi, 2006). For example, after the earliest Permian glacial interval was over in the Early Sakmarian, a substantial and steep climatic gradient was developed during the Asselian to Sakmarian along Gondwana’s northern margin which is is exemplified by the contrasting brachiopod and fusuline faunas. The warm-water Boreal Realm faunas, including the brachiopods *Neochonetes, Costispinifera, Calliprotonia, Juresania* and many others, flourished in the seas of Iran and adjacent Arabia, and that realm extended northwards to the Ural and Russian Platform sectors of Pangea. Those brachiopods contrast sharply with the lower-diversity and colder-water faunas to be found from Karakorum and Afghanistan all the way round to Australia, a contrast which Angiolini et al. (2007) attributed to the existence of an oceanic gyre. Shen et al. (2000) found that the 141 known genera of Late Permian (Changhsingian) brachiopods were divided between five provinces, of which three are found along the Neotethys shelf of Gondwana in a cline from the higher-latitude Austrazean Province in New Zealand (descendants of a province which previously occupied a considerable area of Gondwana in the Early Permian), through the temperate Himalayan Province, to the Western Tethyan Province in the Middle East, which was at an equatorial latitude. However, by the Late Permian, the Neotethys had widened enough to have allowed the separate development of the Cathaysian Province in South China and Sibumasu on its other side.

At the end of the Permian there occurred the most substantial biological extinction event ever seen (Wignall, 2007), when approximately 75% of the animals and plants perished, chiefly because of the very negative atmospheric and subsequent temperature effects caused by the outpourings of the Siberian Traps LIP at 251 Ma, but also because of the smaller amount of coastlines available for the establishment of the varied biological niches around Pangea and other continents. Such niches would have been necessary to make homes for a larger number of more diverse faunas, particularly of benthic marine invertebrates. However, the overall global climate had deteriorated before then, as can be seen by the diminishing numbers of bioherms and other carbonate rocks in the Late Permian, in contrast to the Early and Middle Permian, when they were abundant and widespread.

8.8. Mesozoic postscript.

Pangea had begun to break up long before the Palaeozoic had ended; for example, the Neotethys Ocean opened in the Permian to separate many areas originally in Gondwana away from the old craton (Fig. 18). However, although that breakup proceeded steadily throughout the Mesozoic, most of the old Gondwana sector remained a coherent continental entity until well into the Jurassic. Triassic climates were warm there, and many red beds, such as the New Red Sandstone of Britain, were deposited. The Palaeotethys Ocean closed in the Middle East at about end-Triassic to earliest Jurassic time, contemporaneously with the opening of two branches of the Neotethys Ocean in the same region (Sosson et al., 2010).

We present a new palaeogeographical reconstruction (Fig. 19) at the Triassic-Jurassic boundary time at 200 Ma, when most of Pangea was still united (Ruiz-Martínez et al., 2012; Seton et al., 2012), and before the Central Atlantic Ocean started to open between North America and Africa-South America at around 195 Ma (Labails et al., 2010; Gaina et al., 2013). The eventual sites of the subsequent Atlantic and Indian Ocean openings are also shown on Fig. 19 as thick white stippled lines. It is notable that some fragments of old Gondwana, such as Florida and the eastern sector of Avalonia, remained attached to the North American side of the Atlantic Ocean rather than staying with their original neighbours located in today’s continental areas east of the Atlantic. The opening of the Central Atlantic Ocean occurred shortly after a massive episode of volcanism, the Central Atlantic Magmatic Province (CAMP), which extends over a vast area (see Fig. 6), more than 10^6 km^2 (McHone, 2002; Ruiz-Martínez et al., 2012), and which was intruded at around 201 Ma. The plume head probably impinged the lithosphere beneath the southern tip of Florida, and eventually led to Pangea breaking up at sites different from the older suture lines. We link CAMP to a plume derived from the African PGZ and kimberlites which were also intruded into southern Africa at about the same time.

The final breakup of Gondwana (white dotted line between West and East Gondwana in Fig. 19) occured at around 175 Ma (Gaina et al., 2013), and shortly after the Karoo LIP (183 Ma), which affected vast parts of Southern Africa and East Antarctica (Fig. 6). The Karoo LIP (Fig. 21) and abundant Jurassic kimberlites were all sourced from the African PGZ. Indeed no Mesozoic and Cenozoic kimberlites globally have been sourced from the Pacific PGZ because no continents have overlain the Pacific LLSVP since then.

9. Discussion and conclusions

9.1. *Gondwana in space and time*

For more than two hundred million years, Gondwana was by far the largest superterrane known, from its formation in the Late Neoproterozoic until its combination with Laurussia to form the Pangea supercontinent during Carboniferous times. It spanned all the southern palaeolatitudes from the pole to over 20°N for most of the Palaeozoic. Gondwana's formation was the unification of over ten Precambrian cratons, all individually substantial, progressively from the Late Neoproterozoic at about 600 Ma until well into Early and Middle Cambrian times during the Pan-African, Brasiliano, Pampean, Kunguuan, and Cadomian orogenies. We here present new palaeogeographical reconstructions, chiefly for the Palaeozoic, which reflect the accretion of many terranes at Gondwana's active margins. Those margins include southwestern Gondwana (South America) and southeastern Gondwana (eastern Australasia) for most of the Palaeozoic, and at some times the subduction zone at the heart of that activity appear to have been united, so that the whole very long southwestern, southern and southeastern margin of the superterrane may have been one of the most extensive continuous subduction zones ever known. Palaeomagnetic data, as well as the locations of LIPs and kimberlites originating at the PGZ, have enabled us to orientate and position Gondwana and adjacent continents much more securely than has hitherto been possible, particularly for the Palaeozoic. Palaeolatitudes from our reconstructions are confirmed by the location of evaporites through time (Fig. 20). The largest latitudinal peak of evaporites is seen between 25° and 30° South or North and about half plot within the bounds of the present day subtropics (25° to 40°). Some plot at somewhat lower latitudes, but this because the Earth was spinning 8-13% faster in the Palaeozoic.

The provincial affinities of the changing faunas and faunas through the Palaeozoic much varied. At some times, such as the Early Ordovician, the Early Devonian, and the Permian, the more pronounced climatic belts, as well as geographical separations, make the distributions of those biota of great significance in positioning both tectonic units and the various sectors of the Gondwanan (subsequently Pangean) craton. However, at other times the climates were much more equable, and consequently there was much less provincial differentiation, and thus the biota is much less useful for indicating palaeogeography. The many complications and problems in interpretation are accentuated by the very varied amount of work that has or has not been done in describing the individual faunal and floral assemblages, and resolving their affiliations, over much of the huge area considered in this paper.

Although the overall changing tectonic unit positions and their palaeogeographical scenarios through time are far better known than they were thirty and more years ago, there are continuing controversies. For example, the original position of the combined and substantial South China-Annamia continent, which was certainly originally part of the Gondwanan cratonic assemblage in the Late Neoproterozoic is uncertain: in general we agree with some authors who have placed it outboard of northwest India, but it may have been much further eastwards and outboard of Australia. The detailed timing of its separation from the main craton is also uncertain; it might have been as late as Early Cambrian (about 540 Ma), but seems more likely to have been 10 to 20 myr earlier, although no date is yet proven.

Even though much is now well constrained on the relative positioning and timings of the many peri-Gondwanan accreted terranes in eastern Australasia and southwestern South America (Argentina and Chile), so many subsequent tectonics have affected the northwestern South America, central America, and southern European terranes, that their Early Palaeozoic areas, positions and even identities are still poorly constrained. Comparably, the string of terranes stretching from Turkey to Tibet require much additional study, not helped by the relative inaccessibility of some parts of them.

9.2. *Gondwana from top to base*

Earth is today, and was probably also through the Phanerozoic, dominated by a degree-2 convection mode with upwelling associated with the antipodal LLSVPs beneath Africa and the Pacific. The LLSVPs also dominate the residual geoid. Gondwana was at times underlain by hotter than average mantle due to its passage over the LLSVPs, and their margins are the principal PGZs that have led to sporadic LIP and kimberlite volcanism. Since Pangea assembly, 16 LIPs have been derived from the African PGZ, and since the breakup of Gondwana at around 170 Ma, the opening of the West Somali and Mozambique Basins (Gaina et al., 2013), six major plumes have penetrated the Gondwanan continental lithosphere, leading to LIPs in Namibia/Brazil (Etendeka-Parana), Australia (Bunbury), India (Rajhmahal and Deccan), Madagascar and NE Africa (Afar). Those six LIPs plot at a great circle distance of 3.4 ± 2.0^{o} from the PGZ, and all except Parana-Etendeka (reconstructed in a TPW-corrected palaeomagnetic frame), have been reconstructed in a mantle reference frame.

There are only two Gondwanan LIPs in the Palaeozoic, and kimberlites are quite scarce. We have identified about 83 dated kimberlites, the majority are Cambrian in age and overlapping in age with the Kalkarindji LIP (510 Ma) in western Australia (Fig. 9). Those were all related to the African PGZ (Figs. 10, 21). A minor kimberlite event is also identified in western Australia during the Devonian and linked to the Pacific PGZ (Fig. 14). All the Mesozoic kimberlites (66 in total) are linked to the African LLSVP. All four known LIPs from 510 to 183 Ma (the lifetime of Gondwana) were derived from plumes associated with the African LLSVP (Fig. 21). Excluding the allochthonous Panjal Traps from our statistical analysis, they plot on average at 2.5 ± 3.4^{o} from the African PGZ.

The African and Pacific LLSVPs have probably been stable for the entire Phanerozoic, and possibly much longer. Their edges, the Plume Generation Zones, are the dominant source of deep plumes, which travel from the base of the mantle to the surface where hotspot lavas are erupting today (Fig. 8), and where episodic LIP activity has led to environmental and climatic crises as well as continental break-ups. LIP activity punctuates plate tectonics by creating and modifying plate boundaries: the Panjal Traps (289 Ma) probably assisted in the opening of the Neotethys; the opening of the Central Atlantic (Fig. 19) was preceded by the emplacement of CAMP (201 Ma); and Karoo (183 Ma) heralded the Jurassic breakup of Gondwana. However, not all LIPs (for example, Kalkarindji, Fig. 10) cause or contribute to changes in plate boundaries, and there are no known plumes associated with the opening of the Rheic (Fig. 11) and the Palaeotethys oceans (Fig. 13).

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APPENDIX. The names of orogenies.

As in our paper on Laurentia (Cocks and Torsvik, 2011), we have found that there are many names used for the various orogenies which affected Gondwana and its margins, not all of which are universally familiar, and thus some are listed here,

Achalian Orogeny. Largely Devonian events adjacent to the Famatinian and Pampean arc areas in south-western South America.

Alleghanian Orogeny. Late Palaeozoic orogeny in eastern North America essentially equivalent to the Variscan Orogeny in Europe.

Benambran Orogeny. Late Ordovician to Early Silurian orogeny in eastern Australia.

Bimphedian Orogeny. Late Cambrian to Early Ordovician orogeny in the Himalayan region.

Brasiliano Orogeny. Latest Neoproterozoic to Early Cambrian orogeny in South America, loosely equivalent of the Pan-African Orogeny to its east.

Cadomian Orogeny. Latest Neoproterozoic to Early Cambrian orogeny in southern Europe and northwest Africa.

Caledonian Orogeny. The chiefly Silurian orogeny in Europe and North America caused by the collision of Laurentia and Avalonia-Baltica. It did not directly affect Gondwana, and thus the name should not be used there.

Delamerian Orogeny. Late Proterozoic to earliest Ordovician orogeny in eastern Australia.

Famatinian Orogeny. Largely Ordovician events adjacent to the Famatinian and Pampean arc areas in south-western South America.

Hercynian Orogeny. Largely superseded equivalent name for the Variscan Orogeny in southern Europe.

