Late Neoproterozoic and Early Cambrian palaeogeography: models and problems

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Abstract

We present two alternative sets of global palaeogeographic reconstructions for the time interval 615 – 530 Ma using competing high and low-latitude palaeomagnetic data subsets for Laurentia in conjunction with geological data. Both models demonstrate a genetic relationship between the collisional events associated with the assembly of Gondwana and the extensional events related to the opening of the Tornquist Sea, the eastern Iapetus Ocean (600 – 550 Ma), and the western Iapetus Ocean (after 550 Ma), forming a three-arm rift between Laurentia, Baltica, and Gondwana. The extensional events are probably plume-related, which is indicated in the reconstructions by voluminous mafic magmatism along the margins of palaeocontinents. The low-latitude model requires a single plume event, whereas the high-latitude model needs at least three discrete plumes. Coeval collisions of large continental masses during the assembly of Gondwana, as well as slab pull from subduction zones associated with those collisions, could have caused upper plate extension resulting in the rifted arm that developed into the eastern Iapetus Ocean and Tornquist Sea but retarded development of the western Iapetus Ocean. As a result, the eastern Iapetus Ocean and the Tornquist Sea opened before the western Iapetus Ocean.

The Late Neoproterozoic to Early Cambrian is one of the most enigmatic time intervals in the Earth's history. This interval includes: (i) one or more major global-scale glaciations (e.g., Kirschvink, 1992; Hoffman & Schrag, 2002; Hoffman, 2005), (ii) the explosion of Ediacaran and Cambrian fauna (Knoll, 1992; McCall, 2006), (iii) the final breakup of the Rodinia supercontinent by opening of the Iapetus ocean, Tornquist Sea and Palaeo-Asian ocean (e.g. Bingen et al., 1998; Cawood et al., 2001; Cawood & Pisarevsky, 2006), and (iv) the assembly of the Gondwana supercontinent by closing the Mozambique, Adamastor and Brasiliano oceans (Pimentel et al., 1999, Collins & Pisarevsky, 2005). Knowledge of palaeogeography is crucial to understanding these events and possible linkages between them. However, the palaeogeography of this time interval is unresolved (e.g., Hartz & Torsvik, 2002; Murphy et al., 2004; Collins & Pisarevsky, 2005; Cawood & Pisarevsky, 2006; McCausland et al., 2006; Tohver et al., 2006), caused, in part, by controversy over the North American palaeomagnetic data (McCausland & Hodych, 1998; Pisarevsky et al., 2000, 2001a; Meert & Van der Voo, 2001, Cawood & Pisarevsky, 2006) and the relatively poor palaeomagnetic database for other continents (Pisarevsky, 2005). These controversies have led to hypotheses such as Inertial Interchange True Polar Wander (IITWP, Kirschvink et al., 1997; Evans, 1998, Maloof et al., 2006), or an anomalously large non-dipole component of the Earth's magnetic field (e.g., McCausland et al., 2003).

Development of the Iapetus Ocean is one of the key palaeogeographic events during the late Neoproterozoic to early Palaeozoic time interval. Although there is broad agreement on the timing of the rift–drift stages in its development (e.g., Bingen et al., 1998; Cawood et al., 2001; Williams and Hiscott, 1987), understanding of the mechanisms that led its opening remain elusive. In order to gain insights into these mechanisms we utilize regional aspects of the latest Neoproterozoic palaeogeography that have already been published (Powell & Pisarevsky, 2002; Murphy et al., 2004; Collins & Pisarevsky, 2005; Cawood & Pisarevsky, 2006), with some modifications based on recently published data. We focus on the boundary forces affecting the unified Laurentia-Baltica-Amazonia-West Africa plate immediately prior to the onset of the development of Iapetus opening and on the distribution and orientation of dyke swarms in the heart of that plate.

The assembly of Gondwana is broadly coeval with the development of the Iapetus Ocean (Grunow et al., 1996; Cawood, 2005; Buchan & Cawood, in press). Models for Gondwana assembly have evolved dramatically through the last decade – from a relatively simple situation involving the collision of two large continents, East and West Gondwana (e.g., Dalziel, 1992) to a multi-stage assembly of a number of smaller continents and terranes (Collins & Pisarevsky, 2005). The latter model includes the accretion of fragments of the future enigmatic Avalonian continent onto the Gondwanan margin – an event that played an important role in Iapetus Ocean history (Murphy et al., 2004).

As the emphasis of this paper is on the potential relationship between the development of the Iapetus Ocean and the assembly of Gondwana, we do not consider other continental blocks, such as North and South China, Indochina, Tarim or Omolon. Only a preliminary model of the Siberian drift history is presented in view of ongoing studies on this continent and the controversy regarding its potential Laurentian connections (Pisarevsky & Natapov, 2003 and references therein).

Palaeomagnetic constraints for the latest Neoproterozoic – Early Cambrian drift history

Table 1 presents the latest palaeopoles for the interval 615 to 530 Ma with a reliability index Q ≥ 3 (Van der Voo, 1990), dominated by data from three continents – Laurentia, Baltica, and Australia. Data from Laurentia are relatively abundant, but also controversial in forming two groups of roughly similar reliability, one that supports a low-latitude position for Laurentia and the other that supports a high-latitude position between ~ 600 and 560 Ma. Discussion of this controversy is provided by Cawood & Pisarevsky (2006), but we emphasize that if all these late Neoproterozoic palaeopoles are primary and their ages are correctly assigned, then they are difficult to explain through normal plate tectonic mechanisms and processes such as IITPW or a more rapid style of plate tectonics may need to be invoked (e.g. Evans, 2003). An alternative explanation is that some of these data are misleading, being either the result of remagnetisation or incorrect deciphering of the palaeomagnetic signal (e.g. Hodych et al., 2004). We think that the question is still open and at present it is impossible to indicate any preference between the two datasets. Accordingly, we evaluate the tectonic significance of two alternative models for the latest Neoproterozoic – Early Cambrian palaeogeography, naming them as "high-latitude" and "low-latitude" models depending on the chosen set of Laurentian palaeopoles.

Palaeopoles for Baltica between 650 and 540 Ma (Table 1) are also incompatible with a smooth Apparent Polar Wander Path (APWP), and several alternative APWPs

Table 1. Late Neoproterozoic and Early Cambrian palaeomagnetic poles.

Object	Pole		dp/dm	Q	Age	Reference
	(ºN)	(ºE)	(º)		(Ma)	
Baltica						
Egersund Dykes, Norway	-28	232	15/18	3	616 ± 3	Storetvedt (1966); Bingen et al. (1998)
Egersund Dykes, Norway	-22	231	16/21	4	616 ± 3	Poorter (1972); Bingen et al. (1998)
Fen Complex, Norway	-56	330	7/10	4	583 ± 15	Meert et al. (1998)
Winter Coast sediments, Russia	25	312	2/4	6	555.3 ± 0.3	Popov et al. (2002); Martin et al. (2000)
Zolotitsa sediments, Russia	32	293	2/3	6	550 ± 5	Popov et al. (2005)
Verkhotina sediments, Russia	32	287	2/3	5	550 ± 1	Popov et al. (2005)
Zolotitsa sediments, Russia	28	290	4/4	6	550 ± 5	Iglesia Llanos et al., 2005
Volhynia lavas & tuffs*, Russia	34	306	-	4	551 ±4	Nawrocki et al. (2004); Compston et al. (1995)
Torneträsk Formation, Sweden	56	296	12/15	4	545 – 520	Torsvik and Rehnström (2001)
Laurentia						
Long Range Dykes (5 dykes)**	19	355	15/21	5	615 ± 2	Murthy et al. (1992); Kamo and Gower (1994)
Cloud Mountain Basalt	-5	352	2/4	3	605 ± 10	Deutsch & Rao (1977); Stukas & Reynolds (1974)
Callander Complex	46	301	6/6	5	575 ± 5	Symons & Chiasson (1991)
Catoctin Volcanics A	43	308	9/9	5	564 ± 9	Meert et al. (1994); Aleinikoff et al. (1995)
Catoctin Volcanics B	4	13	10/10	4	564 ± 9	Meert et al. (1994); Aleinikoff et al. (1995)
Sept Iles Intrusion A	-20	321	5/9	5	565 ± 4	Tanczyk et al. (1987); Higgins & van Breemen (1998)
Sept Iles Dykes B	59	296	10/10	4	<565 ± 4	Tanczyk et al. (1987); Higgins & van Breemen (1998)
Buckingham lavas	10	341	7/10	4	573 ± 32	Dankers and Lapointe (1981)
Johnnie Formation	10	342	5/10	4	570 ± 10	Van Alstine & Gillett (1979); Hodych et al. (2004)
Skinner Cove Formation	-15	337	9/9	4	550 ± 3	McCausland & Hodych (1998); Cawood et al. (2001)
Australia						
Yaltipena Fm., SA	-44	353	8/8	7	620–630	Sohl et al., 1999
Elatina Fm., SA	-39	6	9/9	7	600–620	Sohl et al., 1999
Elatina Fm., SA	-52	347	11/11	7	600–620	Schmidt and Williams, 1995
Elatina Fm., SA	-54	327	1/1	6	600–620	Schmidt et al., 1991
Elatina Fm., SA	-51	337	2/2	5	600–620	Embleton & Williams, 1986
Brachina Fm., SA	-33	328	16/16	6	590–610	McWilliams & McElhinny, 1980