Kanimblan Orogeny. Middle Devonian to Carboniferous orogeny in eastern Australia.

Kuungan Orogeny. Latest Neoproterozoic to Early Cambrian orogeny linking India and East Antarctica.

Ocloyic Orogeny. Ordovician orogeny in the Eastern Cordillera and Puna areas of Argentina.

Pampean Orogeny. Latest Neoproterozoic and Cambrian events adjacent to the Famatinian and Pampean arc areas in south-western South America.

Pan-African Orogeny. Latest Neoproterozoic to Early Cambrian orogeny linking the various earlier cratons in Africa and adjacent areas.

Ross Orogeny. Early Palaeozoic orogeny, when marginal terranes were accreted to Antarctica.

Tabberabberan Orogeny. Late Silurian and Devonian orogeny in eastern Australia.

Tyennan Orogeny. Cambrian orogeny in Tasmania and adjacent southeastern Australia.

Variscan Orogeny. Variably-defined major orogeny in the Devonian and Carboniferous of southern Europe and adjacent areas.

Figure Captions

Fig. 1. Palaeomagnetic sites from which data were used to construct the Gondwana apparent polar wander path (APWP) in Figure 2. Green small dots are clastic sedimentary sites where the data were corrected for potential inclination shallowing (see text). Red solid dots are volcanic or limestone sites. Intra-cratonic boundaries after Torsvik et al. (2009a, 2012). DML, Dronning Maud land; LVB, Lake Victoria Block; M, Madagascar.

Fig. 2. APWP for Gondwana (Southern Africa Frame) from 550 to 170 Ma using the spherical spline method (after Torsvik et al., 2012, fig. 11). Mean poles are shown at 10 Myr intervals and their quality is graded as high (white circles), medium (based on one single pole; brown filled circles), or low (interpolated; red filled circles). The APWP is draped on a core Gondwana configuration where Southern Africa is kept fixed in present day co-ordinates. M, Madagascar.

Fig. 3. **a**, icehouse (cold) and greenhouse (hot) conditions, and the latitudinal drift of the northern Africa sector of Gondwana (0^oN, 30^oE) from the Latest Neoproterozoic (550 Ma) to the Jurassic (170 Ma). Based on the APWP in Fig. 2. **b**, Latitudinal velocity for a central Gondwana location based on palaeomagnetic data. **c**, Absolute velocity of central Gondwana (Southern Africa: 0^oN-30^oE) in a true polar wander corrected hybrid mantle frame.

Fig. 4. Global palaeogeography in the Early Cambrian at 540 Ma, after most of Gondwana had become united. The top diagram is a true polar wander (TPW) corrected reference frame (mantle frame) that should be used to compare surface processes (e.g. LIPs and kimberlites) with processes in the deep mantle, e.g. the plume generation zones (PGZ) at the margins of the Large Low Shear Velocity Provinces (LLSVPs). Our Palaeozoic reconstructions Figs. 10-18) are calibrated in longitude in such a way that LIPs and kimberlites directly fall over the African or Pacific PGZ (red thick lines). Kimberlites in Laurentia (Canada: 542-535 Ma) and Gondwana (South Africa, 538 Ma) overly the Pacific and African PGZ respectively (Torsvik et al. 2013a), which calibrates their longitude, whilst latitude and rotation are derived from TPW-corrected palaeomagnetic data. The longitude calibration is outlined in Torsvik et al. (2008a, 2013a). The lower diagram shows the same

reconstruction in a palaeomagnetic (PM) reference frame that is also used in Figs. 10-19. This reference frame must be used when attempting to relate facies and fauna to climatic zonation. In order to show how well kimberlites (in this case) and LIPs relate to the deep mantle, we have rotated the African and Pacific PGZs to account for TPW; so in effect the PM reconstruction show both the relation to the spin axis as well as the deep mantle (exemplified by the rotated PGZs). The Kazakh and Mongolian terranes and microcontinents, and the Pontides Terrane, are not shown since their positions are uncertain. A, Afghan Terrane; ATA, Armorican terrane Assemblage; E, Ellsworth-Whitmore Mountains; F, Falkland Islands; MBL, Marie Byrd Land: NZL, New Zealand; PGZ, Plume generation Zone; Quiang., Qiantang Terrane; TH, Tethyan Himalaya.

Fig. 5. Map showing Precambrian cratons (Gubanov and Mooney, 2009) and the distribution of kimberlites known in the Gondwanan region plotted on an end-Palaeozoic base map at 250 Ma. Blue shading, Late-Neoproterozoic to Early Cambrian orogenic belts; light grey shading, Phanerozoic cover rocks. AZC, Amazonian Craton; COC, Congo Craton; EAC, East Antarctica Craton; GAC, Gawker Craton; KAC, Kalahari Craton; M, Madagascar; NAC, North Australia Craton; PIC, Pilbara Craton; RPO, Rio de La Plata Craton; SFC, Sao Francisco Craton; WAC, West African Craton; YIC, Yilgara Craton.

Fig. 6. The distribution of Large Igneous Provinces (LIPs) in the Gondwana region plotted on an end-Palaeozoic base map at 250 Ma. Only Kalkarindji (510 Ma), CAMP (201 Ma), Panjal Traps (PJ, 289 Ma) and Karoo (183 Ma) erupted between 550 and 170 Ma (black outlines), i.e. during the lifetime of Gondwana. Abbreviated LIPs are: CAMP, Central Atlantic Magmatic Province; RH, Rajhmahal Traps (118 Ma); BU, Bunbury Basalts (132 Ma). LIP volcanism in Madagascar and Afar are dated to about 88 and 30 Ma.

Fig. 7. Hotspots globally draped on the SMEAN shear-wave velocity anomaly model at 2800 km depth (Becker and Boschi, 2002). Velocity anomalies (δVs) in percent and red denotes regions with low velocity. The −1% contour, approximating to the plume generation zone (PGZ) of Burke et al. (2008), is shown as a thick red line. Horizontal gradients (calculated in Torsvik et al., 2006) in shear-wave velocity anomaly (% $\delta Vs/^{\circ}$) are indicated where they exceed 0.16 percent per degree. Hotspots mentioned in the text are named. The African and Pacific LLSVPs are antipodal and centred nearly on the equator. The lower diagram

(modified from Trønnes, 2010) is a cartoon illustrating how plumes are generated in the PGZ near the core-mantle boundary (along the edges of a LLSVP) and rise to the surface in 20-50 Myrs, producing hotspots and kimberlites, or catastrophic upper mantle melting leading to LIPs. ppv, post-perovskite.

Fig. 8. Current location of hotspots (red and white circles) in the African realm and their calculated surface hotspot motion (Doubrovine et al., 2012) plotted on the SMEAN shear-wave velocity anomaly model (see Fig. 7 for detailed caption). The SMEAN zero contour is also shown as a black stippled line and forms the approximate outline of the African LLSVP. Seven hotspots are argued to have originated from deep plumes on various criteria (Steinberger, 2000; Courtillot et al., 2003; Ritsema and Allen, 2003; Montelli et al., 2004, 2006) are shown as white circles. We also show the reconstructed location of six LIPs that impinged Gondwanan continental lithosphere, but after Gondwana breakup (134-31 Ma). These are Bunbury (B), Madagascar (M), Karoo (K), Parena-Etendeka (P), Afar (A) and Deccan (D). Some active deep-plume-sourced hotspots are commonly linked to older LIPs; for example, Tristan is linked to the ~134 Ma Parana-Etendeka LIP, whereas Reunion has been linked to the ~65.5 Ma Deccan LIP. In our reconstructions, based on a mantle (moving hotspot) reference frame back to 120 Ma (Doubrovine et al. 2012), the reconstructed LIPs (N=6) plot at 3.4 ± 2.0^{o} from the PGZ.

Fig. 9. Distribution of Gondwanan kimberlites (histogram, 25 Myr bins) and LIPs between 550 and 170 Ma. The four LIPs that affected Gondwana continental crust in the time interval are: KH, Kalkarindji (~510 Ma; Glass et al., 2006); PT, Panjal Traps (~289 Ma; Shellnutt et al., 2011); C, Central Atlantic Magmatic Province (~201 Ma; Ruiz-Martínez et al., 2012); K, Karoo (~183 Ma; Svensen et al., 2012).

Fig. 10. Gondwana and nearby palaeocontinents at 510 Ma, the Late Middle Cambrian. A, Armorica; EWM, Ellsworth – Whitmore Mountains, Antarctica; F, Falkland Islands; M, Mauritia; S, Seychelles. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. The arc fringing South China includes today's Japanese terranes. Dotted red lines are the plume generation zones (PGZ). Solid red lines are

subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 11. Gondwana and nearby palaeocontinents at 480 Ma, the Early Ordovician, at about Tremadocian-Floian (previously Arenig) boundary time. MBL, Marie Byrd Land; NZ, New Zealand; P, Papua New Guinea. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. The arc fringing South China includes today's Japanese terranes. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides.

Fig. 12. Gondwana and nearby palaeocontinents at 445 Ma, the Latest Ordovician (Hirnantian), showing the extent of the glacial icecap, and also the distribution of the *Hirnantia* brachiopod Fauna, updated from Rong and Harper (1988) and Torsvik and Cocks (2011). F, Florida; MBL, Marie Byrd Land, Antarctica; NZ, New Zealand; Pat., Patagonia. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. The arc fringing South China includes today's Japanese terranes. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides.

Fig. 13. Gondwana and nearby palaeocontinents at 400 Ma, the Early Devonian (Emsian), showing the distribution of the provincial brachiopod faunas, updated from Cocks and Torsvik (2002, fig. 9). ATA, Armorican Terrane Assemblage; DML, Dronning Maud Land; EWM, Ellsworth – Whitmore Mountains, Antarctica; MT, the Mexican terranes of Mixteca-Oaxaquia and Sierra Madre; P, Precordillera Terrane, Argentina; Pat., Patagonia; Sib., Sibumasu. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 14. Gondwana and nearby palaeocontinents at 370 Ma, the Late Devonian (Famennian). ATA, Armorican Terrane Assemblage. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig.15. Gondwana and nearby palaeocontinents at 340 Ma, the Early Carboniferous (Visean), just prior to its union with Laurussia to form Pangea. NZ, New Zealand; T, Taurides, Turkey; TI, Thurston Island, Antarctica. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Note the extensive strike-slip between Gondwana and the Laurentian sector of Laurussia prior to their union at about 325 Ma. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 16. The Gondwana sector and other adjacent areas within Pangea at 310 Ma, the Late Carboniferous (Moscovian). HK, Hutag Uul-Songliao and Khanka-Jiamusu-Bureya terranes; MBL, Marie Byrd Land, Antarctica; MT, the Mexican terranes of Mixteca-Oaxaquia and Sierra Madre; NZ, New Zealand; TI, Thurston Island, Antarctica. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 17. The Gondwana sector and other adjacent areas within Pangea at 280 Ma, the Early Permian (Artinskian). HK, Hutag Uul-Songliao and Khanka-Jiamusu-Bureya terranes; MBL, Marie Byrd Land, Antarctica; NZ, New Zealand; PT, Panjal Traps LIP, India; TI, Thurston Island, Antarctica. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides.