Bunyeroo Fm., SA	-18	16	7/12	6	550–620	Schmidt & Williams, 1996
Albany Belt Dykes	-38	347	12/12	4	520–600	Harris and Li, 1995
Upper Arumbera Sandstone	-47	333	3/3	7	530–560	Kirschvink, 1978
Todd River Dolomite	-43	340	6/6	7	530–545	Kirschvink, 1978
Hawker Group	-21	15	9/9	5	530–545	Klootwijk, 1980
Antrim Plateau Volcanics	-9	340	17/17	4	520–570	McElhinny and Luck, 1970
India						
Bhander and Rewa Series	-47	33	6/6	5	530–560	McElhinny et al.,1978
Amazonia						
Puga Cap Carbonate	83	113	6/9	4	580–630	Trinidade et al., 2003
Gondwana						
Mean 540 -560 Ma pole	-10	330	7/7		540–560	McElhinny et al., 2003
Mean Early Cambrian pole	23	334	15/15		525–540	McElhinny et al., 2003
Siberia						
Bolshaya Lena redbeds	3	348	6/10	5	542–630	Pisarevsky et al., 2000
Minya Fm	34	217	9/15	3	542–630	Kravchinsky et al., 2001
Shaman Fm	32	251	7/14	4	542–630	Kravchinsky et al., 2001
Biryusa dykes	25	301	14/28	4	608–618	Metelkin et al., 2005
Kesyussa Fm, Olenek River	38	345	9/15	5	535–542	Pisarevsky et al., 1997
Lena River sediments	17	245	3/6	5	513–542	Kirschvink & Rozanov, 1984

Note: Q - Quality factor after Van der Voo (1990) and ranges from 0 to 7 with the later representing the highest quality data

* mean of two poles

** recalculated by Hodych et al. (2004)

have been debated (Popov et al., 2002). This issue is also discussed by Cawood & Pisarevsky (2006) but, importantly, a consistent group of ~550 – 555 Ma palaeopoles from both northern and southern Baltica (Popov et al., 2002, 2005; Iglesia Llanos et al., 2005; Nawrocki et al., 2004) and the coeval Skinner Cove Laurentian pole (McCausland & Hodych, 1998) undoubtedly indicate that Baltica was separated from Laurentia by ~ 550 Ma (cf. Cawood et al., 2001).

In Australia, palaeomagnetic information from a drill hole through strata in the Neoproterozoic Officer basin shows that Australia probably inhabited low latitudes from ~820 Ma until the Early Cambrian (Pisarevsky et al., 2001b; Pisarevsky, 2001; Pisarevsky et al., in press). From ~650 Ma to 550 Ma there is a swathe of palaeopoles, albeit with poor age constraints in many cases. Nevertheless, they form a consistent pattern that places Australia in low latitudes throughout this time, with the southern margin of the continent being near the equator at 600 Ma (Schmidt et al., 1991; Schmidt and Williams, 1995; Sohl et al., 1999). One pole from the Bunyeroo Formation, associated with the Acraman impact structure (Schmidt and Williams, 1996), falls outside the main group of palaeopoles. This could be evidence for rapid rotation of Australia, or IITPW, at ~590 Ma. However, impact-related rocks are not well understood palaeomagnetically. Also, no such deflection in palaeolatitude has been found so far by palaeomagnetic studies of Australian sedimentary sections in drill-holes (Pisarevsky et al., 2001b; Pisarevsky, 2001; Pisarevsky et al., in press).

There are no reliable late Neoproterozoic palaeomagnetic poles from the pre-assembly Congo or Kalahari blocks. The post-orogenic 547 Ma Sinyai dolerite intrudes the East African orogen and provides a pole for this part of proto-Gondwana (Meert and

Van der Voo, 1996; McElhinny et al., 2003). In India, palaeomagnetic data from the Bhander and Rewa series are only broadly constrained as Neoproterozoic or Early Cambrian (McElhinny et al., 1978; Evans, 2000). Recently Chirananda De (2003) reported the discovery of medusoid fossils of Ediacaran affinity at the base of Bhander Group, apparently below the strata sampled by McElhinny et al. (1978). If so, the time range for the Bhander pole might be narrowed to between 560 and 530 Ma.

The Puga cap carbonate palaeopole from Amazonia (Trindade et al., 2003) indicates low latitude for Amazonia around 600 Ma. This pole is suspiciously close to the present-day pole, so it may represent a recent remagnetisation. However, the possibility that this pole is correct and that São Francisco/Congo did not collide with Amazonia until after ~635 Ma along the Pampean–Araguaia Orogen cannot be discounted (Trindade et al. 2006).

The latest Neoproterozoic Siberian palaeomagnetic database is controversial. The poles are derived from sedimentary successions that are poorly dated (Table 1). The only reasonably well dated pole is from the 612 Ma Biryusa dykes (Metelkin et al., 2005; age from Gladkochub et al., 2006), but has been calculated from only three dykes. Possible reasons for the discordance of Siberian poles have been discussed previously (e.g., Pisarevsky et al., 1997; Smethurst et al., 1998), including IITWP (Evans, 1998). The reconstructions used in those discussions placed the northern margin of Siberia against the northern margin of Laurentia. Recently published Late Mesoproterozoic palaeomagnetic data (Gallet et al., 2000; Pavlov et al., 2000, 2002) suggest that the only permissible configuration at 1050 – 950 Ma involved Siberia separated from Laurentia with its southern margin facing towards the northern margin of Laurentia (Pisarevsky &

Natapov, 2003). On the other hand, the mid-Cambrian position of Siberia is supported by good palaeomagnetic evidence (Smethurst et al., 1998), implying that this continent rotated almost 180 degrees during the Neoproterozoic. Possible evidence of a rifting event in southern Siberia (Gladkochub et al., 2006) at ~ 740 Ma implies that this rotation occurred in Late Neoproterozoic times.

Key fragments of the latest Neoproterozoic – Early Cambrian palaeogeography

Iapetian realm

Among various published configurations of Laurentia, Baltica, and Amazonia (e.g., Dalziel, 1997; Hartz & Torsvik, 2002; Cawood et al., 2003; Pisarevsky et al., 2003), the reconstruction shown in Fig. 1 (after Pisarevsky et al., 2003) is the only one that fits both published palaeomagnetic data and geological constraints (Cawood & Pisarevsky, 2006). In particular, it is consistent with the existence of the long-lived Meso- to Neoproterozoic passive continental margin along the eastern and north-eastern edge of Baltica (Fig. 1, NB unless otherwise stated, all geographic references are in present coordinates), which was converted into an active margin between 600 and 550 Ma (e.g., Nikishin et al., 1996; Olovyanishnikov et al., 2000; Willner et al., 2001, 2003; Maslov & Isherskaya, 2002; Roberts & Siedlecka, 2002; Puchkov, 2003 and references therein). The reconstruction is also supported by the absence of any evidence for the Cambrian rifting and continental break-up along the Uralian margin of Baltica (Maslov et al., 1997) required by other models (e.g. Hartz & Torsvik, 2002).