Fig. 18. Gondwana and other adjacent sectors within Pangea at 250 Ma, the Permian-Triassic boundary time. AP, The Antarctic Peninsula; CH, Chortis Terrane, Mexico; MT, the Mexican terranes of Mixteca-Oaxaquia and Sierra Madre; T, Taurides, Turkey. The strings of island arcs shown are diagrammatic, since the individual extent of each terrane within the arcs and the extent to which particular terranes were above sea level are uncertain. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 19. Gondwana and other adjacent sectors within the still largely united Pangea at 200 Ma, Triassic-Jurassic boundary time. Palaeolongitudes at 30° intervals were calculated from the position of Pangea over the Africa LLSVP. The black dotted lines indicate the closed Iapetus and Rheic sutures, and the white dotted lines the future zones of the breakup of Pangea to form the Atlantic Ocean at 195 Ma and the Indian Ocean at 175 Ma. The 'Greater India' area is subjectively added as a northern extension of India at this time (following van Hinsbergen et al., 2012). The island arcs which undoubtedly surrounded parts of the supercontinent are omitted. AP, The Antarctic Peninsula; C, centre of the Central Atlantic Magmatic Province LIP (for its vast extent, see Fig. 6); DML, Dronning Maud Land, Antarctica; F, Falkland Isles, Fl, Florida; MBL, Marie Byrd Land, Antarctica; MT, the Mexican terranes of Mixteca-Oaxaquia and Sierra Madre; Pat., Patagonia; TI, Thurston Island, Antarctica; Y, Yucatan. Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

Fig. 20. **a.** The latitude centres of the evaporites, taken from our new maps. They plot near the subtropics (mean 26 ± 6^{o} S for the southern hemisphere evaporites), or at somewhat lower latitudes (e.g. West Australia in the Late Ordovician and Laurentia/Laurussia in the Permian). Today the subtropics are generally between 25° and 40° S or N, and thus the distribution of Palaeozoic evaporites is on average within the low end of the range of today's subtropics. But note that the Earth was spinning 8-13% faster in the Palaeozoic, which would have pushed the subtropics nearer the Equator. **b.** Same data as in (a) but the absolute latitude values are plotted in a histogram. The largest peak (37.5%) is noted between 25 and 30^{o} South or North, and 50.1% of the plots are within the bounds of the present day subtropics. The mean latitude for both hemisphere evaporites is 22 ± 9^{o}.

Fig. 21. Reconstructed Gondwanan (550-170 Ma) kimberlites (green diamonds) and LIPs (black annotated circles) draped on the SMEAN tomographic model (see Figs. 7 and 8 for captions). We only show kimberlites linked to plumes derived from the plume generation zones of the African Large Low Shear-wave Velocity Province (LLSVP). In our model, reconstructed kimberlites (N=144) for Gondwana plot at a distance of 4.5 ± 4.7^o from the African and Pacific (not shown in this figure) PGZs. Three reconstructed LIPs, Kalkarindji (KH, 510 Ma), the Central Atlantic Magmatic Province (C, 201 Ma) and Karoo (K, 183 Ma), plot at 2.5 ± 3.4^o from the African PGZ. Panjal Traps (PT, 289 Ma) excluded from the statistical analysis since it is allochtonous. See Fig. 7 for further details.

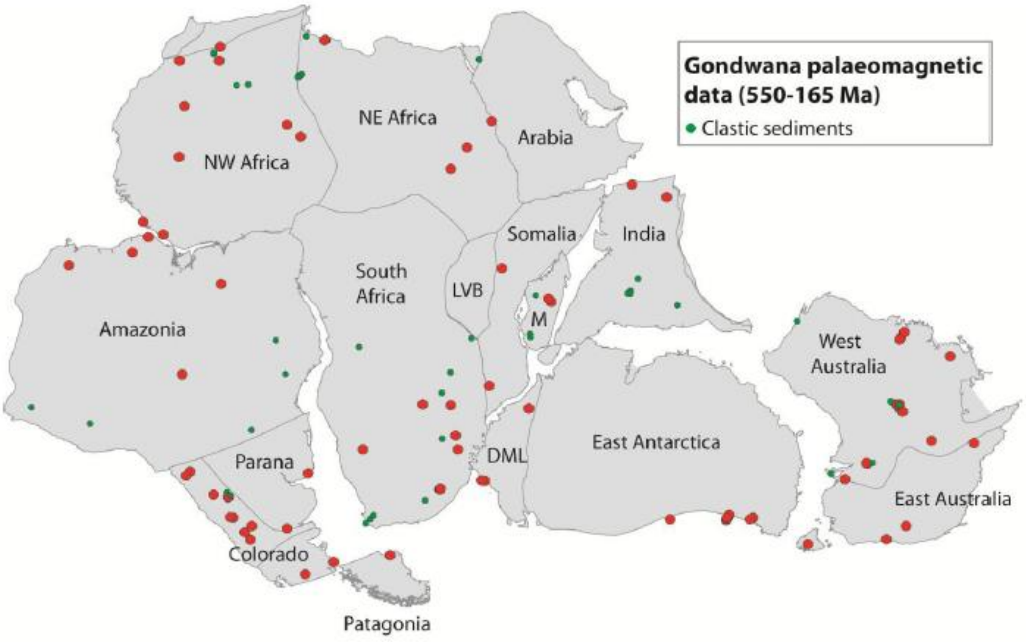
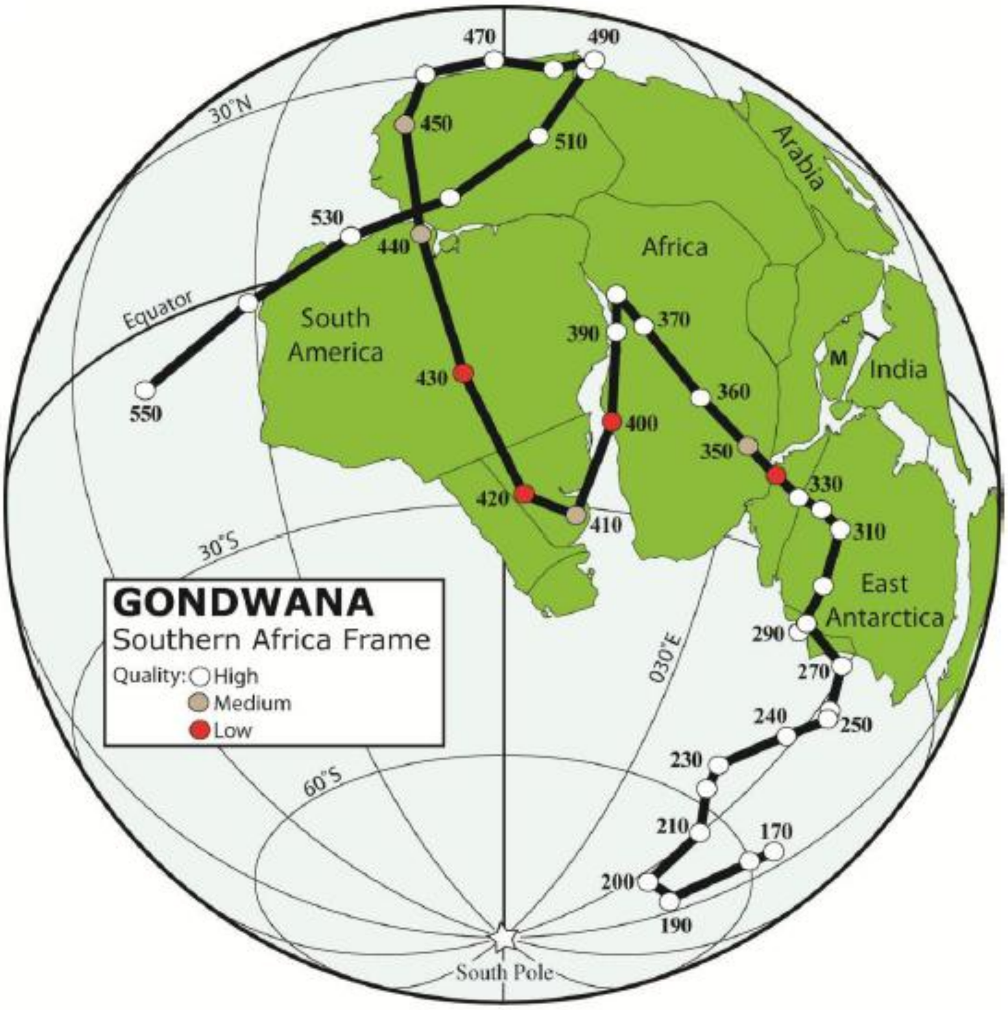


Figure 1 (Torsvik & Cocks GR2013)



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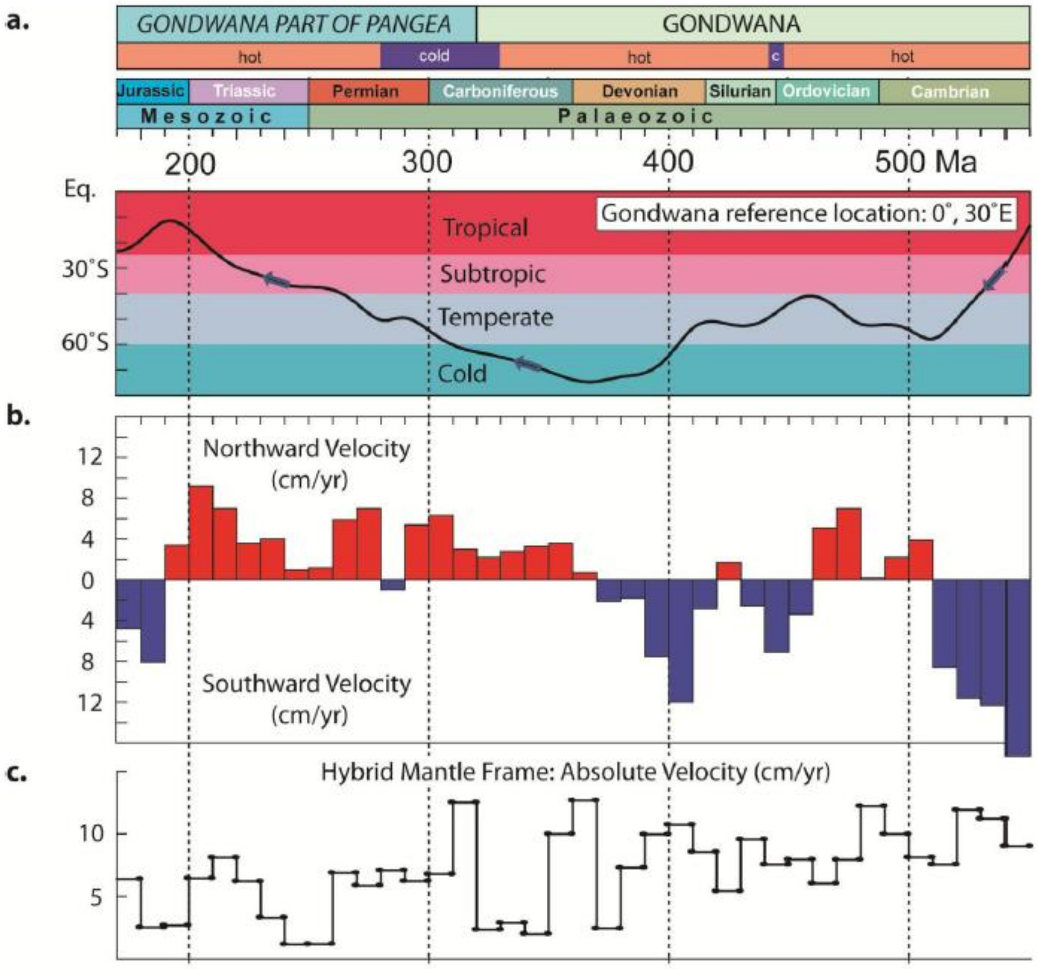