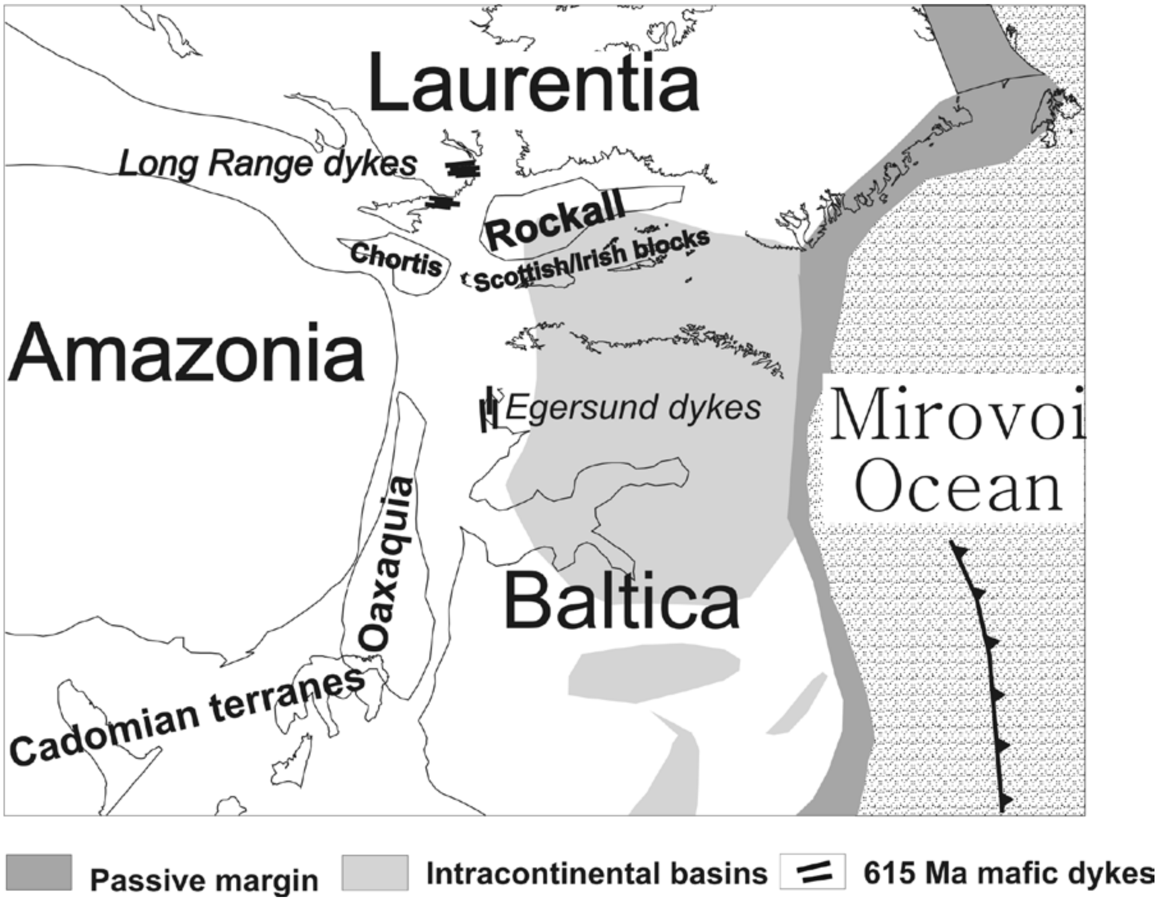

Fig. 1. Pre-Iapetian (~ 615 Ma) palaeogeographic reconstruction of Laurentia, Baltica, and Amazonia.

At the beginning of the Ediacaran (~ 630 – 600 Ma), Laurentia, Baltica, and Amazonia, probably still formed a single continental block – the last fragment of the Rodinia supercontinent (Fig. 1), which had begun to disperse between 800 and 750 Ma (Wingate & Giddings, 2000). The ~ 615 Ma Long Range (Laurentia) and Egersund (Baltica) mafic dyke swarms are both rift-related according to their geochemical characteristics (Bingen et al., 1998; Puffer, 2002) and are possible indicators for the onset of rifting that eventually resulted in the separation of Baltica from Laurentia and

Amazonia and the opening of both the eastern Iapetus Ocean and the Tornquist Sea (Kamo et al., 1989; Kamo & Gower, 1994; Bingen et al., 1998; Puffer, 2002). These magmatic events were followed by more widespread rift-related mafic magmatism at ~ 610 – 550 Ma along the eastern margin of Laurentia (Halliday et al., 1989; Cawood et al, 2001; Puffer, 2002), the Scandinavian margin of Baltica (e.g., Bingen et al., 1998; Roberts et al., 2004), and the south-western margin of Baltica (e.g., Compston et al., 1995; Poprawa et al., 1999; Shumlyanskyy & Andréasson, 2004; Elming et al., 2005). Keppie et al. (2006) reported a ca. 546 Ma plume-related mafic dyke swarm in Oaxaquia, Mexico, which in our reconstruction is in close juxtaposition to the western Ukrainian volcanic province of similar age (e.g., Keppie & Ramos, 1999; Shumlyanskyy & Andréasson, 2004; Elming et al., 2005).

The locations of these magmatic provinces and the trends of most of these dyke swarms are shown in Fig. 2. This configuration suggests three branches of a plume-related rifting event, with the plume centre at the triple point between Laurentia, Baltica and Amazonia. Two of these branches broadly coincide with the strikes of the Grenville and Sveconorwegian orogenic belts, suggesting a degree of inheritance, whereas the third arm, extending between west Baltica and northeast Laurentia, cuts across structural trends (Cawood et al., in press). In western Scandinavia, the rift-to-drift transition occurred around 600 – 580 Ma, followed by a developing passive continental margin (Bingen et al., 1998; Greiling et al., 1999; Siedlecka et al., 2004). In contrast, Cawood et al. (2001) reported that the rift-to-drift transition along the Laurentian mainland (juxtaposed to Amazonia in our reconstruction) occurred in Early Cambrian times, i.e. significantly later than in the western Scandinavia, implying failure of the first attempted rift between Laurentia and Amazonia, possibly indicated by the ~600 Ma Grenville dykes (e.g., Cawood et al., 2001). The second attempt in Early Cambrian time, however, was successful. For two other arms, between Baltica and Rockall/Greenland/Scottish blocks and between Baltica and Oaxaquia/Amazonia, the rift-to-drift transition was successfully completed ~600–580 Ma and led to the opening of the eastern Iapetus Ocean and the Tornquist Sea in Ediacaran times (Bingen et al., 1998; Greiling et al., 1999; Siedlecka et al., 2004).

In our scenario opening of the eastern Iapetus Ocean and Tornquist Sea was followed by the opening of the western Iapetus Ocean when Amazonia and Laurentia broke apart (Fig. 2). The configuration of the rifting zone between these two continents has been proposed by Thomas (2005, and references therein). A similar model has been proposed by Bingen et al. (1998), but their initial configuration places Baltica against East Greenland. The configuration shown in Figs. 1 and 2 is consistent with published palaeomagnetic data (Cawood & Pisarevsky, 2006, and references therein). Moreover, Greiling & Smith (2000) noted similarities between the Neoproterozoic sedimentary successions in Scandinavia and Scotland, and proposed a similar Laurentia-Baltica fit. Carbonatite intrusions in Baltica (the 584 Ma Fen and 589 Ma Alnø complexes, Meert et al, 1998; Walderhaug et al., 2003) and in Laurentia/Greenland at ~574 Ma (St. Honore, Doig & Barton, 1968) and ~600 Ma (Sarfartoq, Greenland , Larsen & Rex, 1992) also surround the centre of the suggested plume, supporting our reconstruction. Recent palaeomagnetic data showing that Baltica and Laurentia were well separated at ~ 550 Ma implies that the eastern Iapetus Ocean and the Tornquist Sea were already open by that time. This is in accord with the model shown in Fig.2.