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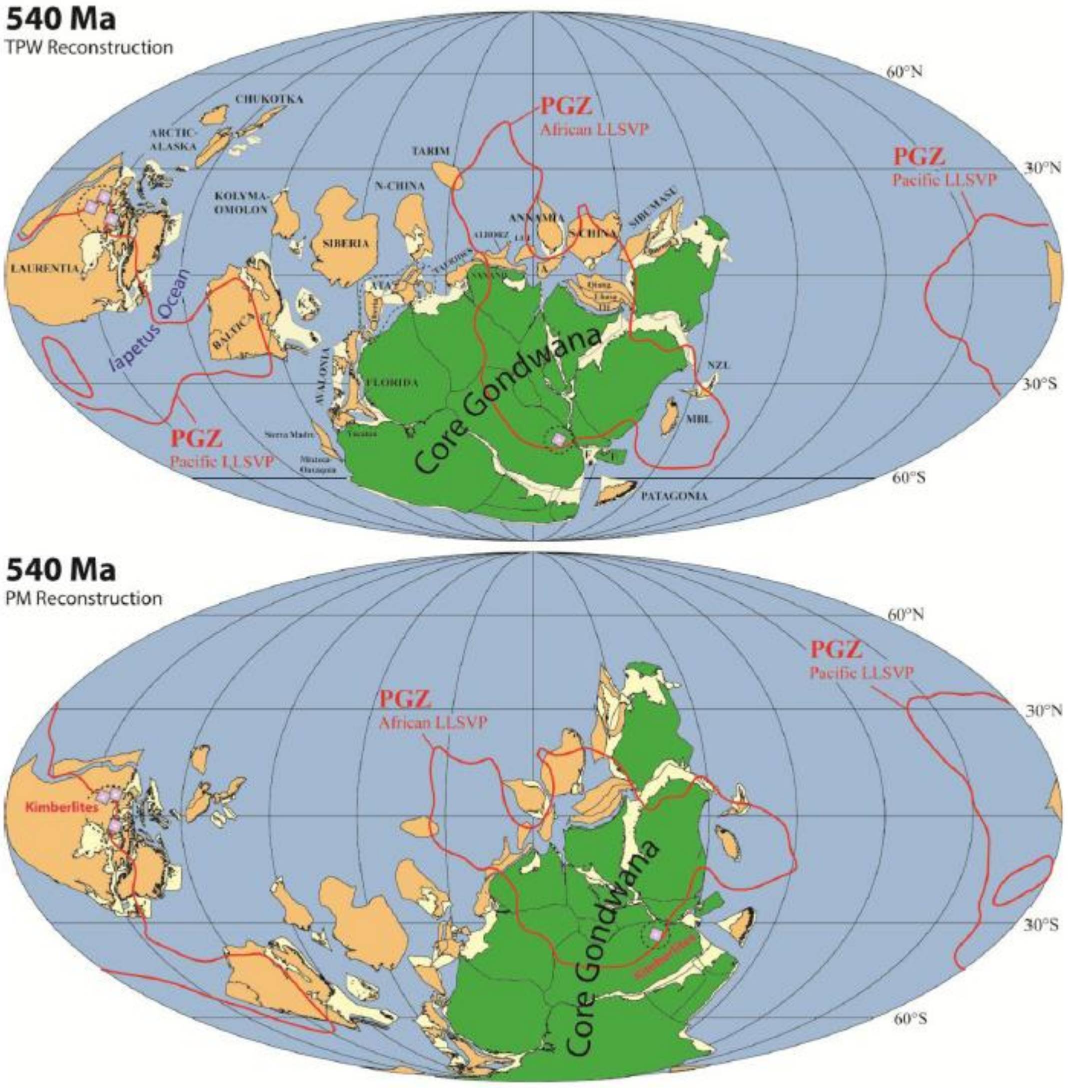

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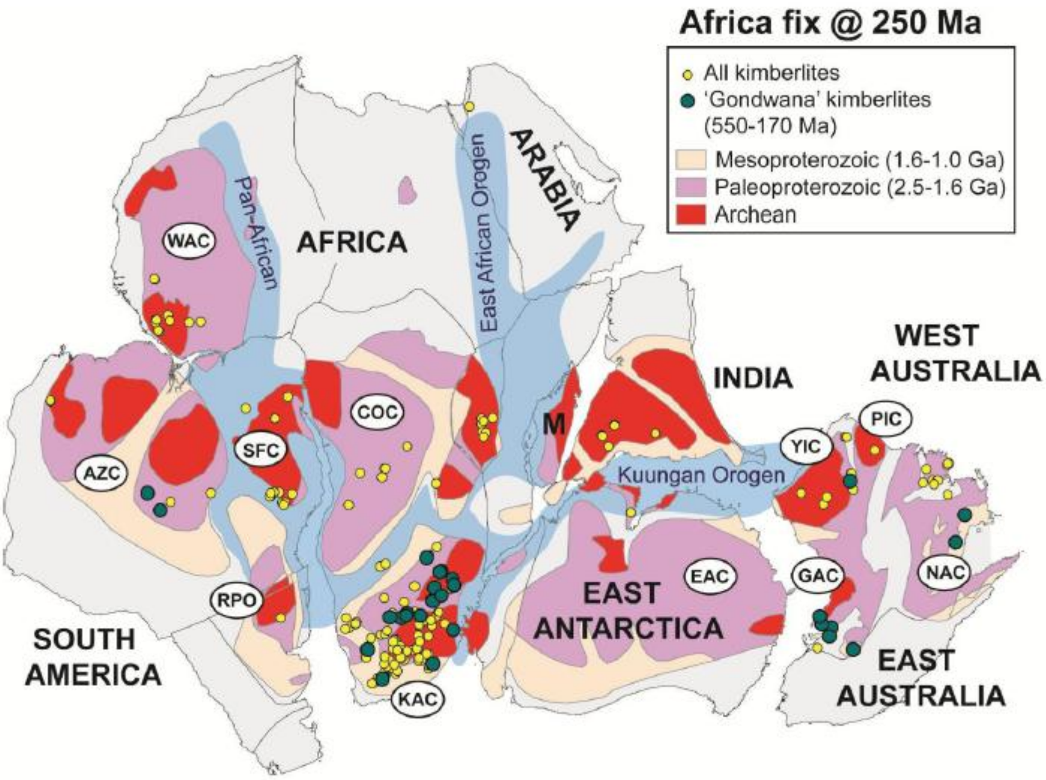

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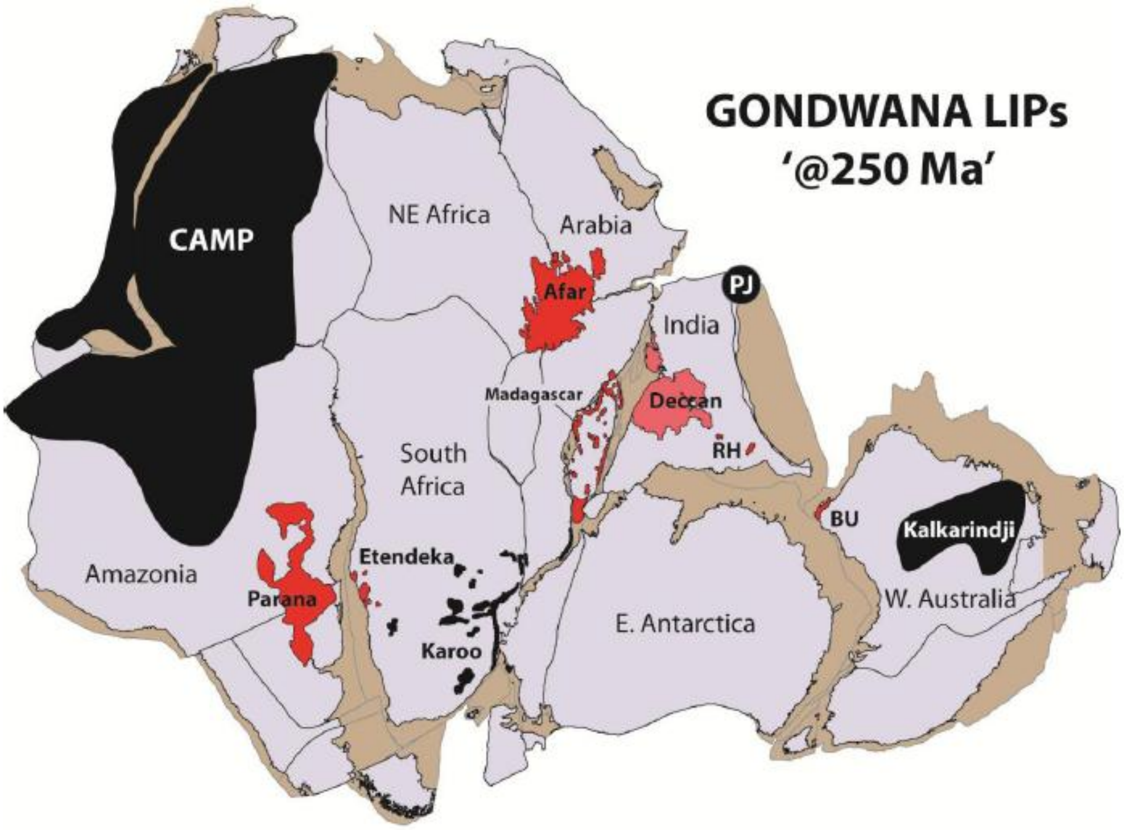

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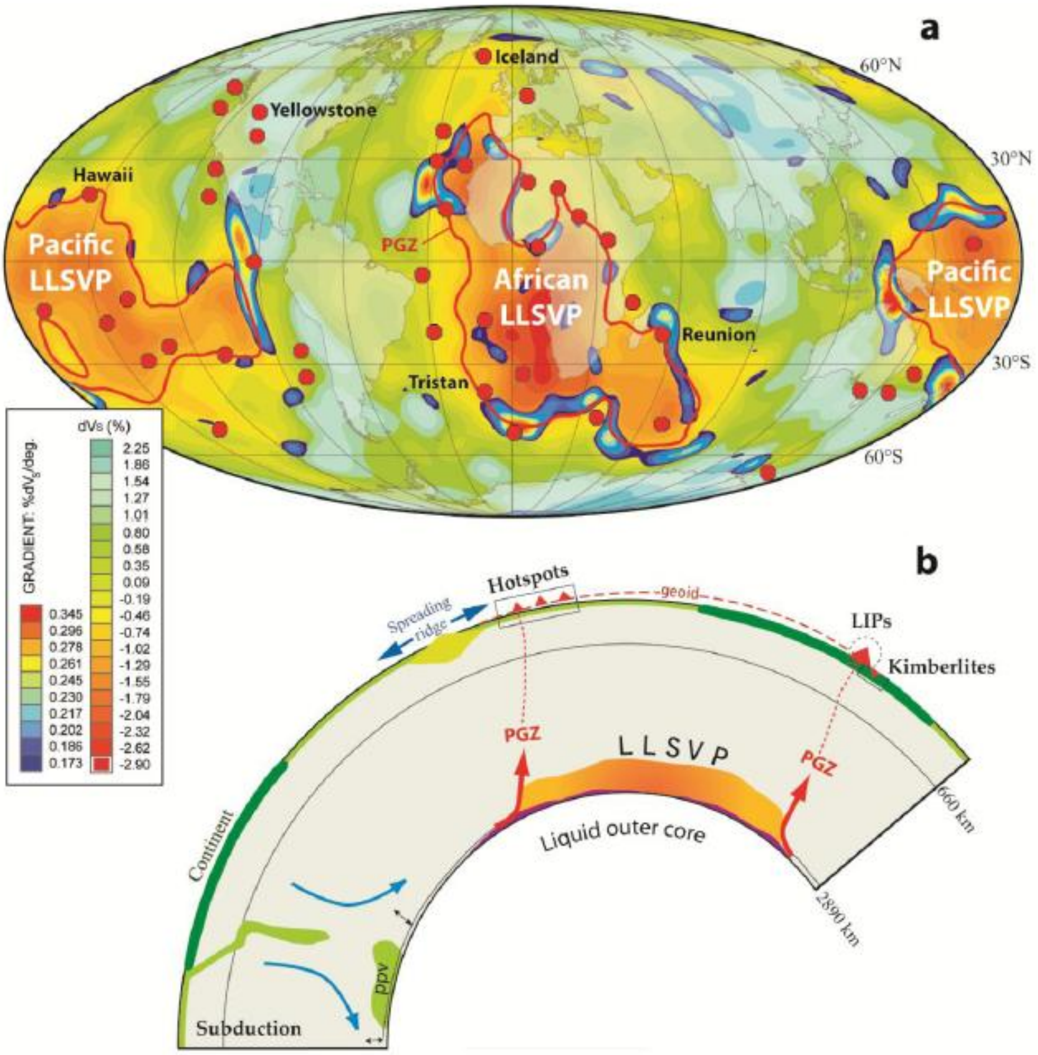

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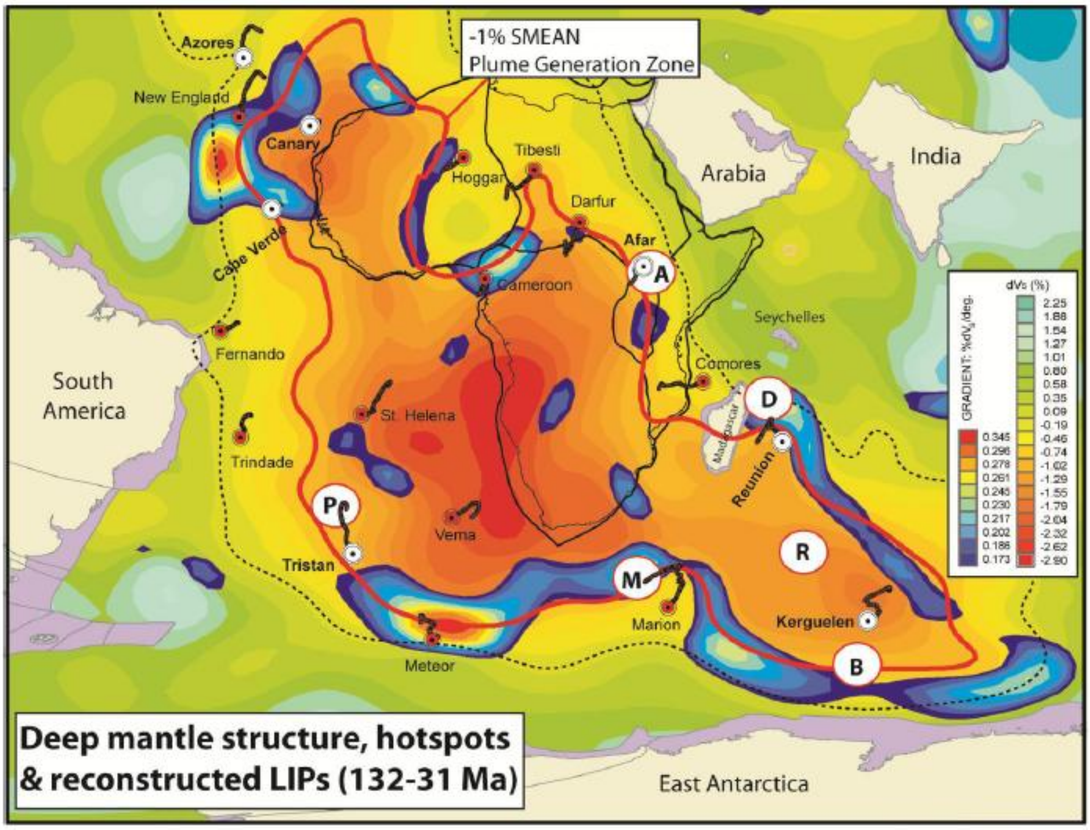

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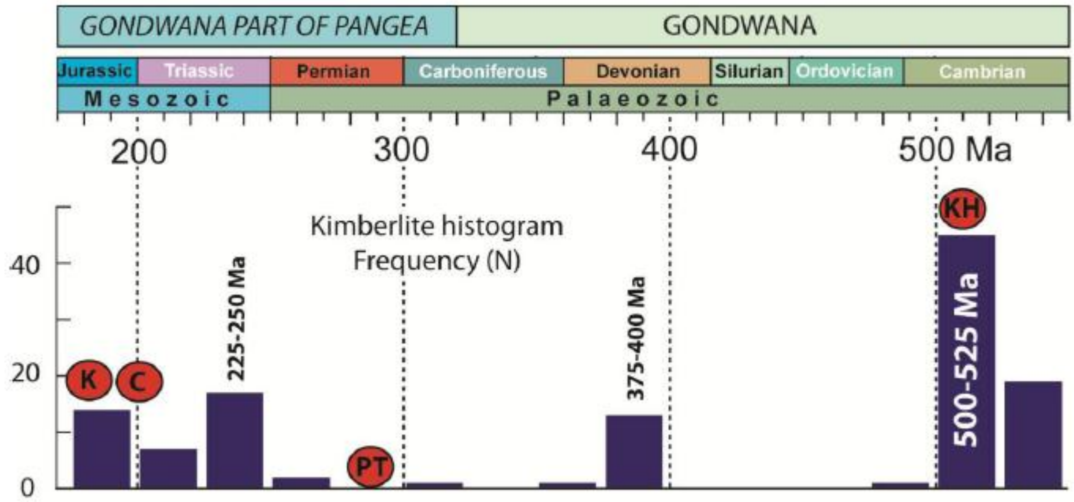

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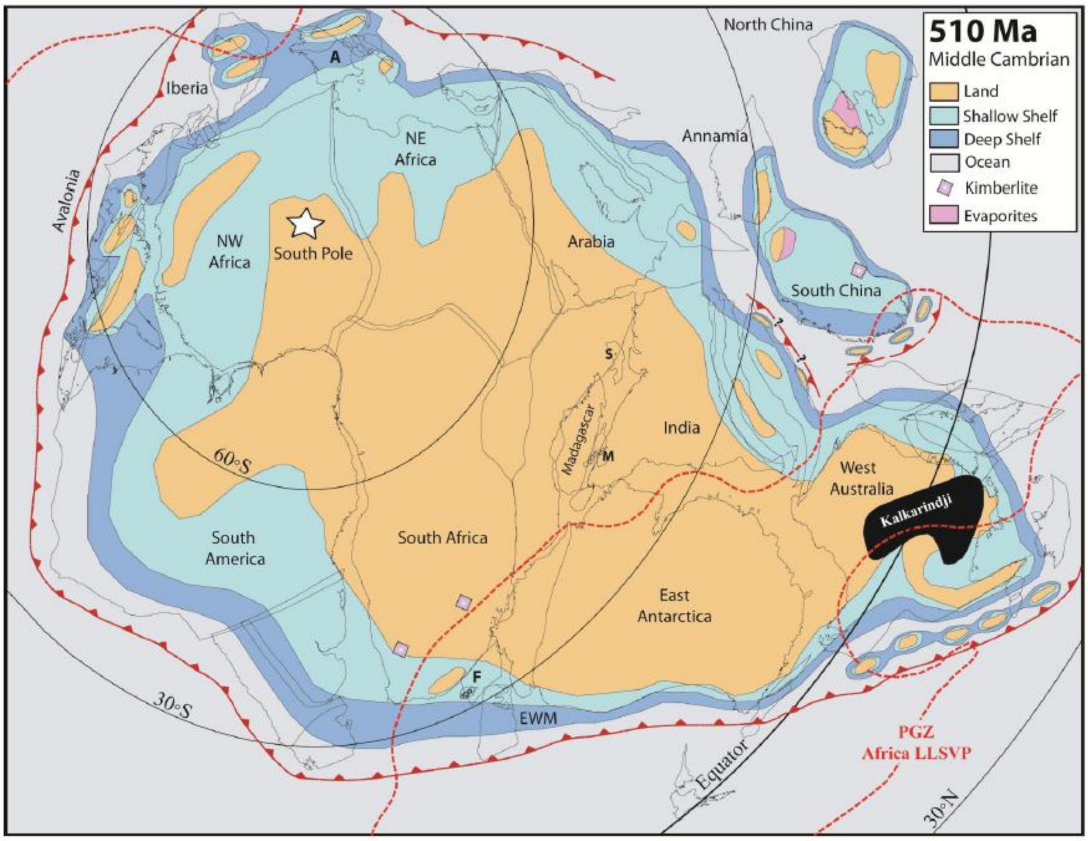

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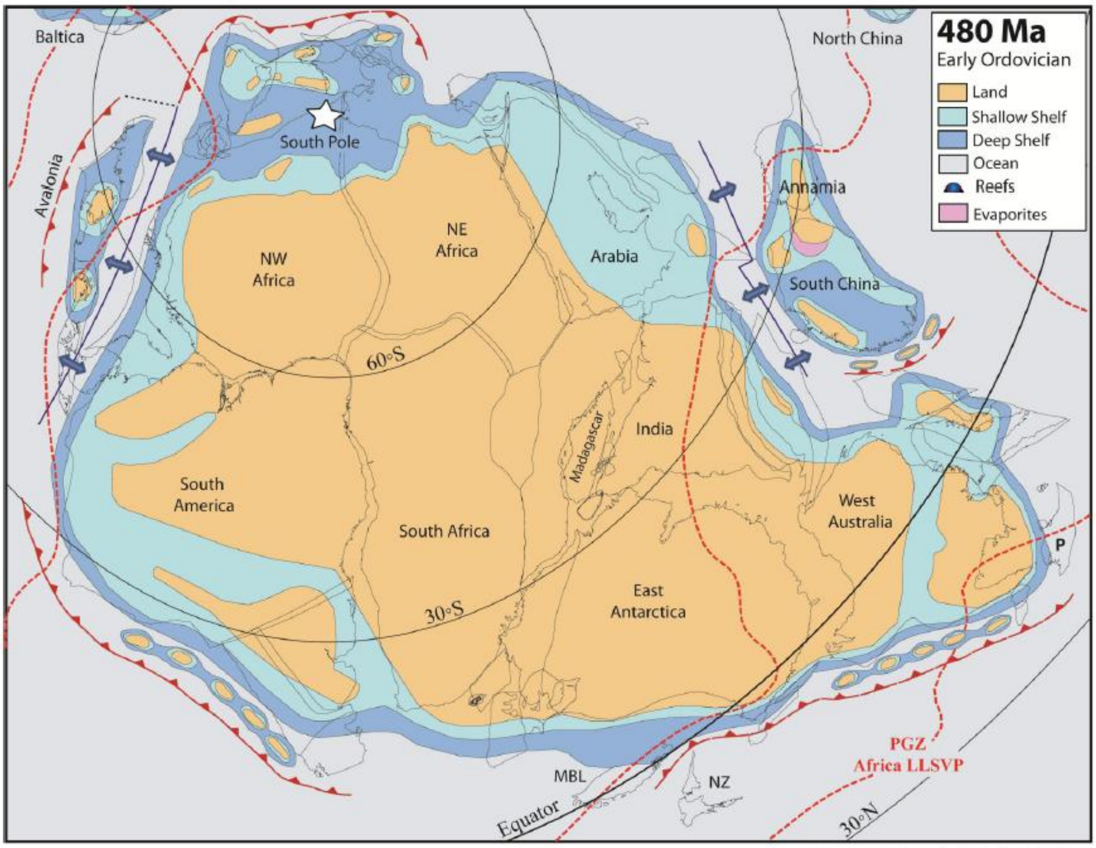