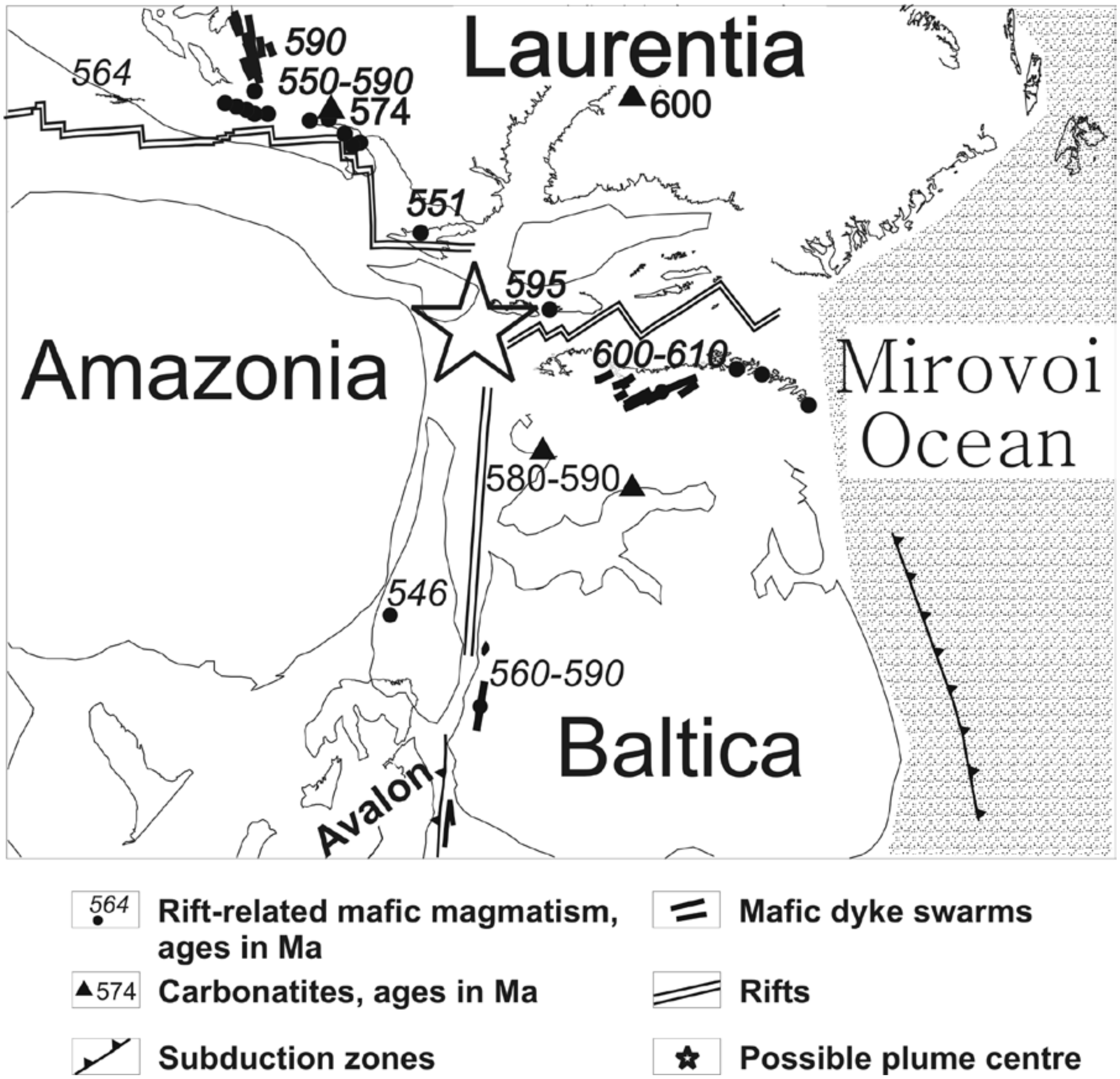

Fig. 2. Distribution of mafic magmatic rocks along incipient rifts between Laurentia, Baltica, and Amazonia at ~ 600 – 550 Ma.

Mirovoian realm

Mirovoi is the name given to the ocean that surrounded Rodinia (McMenamin & McMenamin, 1990), and we extend that definition here to denote the ocean that surrounded Laurentia-Baltica-Amazonia-West Africa immediately prior to Iapetan rifting. We now examine regional tectonothermal events that are coeval with the development of the Iapetus Ocean and evaluate potential geodynamic linkages between these two oceans.

The failure of the Laurentia-Amazonia rift was coeval with oblique subduction beneath the Avalonian–Cadomian belt (Fig. 2) along the northern margin of Amazonia/West Africa (Murphy et al., 2004). We suggest that there may be a geodynamic linkage between these events: subduction directed beneath Amazonia/West Africa could create a counter-force against this rifting of the southern margin of Laurentia. Additionally, the sinistral strike-slip component of Avalonian subduction (Murphy et al., 2000) may have provided an additive force for the rifting between Baltica and Amazonia/Oaxaquia (Fig. 2).

Along the north-eastern margin of Baltica, Roberts & Siedlecka (2002) proposed that in early Ediacaran time there was a subduction zone outboard of the Timanian part of the Baltican margin, directed oceanward (Fig. 2; see also figure 8 of Roberts & Siedlecka, 2002). On the eastern margin of Amazonia, the development of an arc along the margins of the São Francisco craton (Pimentel et al., 1999) indicates another subduction zone outboard of, and directed away from, Amazonia/West Africa. Taken together, the slab-pull forces associated with these subduction zones would also be consistent with the separation of Baltica from Amazonia/Oaxaquia.

Assembly of Gondwana

Hypotheses about the assembly of Gondwana in the Proterozoic (see Collins & Pisarevsky, 2005 for an overview) may be subdivided into three groups: (i) one rigid block, a part of a single supercontinent (e.g. Piper, 2000); (ii) two large Neoproterozoic continental masses – East Gondwana (India-Australia-Antarctica) and West Gondwana (Africa-South America) that amalgamated by the end of Neoproterozoic (e.g., McWilliams, 1981; Dalziel, 1992); and (iii) a number of separately drifting continental fragments that assembled by the latest Neoproterozoic – Early Palaeozoic (e.g., Meert et al., 1995; Torsvik et al., 2001; Powell & Pisarevsky, 2002; Pisarevsky et al., 2003; Collins & Pisarevsky, 2005; Trindade et al., 2006).

Trompette (1994, 1997) proposed the existence of a single West Africa-Amazonia-Rio de La Plata mega-craton in the Meso- and Neoproterozoic on the basis of similarities between the Proterozoic sedimentary successions of three blocks. However, he did not exclude the possibility of minor relative movements between its components. Some palaeomagnetic data indicate the possibility of shearing between Amazonia and West Africa (Onstott & Hargraves, 1981), but no conclusive evidence has been published.

Rio de La Plata is a poorly known craton, with only a few reliable palaeomagnetic data, that generally support an affinity to Amazonia (Trompette, 1994, 1997). Its Precambrian dimensions are similarly uncertain. The Rio de La Plata block, as depicted by Dalziel (1997), for example, included parts of the Pampean terrane as well as the southern extremity of the Guapore block. In contrast, Ramos (1988) envisaged a Pampean – Rio de La Plata collision at 600 – 570 Ma, although recent studies suggest that this could have happened even later, at 530 – 520 Ma (e.g., Trindade et al., 2006). Trompette (1994) considered the possibility of an Amazonian affinity for the southern Guapore cratonic extension. Pimentel et al. (1999) suggested a collision between the São

Francisco craton and the Paraná block between 790 and 750 Ma. In our reconstructions (Fig. 3), we propose three separate blocks: 1) Rio de La Plata *sensu stricto*, which includes basement to the NE and SW of Buenos Aires (Cingolani and Dalla Salda, 2000), but does not include the Luis Alves block and the southern extremity of the Guapore Block, 2) the Pampean terrane, and 3) the Paraná block.

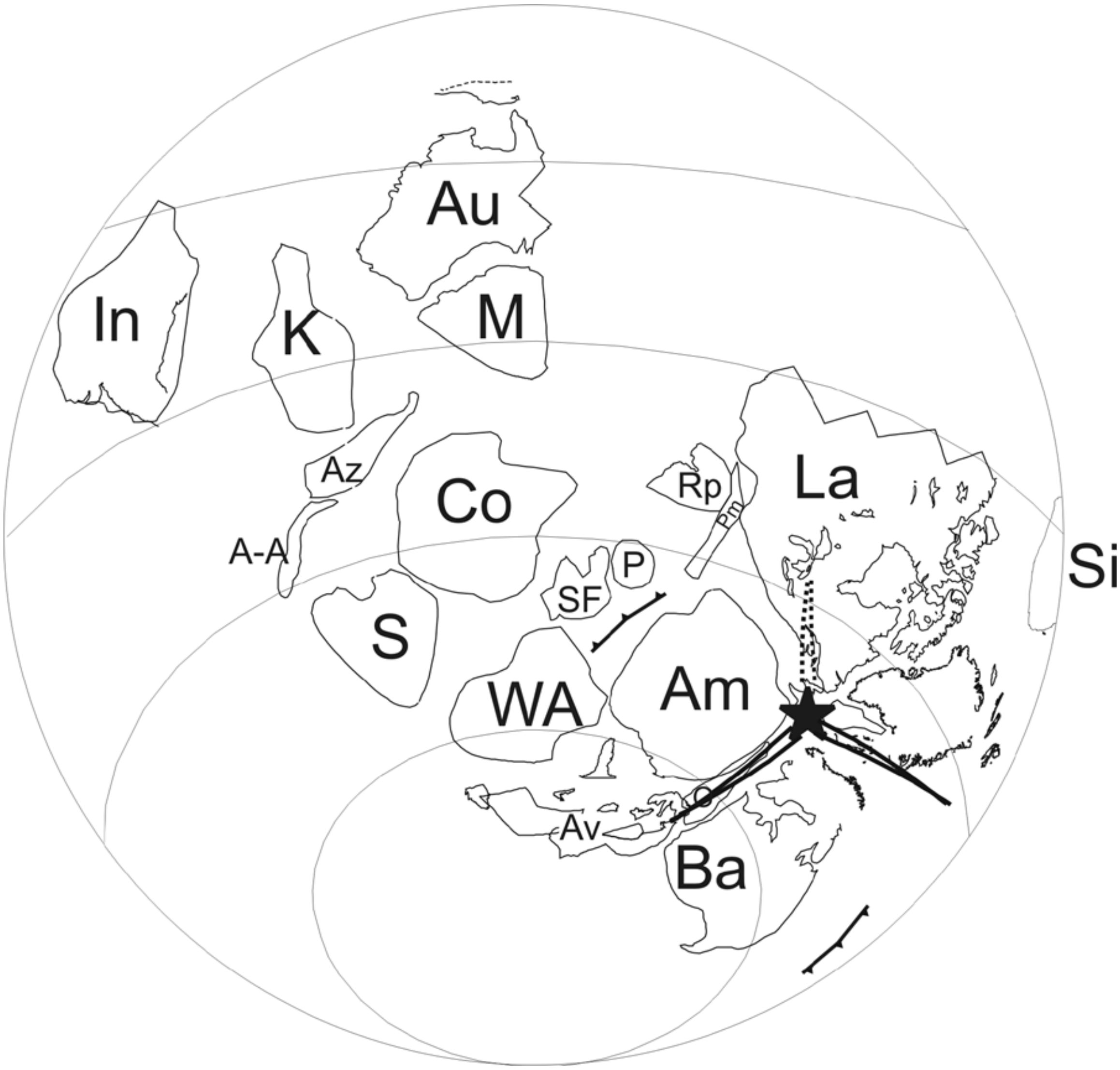

Fig.3. Palaeogeography at ~ 600 Ma. Star denotes the centre of a mantle plume. Successive rifts between Baltica and Laurentia, and between Baltica and Amazonia are shown with solid lines; failed rift between Laurentia and Amazonia is shown with dotted

lines. Subduction zones outboard of Baltica and Amazonia are directed in opposite directions creating an extensional strain by slab push forces. A-A – Afif-Abas; Am – Amazonia; Au – Australia; Av – Avalonia; Az – Azania; Ba – Baltica; Co – Congo; In – India; K – Kalahri; La – Laurentia; M – Mawson; O – Oaxaquia; P – Paraná; Pm – Pampean; Rp – Rio de La Plata; S – Saharan Metacraton; SF - São Francisco; Si – Siberia.

However, we must emphasize that to the best of our knowledge there are no palaeomagnetic data from Pampean terrane and Paraná block, so their inclusion in our reconstructions (Figs. 4 and 5) are open to dispute. We have generally followed the tectonic model of Ramos (1988) for the Rio de La Plata and Pampean blocks, keeping them in the vicinity of Laurentia, and the model of Pimentel et al. (1999) for Paraná – São Francisco collision. Recent palaeomagnetic data (Sánchez-Bettucci & Rapalini, 2002; Rapalini, 2006) suggest that Rio de La Plata was part of Gondwana by 550 Ma. These data together with other publications (i.e. Rapela et al., 2005) may indicate that our approach to a position and role of Rio de La Plata could be an oversimplification and more sophisticated model for this part of the palaeoglobe should be considered in the future, as it was previously suggested by Omarini et al., 1999).

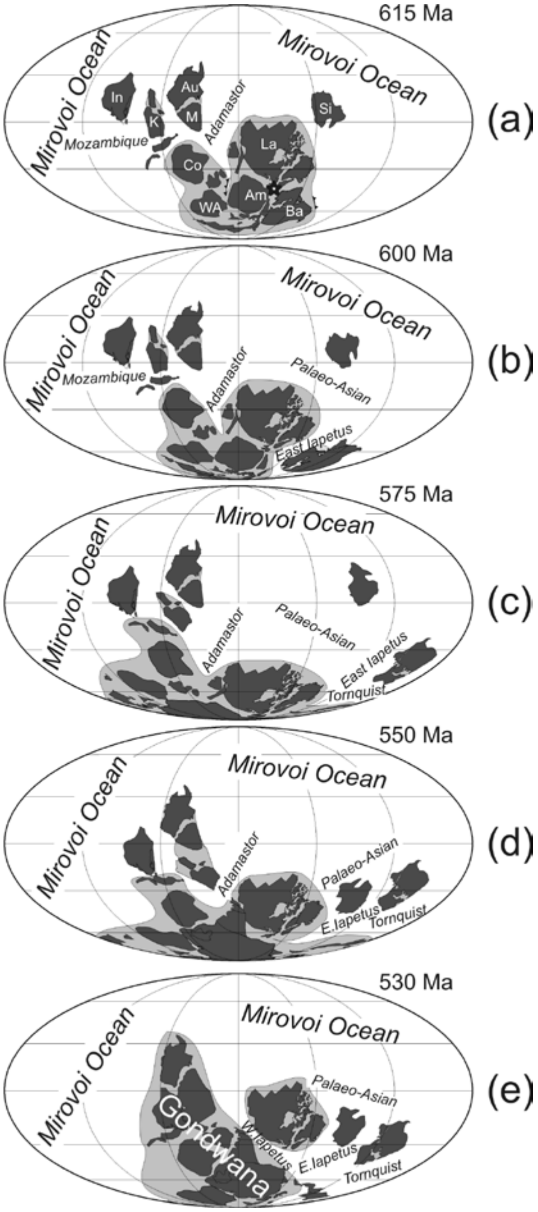

Fig. 4. Global palaeogeography between 615 Ma and 530 Ma, high-latitude model. Euler's rotation parameters are in Table 2.

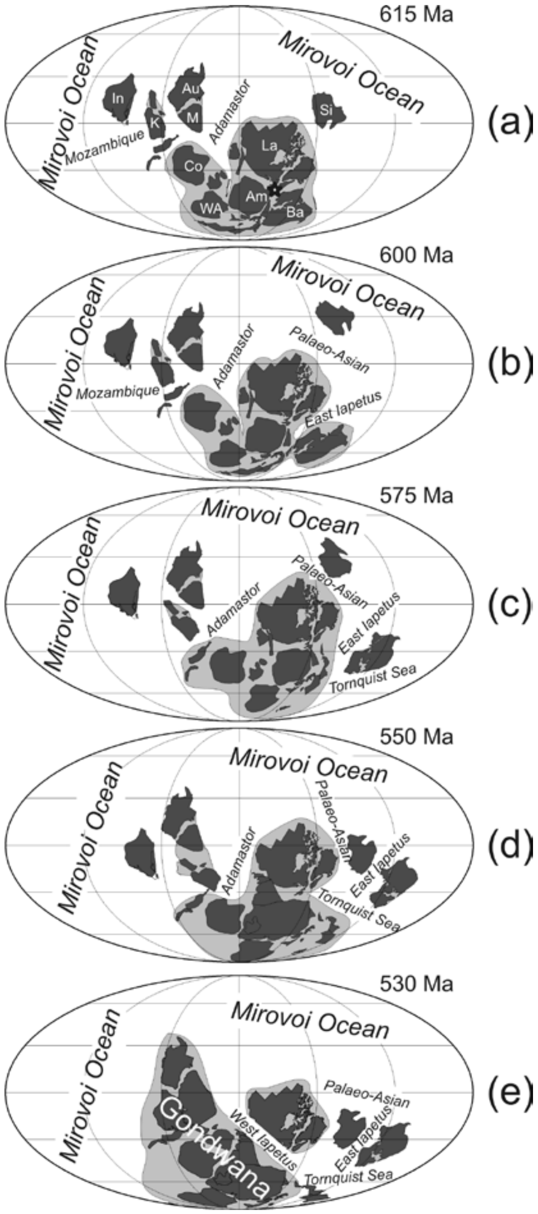

Fig. 5. Global palaeogeography between 615 Ma and 530 Ma, low-latitude model. Euler's rotation parameters are in Table 2.