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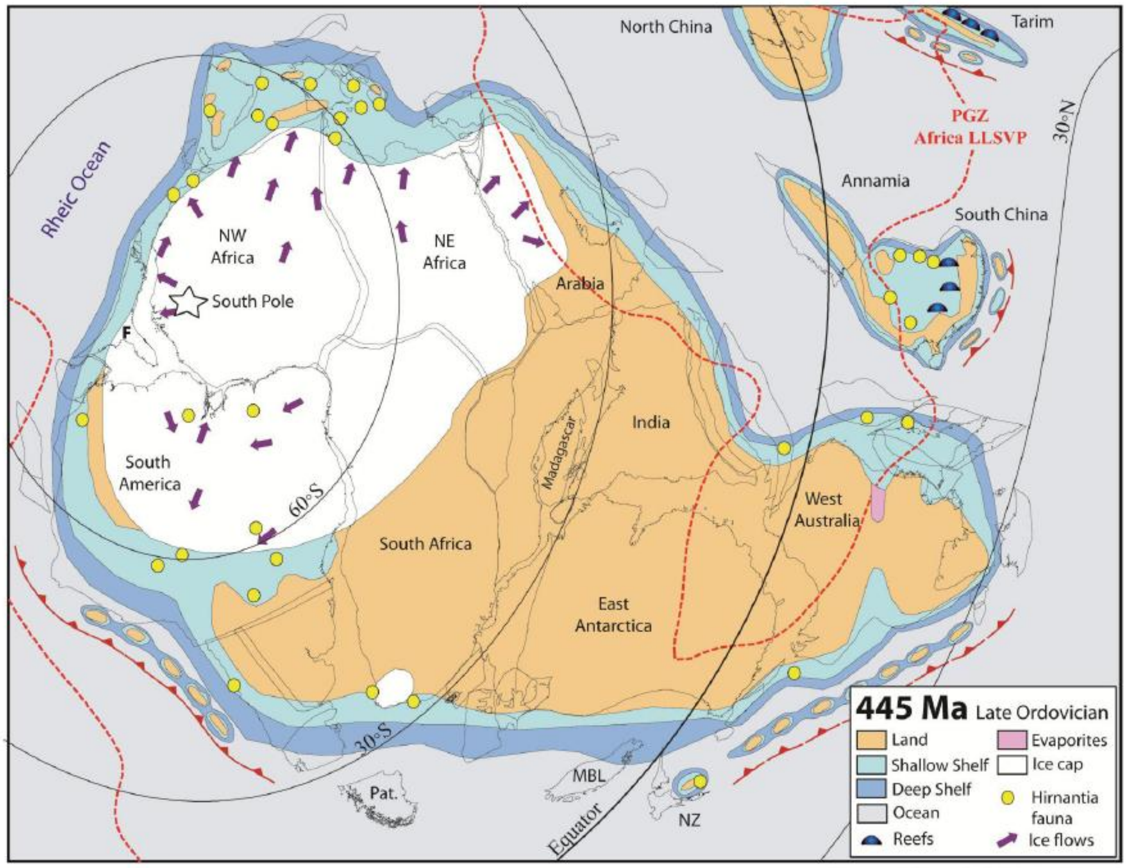

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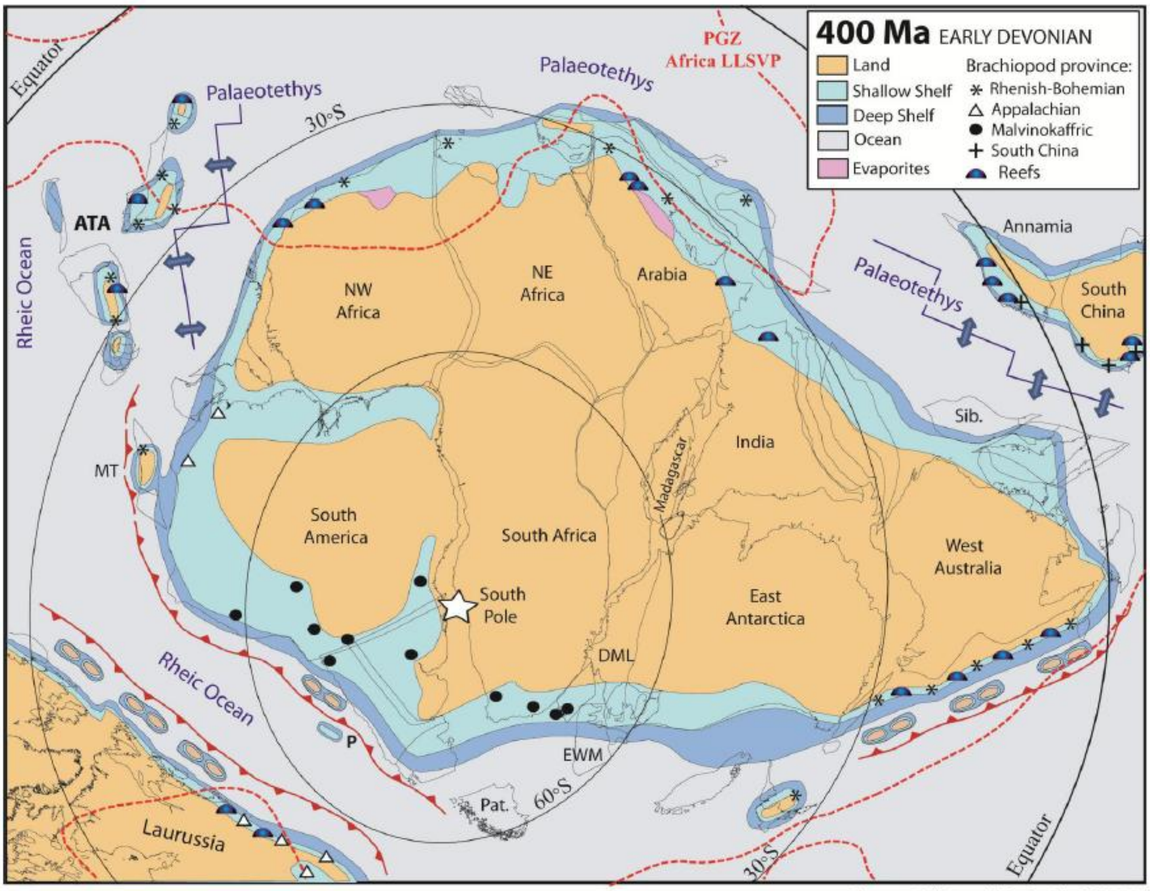

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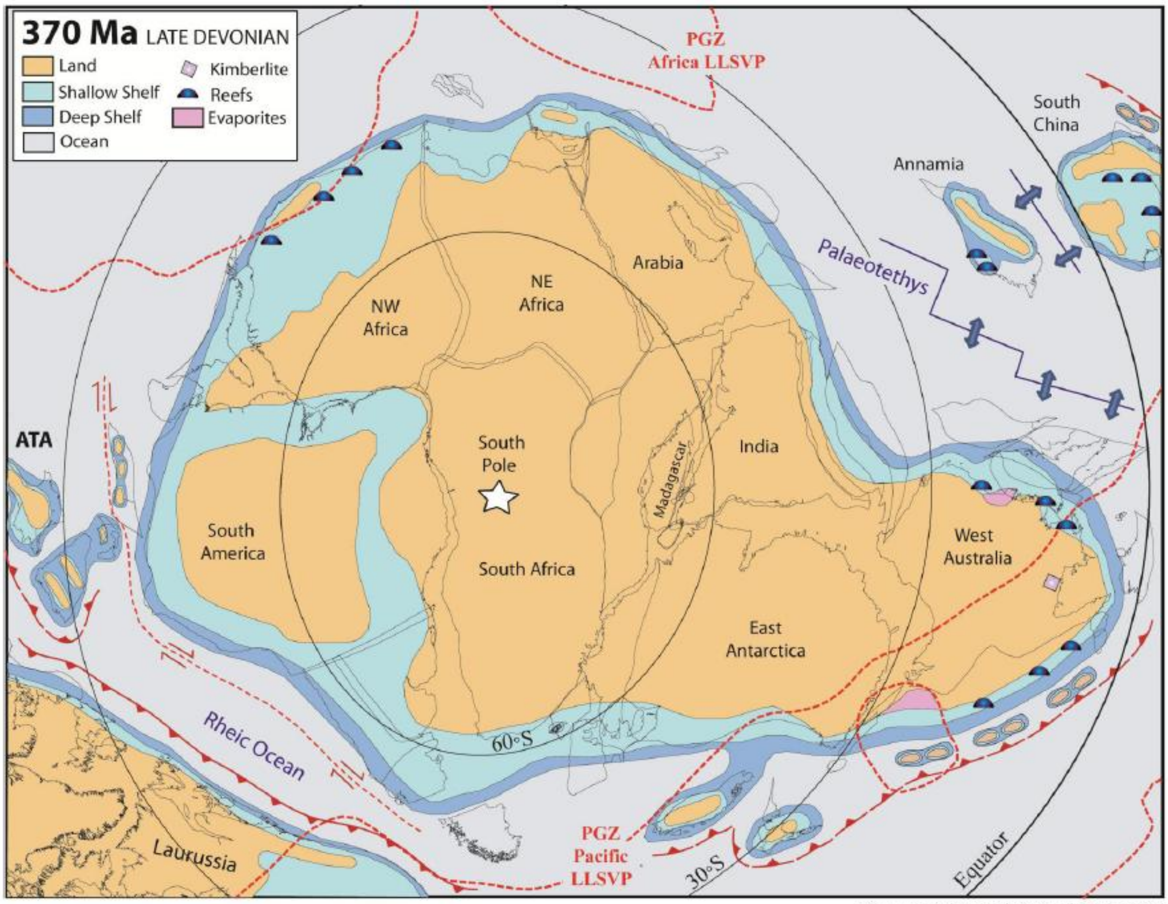

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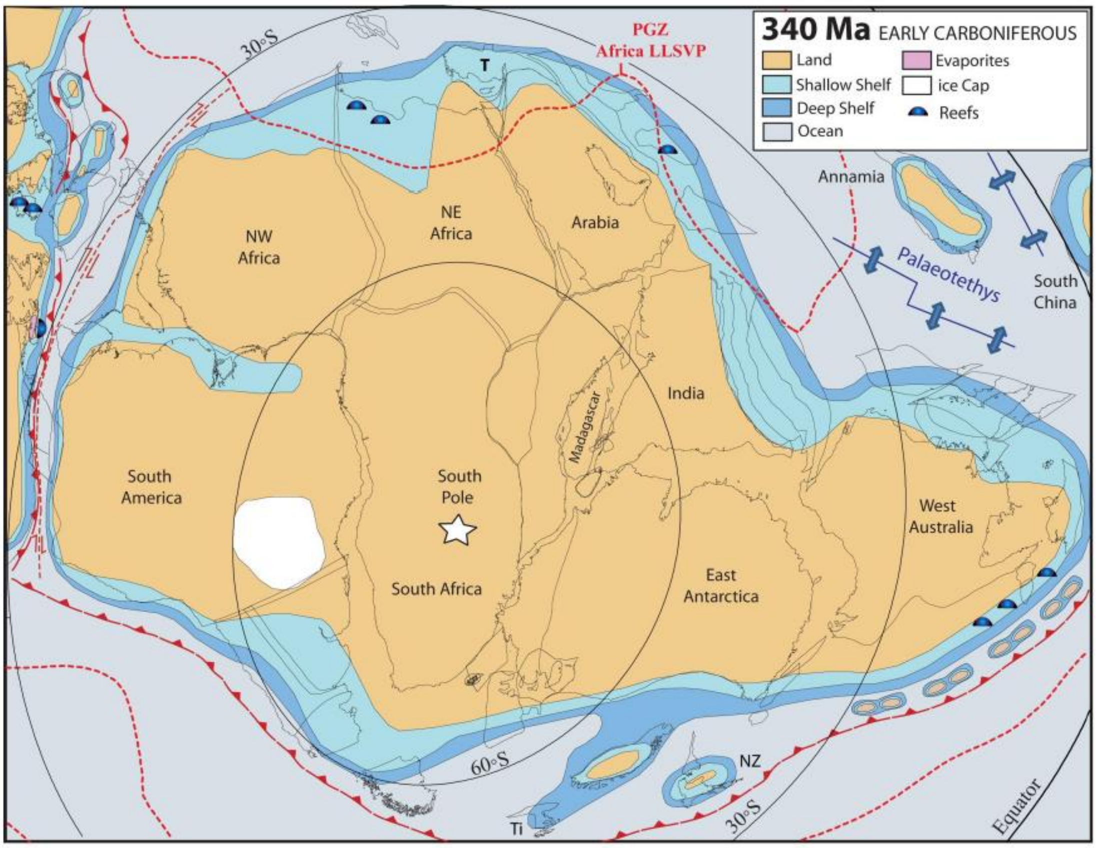