The Congo/São Francisco craton, according to palaeomagnetic data (Meert et al., 1995; Wingate et al., 2005) and geological evidence (Kröner & Cordani, 2003; Collins & Pisarevsky, 2005), drifted as a separate continent independent of Rodinia. Along its northern margin, peak Neoproterozoic metamorphism accompanied by deformation is reported to have occurred at ~630 Ma both in Uganda (Leggo, 1974; Appel et al., 2004) and in the Oubanguides Belt of the Central African Republic (Pin and Poidevin, 1987). This deformation and metamorphism is interpreted to reflect the collision between this block and the poorly known Saharan Metacraton (Abdelsalam et al., 2002), which is composed of a number of pre-Neoproterozoic terranes separated by juvenile Neoproterozoic crust (Black et al., 1994; Caby, 2003; Liégeois et al., 2003). This collision is roughly coeval with the ~ 650-600 Ma collision between the São Francisco craton and Amazonia along the Brasília and Araguaia Belts (Pimentel et al., 1991; Moura and Gaudette, 1993; de Alvarenga et al., 2000; Pimentel et al., 2000; Valeriano et al., 2004). In the Dahomeyide Belt, between the collage of pre-Neoproterozoic terranes that make up Nigeria (Dada, 1998) and the West African craton, $^{40}Ar/^{39}Ar$ hornblende ages of 590-580 Ma in the suture-zone nappes provide a younger age constraint on the collisions of these terranes with the Congo craton (Attoh et al., 1997). Hence we suggest that the collision between Congo/São Francisco and Amazonia/West Africa occurred before 600 Ma – roughly coeval with the opening of the eastern Iapetus Ocean and of the Tornquist Sea, and with oblique subduction beneath Amazonia/West Africa that generated ca. 630-570 Ma peak magmatism in the Avalonian-Cadomian belt. Smaller continental blocks, such as Afif-Abas and Azania (Collins & Windley, 2002; Collins & Pisarevsky, 2005), also joined the Congo craton and the Sahara Metacraton roughly at the same time to form the bulk of the East African continent.

Separation between the Kalahari craton and the Congo craton during most of Neoproterozoic is indicated by Meso- to Neoproterozoic eclogites, arc volcanic rocks and ophiolites in the Zambezi Belt (Oliver et al., 1998; Johnson & Oliver, 2000; John et al., 2003; Johnson & Oliver, 2004), which characterize the presence of oceanic crust between them. The timing of the collision between Congo and Kalahari along the Irumide/Zambezi/Damara orogenic system is constrained by the age of the high-pressure metamorphism at 560 – 505 Ma (Vinyu et al., 1999; Jung et al., 2000; Hargrove et al., 2003; John et al., 2003; Johnson & Oliver, 2004; Goscombe et al., 2004). These and other constraints (Collins & Pisarevsky, 2005) suggest that Kalahari collided with Congo significantly later than the collision between Congo/Saõ Francisco and Amazonia (Prave, 1996).

The assumption of the integrity of East Gondwana (Australia/East Antarctica/India) was challenged by Fitzsimons (2000), who has shown that three sectors of the assumed Grenville-age orogenic belt in East Antarctica are significantly different in age and history and are separated from each other by Pan-African belts. Subsequent studies (see Collins & Pisarevsky, 2005 for an overview), including palaeomagnetic data (Torsvik et al., 2001), resulted in the proposal that the Australia/Mawson, India/Rayner and Kalahari/Dronning Maud Land blocks amalgamated shortly before (Powell & Pisarevsky, 2002), or during (Boger et al., 2001) the final amalgamation of Gondwana. In our reconstructions we suggest that this happened at ~ 530 Ma by the oblique collision of India with Australia/Mawson and East Africa and the coeval docking of

Kalahari/Dronning Maud Land to Congo along the Ambezi and Damara belts (Collins & Pisarevsky, 2005). At this time East Antarctica became a single continental block.

Table 2. Euler rotation parameters (to the absolute framework).

Craton/block/terrane	*High-latitude option (Fig.4)*			*Low-latitude option (Fig.5)*		
	Pole		**Angle**	**Pole**		**Angle**
	(°N)	(°E)	(°)	(°N)	(°E)	(°)
			615 Ma			
E.Antarctica (Mawson)	31.3	90.6	96.4	31.3	90.6	96.4
Dronning Maud Land	24.2	65.5	126.1	24.6	66.0	124.2
Australia	49.0	101.3	83.4	49.0	101.3	83.4
Congo	27.6	115.5	150.7	24.8	116.8	151.5
Kalahari	50.9	81.5	141.9	51.0	83.0	140.7
W.Africa	28.4	120.8	160.1	28.4	120.8	160.1
India	67.4	133.2	80.9	67.4	133.2	80.9
Siberia	62.1	-62.4	-163.9	62.1	-62.4	-163.9
Rockall	25.5	-118.5	-116.0	25.5	-118.5	-116.0
E.Avalon	8.1	115.5	162.5	8.1	115.5	162.5
Baltica	23.8	-92.6	-140.9	23.8	-92.6	-140.9
Rio de La Plata	22.4	88.0	154.2	22.4	88.0	154.2
São Francisco	23.3	86.6	149.0	21.0	88.4	147.0
Pampean	22.4	88.5	153.9	22.4	88.5	153.9
Paraná	23.3	86.6	149.0	21.0	88.4	147.0
Amazonia	23.5	92.5	157.0	23.5	92.5	157.0
Laurentia	15.4	-127.4	-106.8	15.4	-127.4	-106.8
Chortis	2.4	23.6	61.1	2.4	23.6	61.1
Oaxaquia	15.8	96.7	-151.2	15.8	96.7	-151.2
W.Avalon	10.9	85.5	159.1	10.9	85.5	159.1
Baffin Land	16.5	-124.3	-109.7	16.5	-124.3	-109.7
N.Alaska	34.9	-95.4	-159.0	34.9	-95.4	-159.0
Greenland	18.9	-118.7	-116.9	18.9	-118.7	-116.9

Table 2 (continue)

600 Ma

E.Antarctica (Mawson)	30.1	92.4	96.3	30.1	92.4	96.3
Dronning Maud Land	21.3	69.1	126.3	22.9	72.7	120.0
Australia	47.7	103.9	83.9	47.7	103.9	83.9
Congo	35.4	117.6	148.0	25.2	122.0	150.9
Kalahari	47.4	84.2	144.6	47.4	90.9	142.0
W.Africa	35.1	121.6	151.1	24.8	125.2	155.1
India	65.4	136.7	83.5	65.4	136.7	83.5
Siberia	53.4	-93.0	-127.7	68.2	-89.5	-129.1
Rockall	17.9	-122.5	-122.3	24.8	-120.4	-104.7
E.Avalon	14.2	115.2	154.7	3.9	119.0	155.7
Baltica	11.4	-103.2	-136.3	19.2	-103.3	-127.6
Rio de La Plata	31.3	85.7	157.0	22.7	92.1	149.9
São Francisco	31.3	86.4	152.6	22.7	93.2	145.8
Pampean	31.3	86.1	156.6	22.7	92.5	149.7
Paraná	31.3	86.4	152.6	22.7	93.2	145.8
Amazonia	31.3	90.5	154.3	22.3	96.8	148.6
Laurentia	8.6	-131.9	-115.4	13.1	-128.9	-95.9
Chortis	4.4	17.1	75.0	10.4	17.3	54.7
Oaxaquia	21.6	98.7	-155.3	11.1	99.0	-160.3
W.Avalon	18.0	84.2	158.2	9.4	89.2	149.0
Baffin Land	9.5	-128.7	-117.5	14.6	-125.6	-98.5
N.Alaska	27.1	-97.8	-159.5	36.3	-97.4	-148.1
Greenland	11.6	-122.9	-123.4	17.8	-119.9	-105.5

575 Ma

E.Antarctica (Mawson)	28.1	95.4	96.3	28.1	95.4	96.3
Dronning Maud Land	16.0	86.3	112.9	19.9	88.2	110.4
Australia	45.3	107.8	84.9	45.3	107.8	84.9
Congo	48.6	123.0	136.9	20.0	132.0	146.7
Kalahari	37.2	102.6	145.4	39.4	106.7	144.5

Table 2 (continue)

W.Africa	46.7	123.3	137.0	18.2	132.1	147.1
India	62.6	144.9	88.3	62.6	144.9	88.3
Siberia	15.5	-119.2	-98.4	37.6	-126.0	-93.4
Rockall	6.3	-128.1	-134.9	23.5	-124.3	-86.0
E.Avalon	18.1	106.0	135.0	9.6	-60.5	-131.4
Baltica	9.0	59.2	139.8	4.6	-118.6	-109.6
Rio de La Plata	44.3	82.4	154.2	20.8	100.8	135.6
São Francisco	45.8	85.2	152.3	21.6	103.7	136.2
Pampean	44.3	82.6	153.9	20.7	101.0	135.5
Paraná	45.8	85.2	152.3	21.6	103.7	136.2
Amazonia	44.3	86.3	150.9	19.9	104.3	135.0
Laurentia	1.4	41.8	131.7	8.3	-132.0	-78.0
Chortis	6.5	9.8	99.3	26.8	2.9	48.3
Oaxaquia	33.4	100.7	-163.7	6.0	101.4	-177.5
W.Avalon	25.3	73.7	145.4	4.3	90.3	115.0
Baffin Land	1.0	45.0	132.6	10.7	-128.3	-80.2
N.Alaska	14.1	-101.2	-161.4	38.8	-101.4	-130.1
Greenland	0.3	-128.9	-136.2	15.6	-122.1	-86.5

550 Ma

E.Antarctica (Mawson)	23.8	100.9	91.8	23.8	100.9	91.8
Dronning Maud Land	18.7	100.9	102.2	18.7	100.9	102.2
Australia	40.5	116.2	82.7	40.5	116.2	82.7
Congo	42.0	126.2	137.9	25.1	133.3	142.4
Kalahari	33.4	118.2	144.6	33.4	118.2	144.6
W.Africa	39.3	122.2	136.0	22.5	130.4	138.8
India	58.3	162.0	100.0	58.3	162.0	100.0
Siberia	3.7	47.7	151.5	1.0	-128.3	-118.7
Rockall	13.5	-124.7	-121.0	23.6	-122.8	-90.4
E.Avalon	14.9	104.3	129.8	0.8	-65.6	-122.1
Baltica	10.9	52.7	127.4	8.9	48.0	122.1
Rio de La Plata	38.1	87.7	144.2	25.2	100.6	131.4

Table 2 (continue)

São Francisco	41.0	90.6	147.6	27.4	103.2	136.6
Pampean	38.1	87.7	144.2	25.2	100.6	131.4
Paraná	41.0	90.6	147.6	27.4	103.2	136.6
Amazonia	38.1	87.7	144.2	25.2	100.6	131.4
Laurentia	4.0	-134.2	-115.6	9.3	-130.7	-82.3
Chortis	0.5	2.7	77.8	14.9	-11.7	51.1
Oaxaquia	26.8	96.1	-168.3	11.3	98.9	178.5
W.Avalon	23.9	72.0	138.0	14.5	83.6	115.9
Baffin Land	4.9	-130.9	-117.2	11.5	-127.1	-84.6
N.Alaska	23.6	-99.3	-155.0	38.1	-99.9	-134.1
Greenland	7.1	-124.9	-122.2	15.9	-121.1	-91.0

530 Ma

E.Antarctica	19.4	107.9	91.5	19.4	107.9	91.5
Dronning Maud Land	21.8	107.5	94.1	21.8	107.5	94.1
Australia	35.2	124.1	85.5	35.2	124.1	85.5
Congo	32.3	125.9	140.1	32.3	125.9	140.1
Kalahari	32.3	125.9	140.1	32.3	125.9	140.1
W.Africa	29.5	122.7	137.6	29.5	122.7	137.6
India	51.0	165.2	126.2	51.0	165.2	126.2
Siberia	5.8	-127.5	-135.6	5.8	-127.5	-135.6
Rockall	24.4	-119.1	-106.2	24.4	-119.1	-106.2
E.Avalon	5.0	106.6	128.5	5.0	106.6	128.5
Baltica	0.8	67.8	105.1	2.1	58.6	118.1
Rio de La Plata	29.5	91.1	137.4	29.5	91.1	137.4
São Francisco	32.2	93.7	141.5	32.2	93.7	141.5
Pampean	29.5	91.1	137.4	29.5	91.1	137.4
Paraná	32.2	93.7	141.5	32.2	93.7	141.5
Amazonia	29.5	91.1	137.4	29.5	91.1	137.4
Laurentia	12.9	-127.8	-97.6	12.9	-127.8	-97.6
Chortis	5.5	0.9	64.3	5.5	0.9	64.3
Oaxaquia	19.2	96.6	-171.5	19.2	96.6	-171.5
W.Avalon	16.4	75.2	127.3	16.4	75.2	127.3

Table 2 (continue)

Baffin Land	14.3	-124.5	-100.3	14.3	-124.5	-100.3
N.Alaska	35.9	-96.2	-149.2	35.9	-96.2	-149.2
Greenland	17.5	-118.8	-107.2	17.5	-118.8	-107.2

Avalonian and related terranes

Avalonia and Cadomian are two of a group of terranes, collectively referred to as peri-Gondwanan. On the basis of faunal, lithostratigraphic, geochemical, and palaeomagnetic data they are traditionally interpreted as remnants of the northern (Amazonian and West African) Gondwanan margin in the Neoproterozoic and Early Palaeozoic (Theokritoff, 1979; Van der Voo, 1988; Murphy and Nance, 1989; Cocks and Fortey, 1990; Keppie, 1993; McNamara et al., 2001; Murphy et al., 2002, 2004; Fortey and Cocks, 2003; Collins and Buchan, 2004), although temporary seaways may have separated Avalonia from Amazonia/West Africa (Landing, 1996, 2005). Peri-Gondwanan terranes are characterized by Neoproterozoic magmatism that records a history of subduction beneath the Amazonian/West African margin (e.g., O'Brien et al., 1983; Keppie, 1993; Murphy et al., 1990; Nance et al., 1991; Egal et al., 1996; Linnemann et al., 2000; von Raumer et al., 2002). Some peri-Gondwanan terranes, such as Avalonia, and Carolinia (Hibbard, 2000; Hibbard et al., 2002), were rifted from Amazonia/West Africa by the Early Ordovician and were subsequently involved in Palaeozoic and Mesozoic orogenesis. As a result, they are preserved as a collection of suspect terranes in the younger orogenic belts of Europe and North America. Avalonia stretches from New England to southeastern Newfoundland (O'Brien et al., 1983; Murphy and Nance, 1989, 1991; Keppie et al., 1991) and includes southeastern Ireland (Max and Roddick, 1989) and southern Britain (Tucker and Pharoah, 1991; Gibbons and Horak, 1996). Other peri-Gondwanan terranes occur in the Armorican massif (Cadomia) of northwestern France (Egal et al., 1996; Strachan et al., 1996), the Iberian peninsula (Quesada, 1990; Eguíluz, et al., 2000; Fernandez-Suarez et al., 2000), isolated inliers in Germany and the Czech Republic (e.g., Bohemian Massif, Linnemann et al., 2000; Zulauf et al., 1999), and recently recognized vestiges in the Alpine belt (Neubauer, 2002; von Raumer et al., 2002).

Sm-Nd isotopic data indicate that early arc-related complexes of Avalonia probably formed outboard of the Amazonian/West African margin within the Mirovoi Ocean, whereas their subsequent metamorphism is interpreted as recording their accretion to this margin (Murphy et al., 2000, 2004; 2006; Nance et al., 2002). In contrast, coeval Cadomian arc magmatism is attributed to melting of the West African craton.

At about 635 Ma, Avalonian-Cadomian voluminous Andean-style arc-related activity commenced broadly synchronously along the Amazonian/African margin. Arc-related rocks typically include calc-alkaline mafic to felsic volcanics, coeval plutons and pull-apart sedimentary basin deposits which contain detritus derived from the arc. Subduction was oblique and had a sinistral component (Nance and Murphy, 1990; Murphy and Nance, 1989; Murphy et al., 1999; Keppie et al., 2003). However, the termination of arc magmatism was diachronous from 590 to 540 Ma (Murphy et al., 1999, 2000; Nance et al, 2002; Keppie et al., 2003), and is marked by the progressive development of an intracontinental strike-slip regime that is interpreted as recording ridge-trench collision, analogous to the Oligocene collision between western North America and the East Pacific Rise and the diachronous initiation of the San Andreas transform margin (Murphy and Nance, 1989; Murphy et al., 1999; Nance et al., 2002).

Middle America Terranes

In addition to these terranes, several crustal blocks in Middle America contain assemblages with Early Palaeozoic fauna that suggest an origin along the northern Gondwanan margin (Keppie and Ramos, 1999). In the Neoproterozoic-early Palaeozoic, these terranes are thought to have lain along either the northern or the western margin of Amazonia (Keppie & Ramos 1999; Keppie & Ortega-Gutiérrez 1999; Keppie *et al.* 2003). In our reconstructions we choose the first interpretation, which places Oaxaquia between Amazonia and Baltica, because it is supported by the palaeomagnetic data (Ballard *et al.* 1989) (Figs. 1 and 2). The Yucatan block is thought to have been contiguous with the Florida basement (Suwannee terrane, probably part of Avalonia, Heatherington et al, 1996). The Grenville-age basement of Oaxaquia and the Chortis block is isotopically transitional between that of the Grenville Belt in Laurentia and basement massifs of Grenville age in Colombia (Ruiz et al., 1999) and is attributed to mixing of juvenile Grenville and Archaean sources (Cameron *et al.* 2004).