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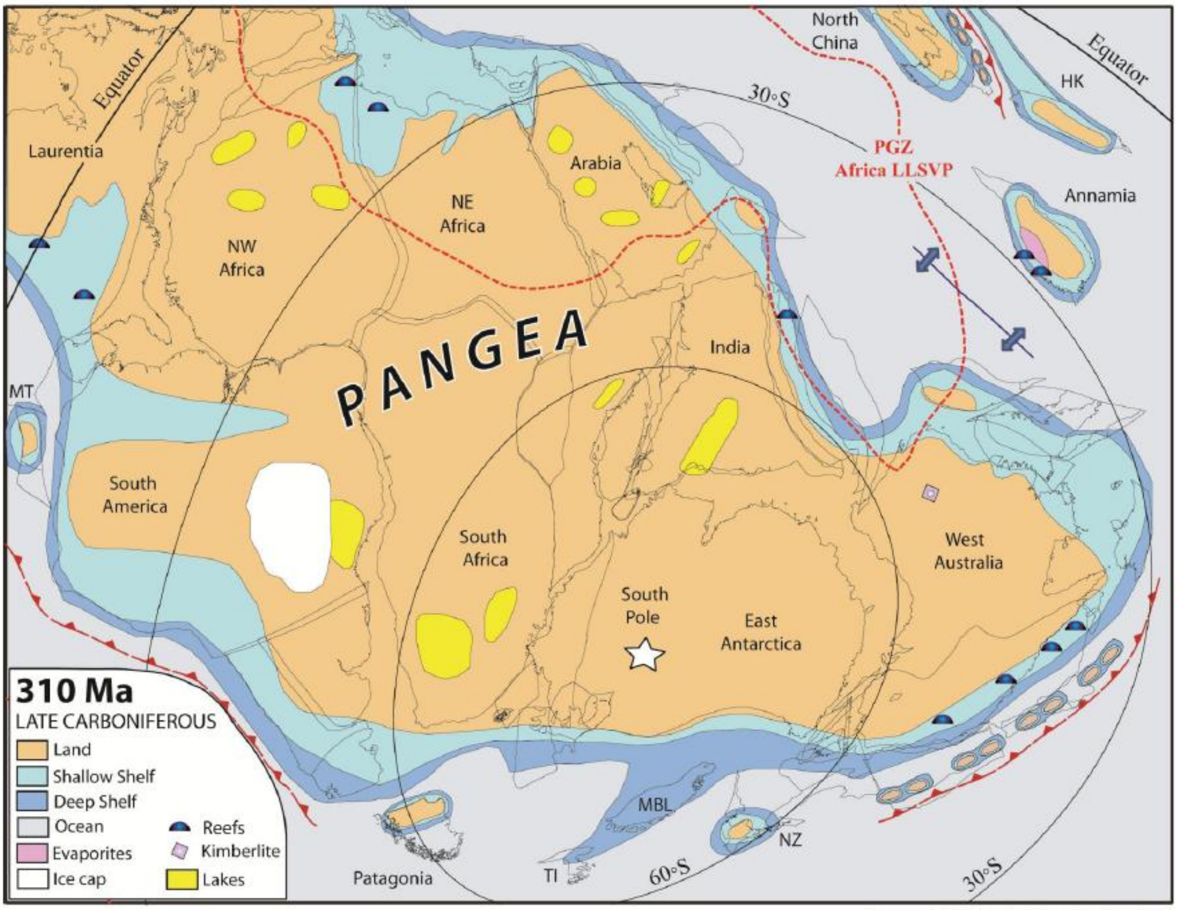

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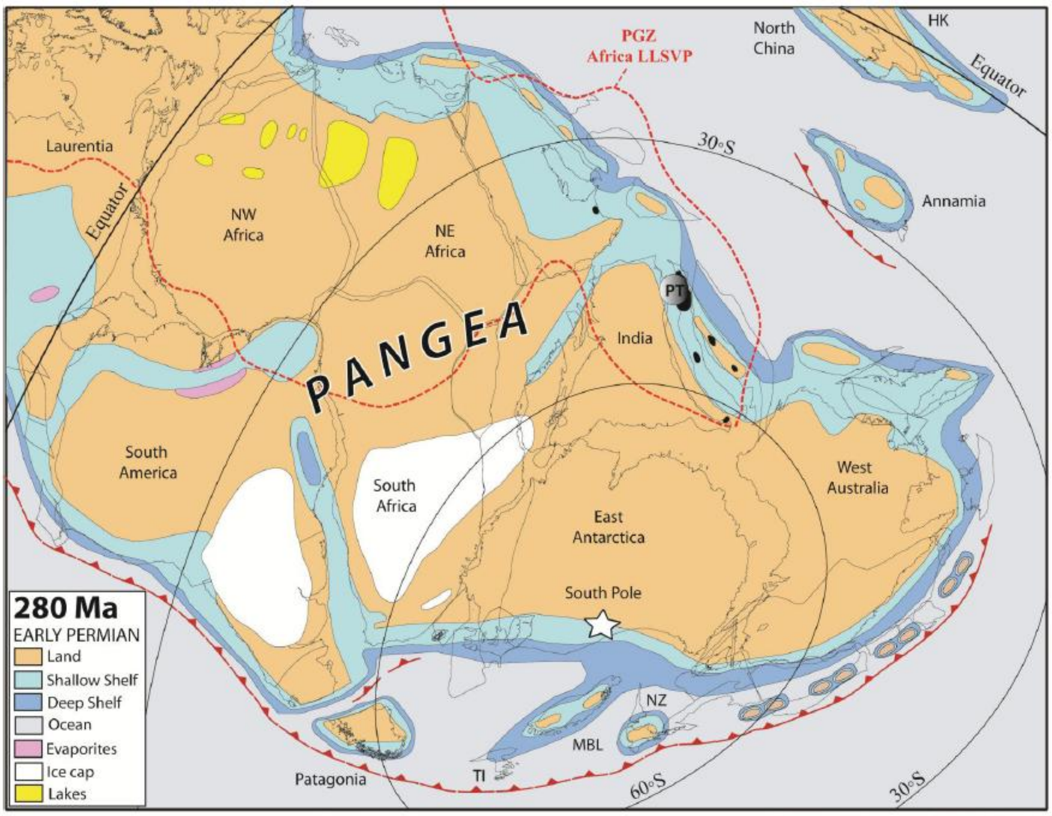

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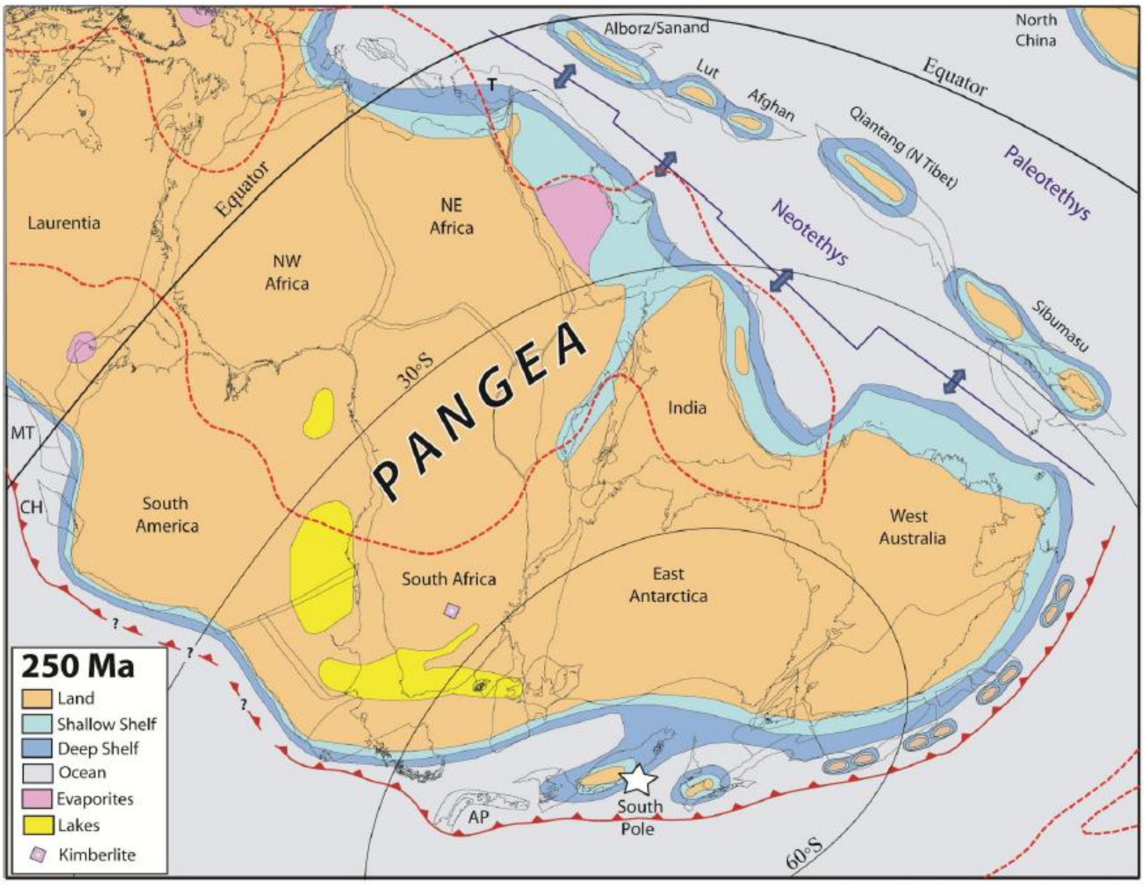

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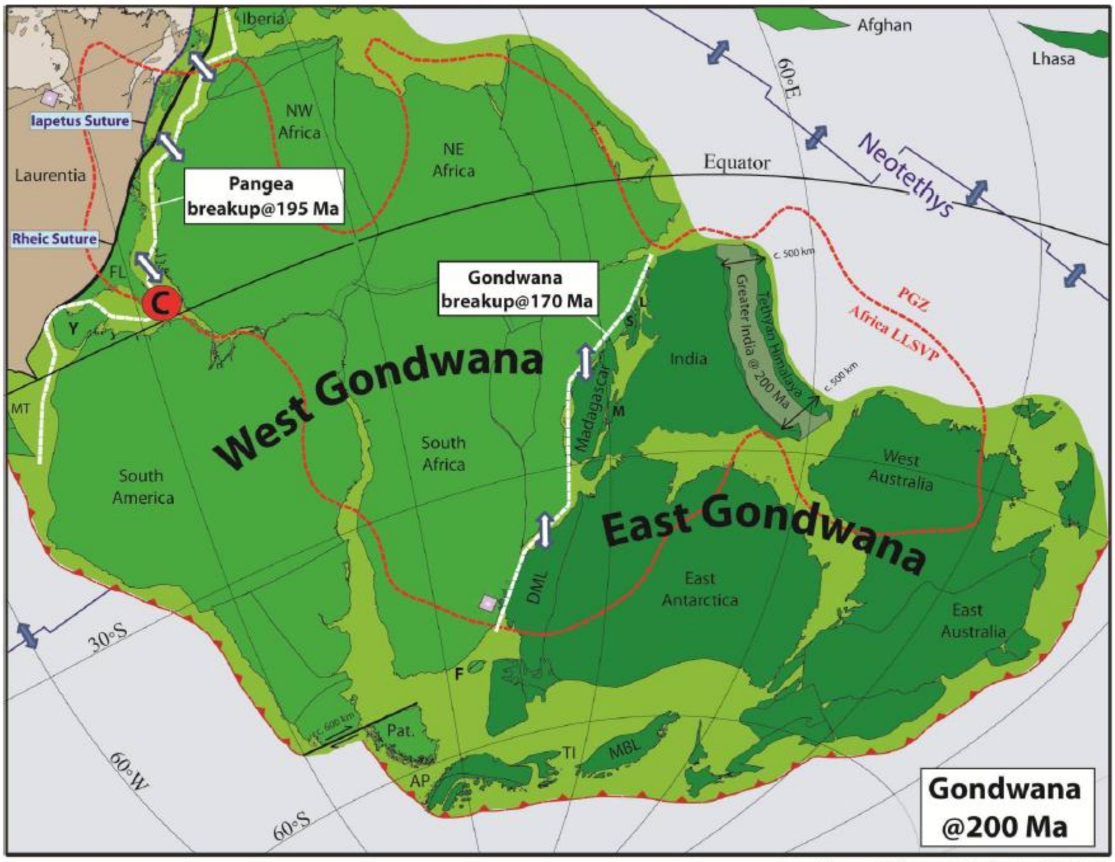