The basement rocks of Oaxaquia are best known. They consist of: (1) a metavolcanic-metasedimentary juvenile arc sequence of uncertain age; (2) a *c*. 1140 Ma, bimodal, within-plate intrusive suite that was deformed and metamorphosed at *c*. 1100 Ma; (3) a *c*. 1012 Ma anorthosite-gabbro that was deformed and metamorphosed in the granulite facies at *c*. 980–1104 Ma; and (4) *c*. 920 Ma post-tectonic calc-alkaline plutonic rocks (Keppie *et al.* 2001; Solari *et al*. 2003; Ortega-Obregón *et al.* 2003). This sequence of magmatic and metamorphic events is broadly consistent with those of the Sveconorwegian orogeny in Baltica (e.g. Gorbatschev & Bogdanova 1993).

615 – 530 Ma palaeogeography

We choose 615 Ma as a starting point for our reconstructions for the following reasons: (i) the Long Range dykes in Laurentia and Egersund dykes in Baltica are precisely dated at 615 Ma and are indicators of the beginning of rifting events in these areas; (ii) there are several reasonably reliable ($Q \geq 3$, Table 1) published palaeopoles of this age (Murthy et al., 1992; Kamo & Gowler, 1994; Storetvedt, 1966; Poorter, 1972; Bingen et al., 1998; Embleton & Williams, 1986; Schmidt et al., 1991; Schmidt & Williams, 1995; Sohl et al., 1999; Metelkin et al., 2005), so that the relative locations of Laurentia, Baltica, Australia, India, and Siberia are reasonably well constrained; (iii) our reconstructions for 615 Ma are identical for both high- and low-latitude models for Laurentia (Fig. 4a and 5a). These diagrams are slightly simplified versions of the reconstruction shown in Fig. 3. We did not use the Amazonian Puga cap carbonate pole (Trindade et al., 2003) and the Australian Bunyeroo pole (Schmidt & Williams, 1996) for the reasons outlined earlier. The ages of the Siberian poles are poorly constrained and so we urge caution in interpreting the movement of Siberia in Figures 4 and 5. Thus the size and shape of the Palaeo-Asian Ocean are schematic.

High-latitude model (Fig. 4)

Laurentian palaeopoles from Table 1 used for this model are: (i) Long Range dykes (data recalculated by Hodych et al., 2004), (ii) Callander Complex, (iii) Catoctin Volcanics A, (iv) Sept Iles Dykes B, and (v) Skinner Cove Formation.

Laurentia/Amazonia/West Africa moved gradually to the south, Baltica generally followed them initially, but started to separate at ~ 600 Ma through the opening of the eastern Iapetus Ocean and the Tornquist Sea (Fig. 4a, b). Australia/Mawson remained at equatorial latitudes. A number of collisions occurred that culminated in the formation of Gondwana. Congo/São Francisco collided with Amazonia, closing the Brasiliano Ocean by ~ 570 Ma. The final collision of the Sahara Metacraton with the Tuareg block and West Africa to form the northern part of Gondwana was completed by ~ 600 Ma (Attoh et al., 1997). Kalahari drifted southeastwards closing the Adamastor Ocean and collided with Congo and Rio de La Plata by 530 Ma. India collided obliquely with Australia/Mawson and East Africa at about the same time. These collisional events could have created southward-directed stresses on the rest of Gondwana, inhibiting it from moving northwards with Laurentia after 550 Ma. This possibly caused Laurentia's separation from Gondwana by opening of the western Iapetus Ocean. Subduction beneath Amazonia/West Africa started at around 600 Ma, creating supportive stresses for the opening of the Tornquist Sea and opposing rifting between Laurentia and Amazonia.

Puffer (2002) suggested that one or two mantle plumes caused the 615–550 Ma mafic magmatism along the east Laurentian margin. The high-latitude model is inconsistent with either of the proposed plumes, if we assume that they were initiated below the asthenosphere. The suggested plume head(s) should occur near 30°S at 615 Ma, near the south pole at 575 Ma and at 60°S at 550 Ma, so at least three discrete plume events are necessary. The migration of Laurentia to high latitudes implied by this model would predict a 615-–575 Ma plume track across Laurentia that also would have influenced the Ediacaran-aged passive margin successions deposited along the western margin (modern coordinates). There is no evidence of this plume track and subsidence curves calculated for these successions (Bond et al., 1984) do not show evidence for a thermal perturbation.

Low-latitude model (Fig. 5)

Laurentian palaeopoles we used for this model are: (i) Long Range dykes (as above), (ii) Cloud Mountain Basalt, (iii) Catoctin Volcanics B, (iv) Sept Iles Intrusion A , (v) Buckingham Lavas, (vi) Johnnie Formation, and (vii) Skinner Cove Formation.

In this model, Laurentia remained at equatorial latitudes between 615 and 530 Ma and Laurentia/Amazonia/West Africa rotated about 40 degrees anticlockwise. This rotation was possibly connected to the collision of Congo/São Francisco with Amazonia/West Africa and the closure of the Brasiliano Ocean. Baltica rifted away from Laurentia and Amazonia after ~ 600 Ma, but not as rapidly as in the high-latitude model. Gondwana assembly occurred in a similar way to the high-latitude model, but with less motion of West Gondwana and, correspondingly, slower relative movement of Kalahari and India with respect to West Gondwana. Nevertheless, docking of Kalahari and India probably still created enough force for the southward motion of Gondwana, which in this scenario facilitated the opening of the western Iapetus Ocean by separation of Gondwana from Laurentia.

As Laurentia drifted only a small distance between 615 and 530 Ma in the low-latitude model, it is consistent with the plume hypothesis of Puffer (2002), requiring only a single stationary plume.

The relationship between Gondwanan and Iapetian events

Regardless of the chosen scenario of the palaeogeographical development between 615 and 530 Ma, it is probable that major events are genetically related. The opposing directions of the subduction outboard of the north-eastern margin of Baltica (Roberts & Siedlecka, 2002) and outboard of the south-western margin of Amazonia (indicated by the presence of a Neoproterozoic magmatic arc on the northwestern margin of the Sao-Francisco-Congo craton, Pimentel et al., 1999) would have necessitated the existence of an extensional regime between these two continents (Figs 4a and 5a). This extensional strain may have supported the rifting along the Tessyer-Tornquist margin of Baltica caused by the coeval mantle plume (Figs 4a and 4a).

The oblique docking of Avalonia to the northern margin of Gondwana at 650 Ma followed by the oblique subduction which produced 630–570 Ma arc magmatism (Murphy et al., 2004), together with the final docking of Congo/São Francisco to Amazonia (Collins & Pisarevsky, 2005) resulted in a combined force on Amazonia inhibiting its separation from Laurentia (Figs 4b,c and 5b,c). As a result, Baltica drifted away from Laurentia/Amazonia and the eastern Iapetus and the Tornquist Sea opened, but the rifting arm between Laurentia and Amazonia failed (Figs 4b,c and 5b,c). Another plume event near the eastern Laurentian margin (in the high-latitude margin), or the same one (in the low-latitude model), as was suggested by Puffer (2002), is supported by the southward-directed stresses on Gondwana caused by the final docking of Kalahari and India from the north and resulted in the separation between Laurentia and Gondwana and in the opening of the western Iapetus Ocean (Figs 4d,e and 5d, e).

Both sets of palaeogeographic reconstructions (Figs 4 and 5) also show the drift of Siberia, permissible within the age uncertainties of published palaeomagnetic data (Table 1). However, this part of our models should be considered as preliminary due to a number of the ongoing studies in Siberia which may cause significant changes.

Conclusions

Two alternative models for the latest Neoproterozoic – Early Palaeozoic global palaeogeography are based on two subsets of the Laurentian palaeomagnetic poles. These groups of palaeopoles are of similar reliability, and new studies are required to distinguish between these models. Alternatively, a non-uniformitarian approach, such as IITPW or non-dipole field could be invoked to explain the results. Both models suggest a geodynamic relationship between the amalgamation of Gondwana and the opening of the Iapetus Ocean. Although both models suggest plume-related rifting between Laurentia, Baltica and Gondwana, the low-latitude model requires a single plume, whereas the high-latitude model needs more than one plume. These rifting events are indicated by voluminous mafic magmatism on the opposite margins of these palaeocontinents and by the rift-drift transition in the sedimentary successions along these margins. Another difference between the two models is the manner of the opening of the western Iapetus Ocean - through the northward movement of Laurentia in the high-latitude model and through the southward movement of Gondwana in the low-latitude model. The openings of the eastern and western Iapetus Ocean and the Tornquist Sea are genetically related to the subduction processes around Amazonia/Baltica and the collisional dockings of Congo, Kalahari, and India that resulted in the assembly of Gondwana.

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