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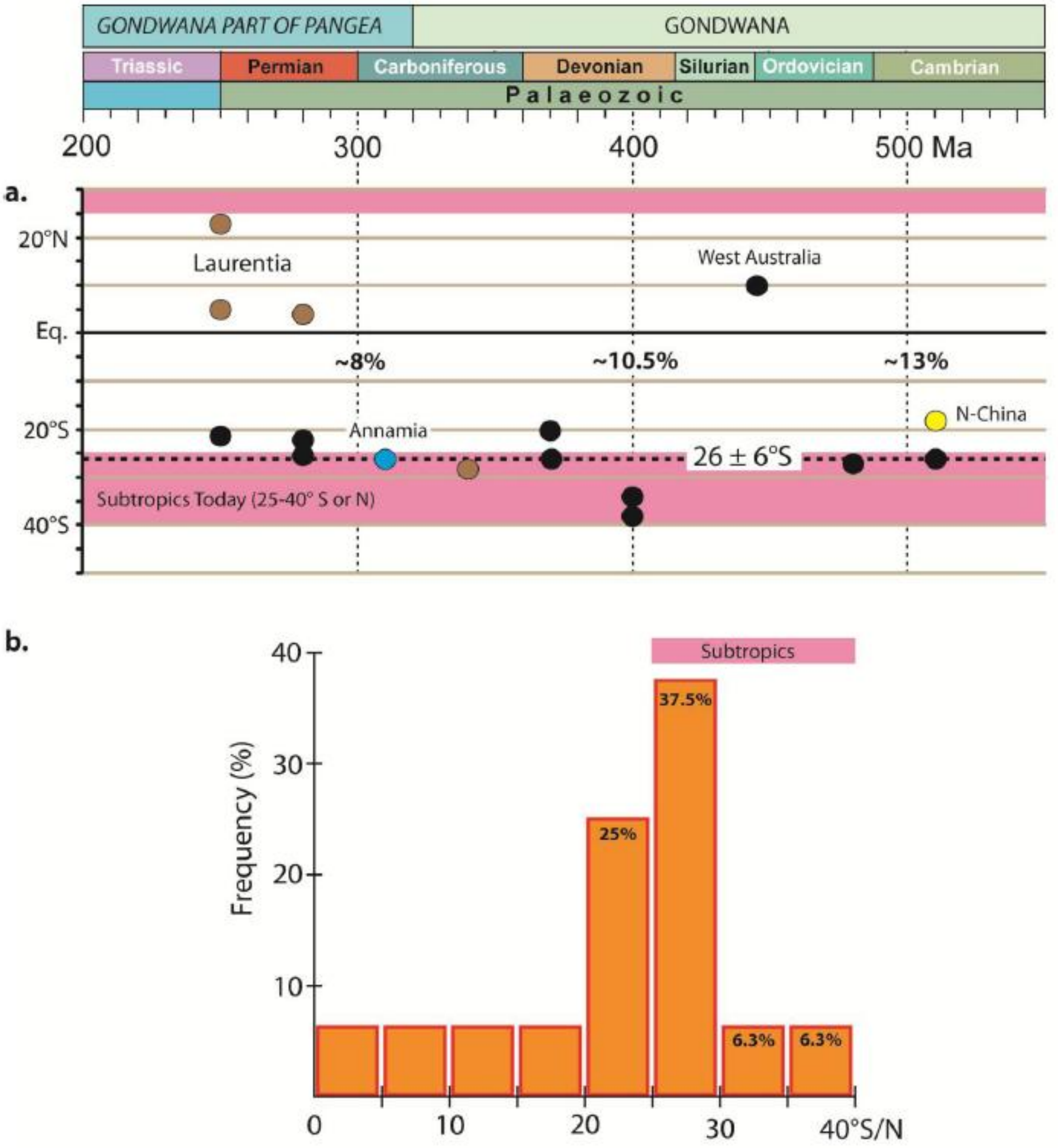

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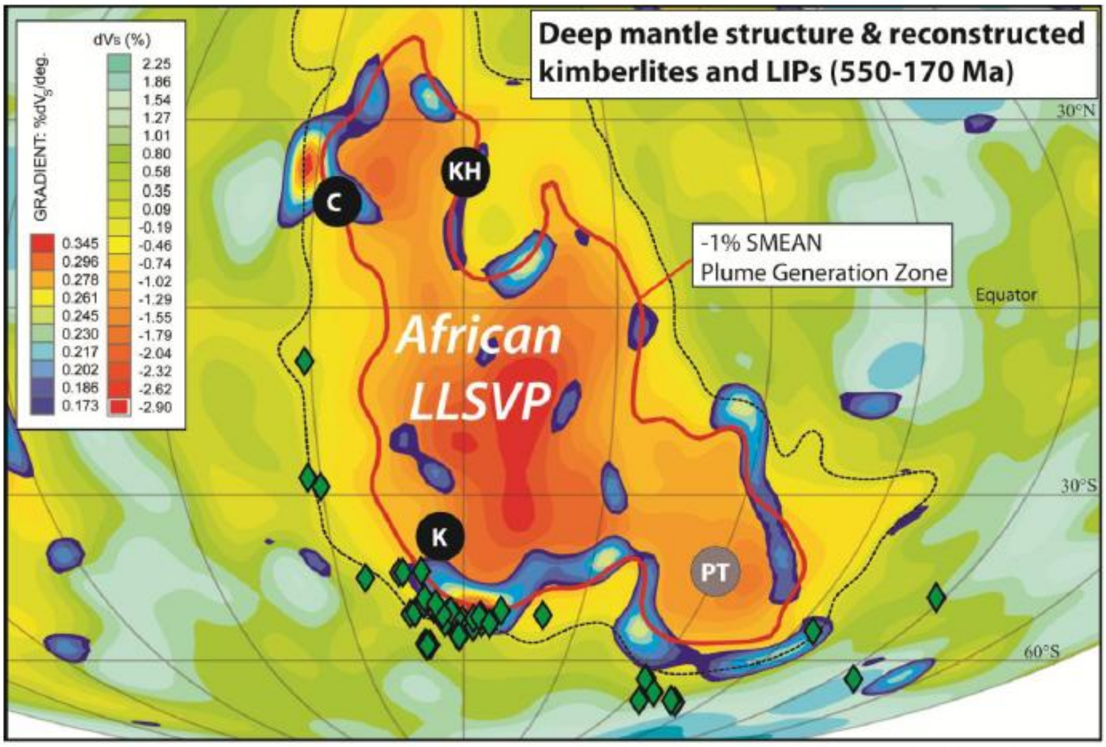

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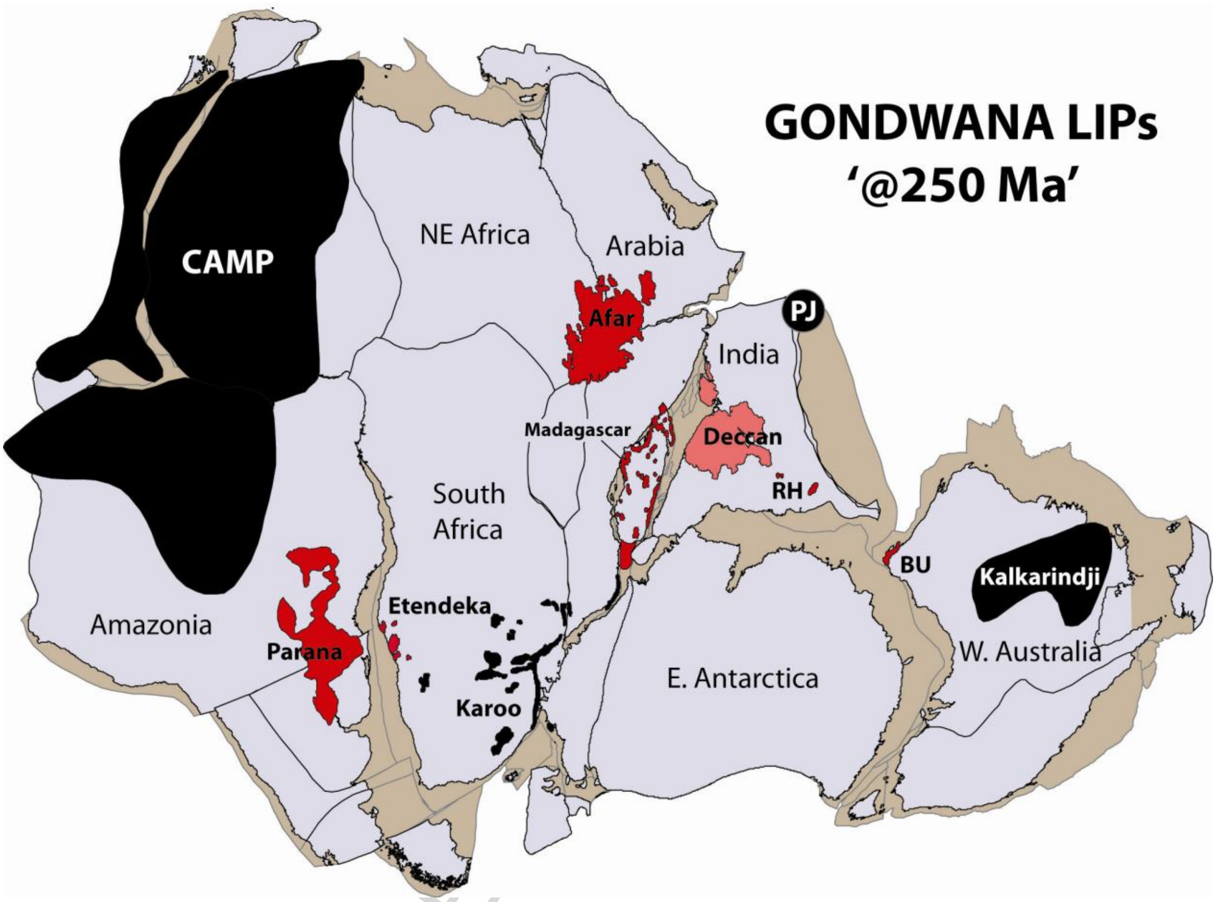

Graphical Abstract

Highlights

Gondwana is reviewed from the Late Neoproterozoic to its fragmentation in the Mesozoic.

New palaeogeographical maps show the distributions of land, shallow and deep shelves, oceans, reefs and other features.

Gondwanan large igneous provinces were derived from plumes linked to the African large low shear-wave velocity province.