Geological Society, London, Special Publications

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Geological Society, London, Special Publications 2009; v. 327; p. 371-404
doi:10.1144/SP327.16

Notes

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Abstract: Palaeomagnetic apparent polar wander (APW) paths from the world's cratons at 1300–700 Ma can constrain the palaeogeographic possibilities for a long-lived and all-inclusive Rodinia supercontinent. Laurentia's APW path is the most complete and forms the basis for superposition by other cratons' APW paths to identify possible durations of those cratons' inclusion in Rodinia, and also to generate reconstructions that are constrained both in latitude and longitude relative to Laurentia. Baltica reconstructs adjacent to the SE margin of Greenland, in a standard and geographically 'upright' position, between *c.* 1050 and 600 Ma. Australia reconstructs adjacent to the pre-Caspian margin of Baltica, geographically 'inverted' such that cratonic portions of Queensland are juxtaposed with that margin via collision at *c.* 1100 Ma. Arctic North America reconstructs opposite to the CONgo + São Francisco craton at its DAmaride–Lufilian margin (the 'ANACONDA' fit) throughout the interval 1235–755 Ma according to palaeomagnetic poles of those ages from both cratons, and the reconstruction was probably established during the *c.* 1600–1500 Ma collision. Kalahari lies adjacent to Mawsonland following collision at *c.* 1200 Ma; the Albany–Fraser orogen continues along-strike to the Sinclair-Kwando-Choma-Kaloma belt of south-central Africa. India, South China and Tarim are in proximity to Western Australia as previously proposed; some of these connections are as old as Palaeoproterozoic whereas others were established at *c.* 1000 Ma. Siberia contains a succession of mainly sedimentary-derived palaeomagnetic poles with poor age constraints; superposition with the Keweenawan track of the Laurentian APW path produces a position adjacent to western India that could have persisted from Palaeoproterozoic time, along with North China according to its even more poorly dated palaeomagnetic poles. The Amazonia, West Africa and Rio de la Plata cratons are not well constrained by palaeomagnetic data, but they are placed in proximity to western Laurentia. Rift successions of *c.* 700 Ma in the North American COrdillera and BRAsiliano-Pharuside orogens indicate breakup of these 'COBRA' connections that existed for more than one billion years, following Palaeoproterozoic accretionary assembly. The late Neoproterozoic transition from Rodinia to Gondwanaland involved rifting events that are recorded on many cratons through the interval *c.* 800–700 Ma and collisions from *c.* 650–500 Ma. The pattern of supercontinental transition involved large-scale dextral motion by West Africa and Amazonia, and sinistral motion plus rotation by Kalahari, Australia, India and South China, in a combination of introverted and extroverted styles of motion. The Rodinia model presented here is a marked departure from standard models, which have accommodated recent discordant palaeomagnetic data either by excluding cratons from Rodinia altogether, or by decreasing duration of the supercontinental assembly. I propose that the revised model herein is the only possible long-lived solution to an all-encompassing Rodinia that viably accords with existing palaeomagnetic data.

Motivation

A full understanding of ancient orogens requires an accurate palaeogeographic framework. By their nature, orogens destroy prior geologic information (via metamorphism, erosion and subduction) and thus challenge our efforts to reconstruct their histories. Reconstructing supercontinents is the greatest palaeogeographic challenge of all, combining patchworks of this partially destroyed information from a series of orogens with a complementary record of rifting and passive margin development, and with quantitative kinematic data. The latter record is best constrained by palaeomagnetic information: for Pangaea by seafloor magnetic anomalies with a supportive record from continent-based palaeomagnetic studies (e.g. Torsvik *et al.* 2008), and for times before Pangaea thus far only by the labourious continent-based method.

Most reconstructions of the early Neoproterozoic supercontinent Rodinia (Fig. 1), involving connections between western North America and Australia + Antarctica (Moores 1991; Karlstrom *et al.* 1999; Burrett & Berry 2000; Wingate *et al.* 2002) and eastern North America adjacent to Amazonia (Dalziel 1991; Hoffman 1991; Sadowski & Bettencourt 1996), have in the former case been negated or superseded by subsequent

From: MURPHY, J. B., KEPPIE, J. D. & HYNES, A. J. (eds) *Ancient Orogens and Modern Analogues.* Geological Society, London, Special Publications, **327**, 371–404.
DOI: 10.1144/SP327.16 0305-8719/09/$15.00

geochronological and palaeomagnetic results (Pisarevsky *et al.* 2003*a*, *b*), and in the latter instance suffered from minimal palaeomagnetic support (Tohver *et al.* 2002, 2006). Configurations that directly adjoin Laurentia and Siberia (e.g. Rainbird *et al.* 1998; Sears & Price 2003) are incompatible with recent palaeomagnetic data (reviewed by Pisarevsky & Natapov 2003), as are reconstructions that directly juxtapose Laurentia and Kalahari (Hanson *et al.* 2004). Kalahari and the composite

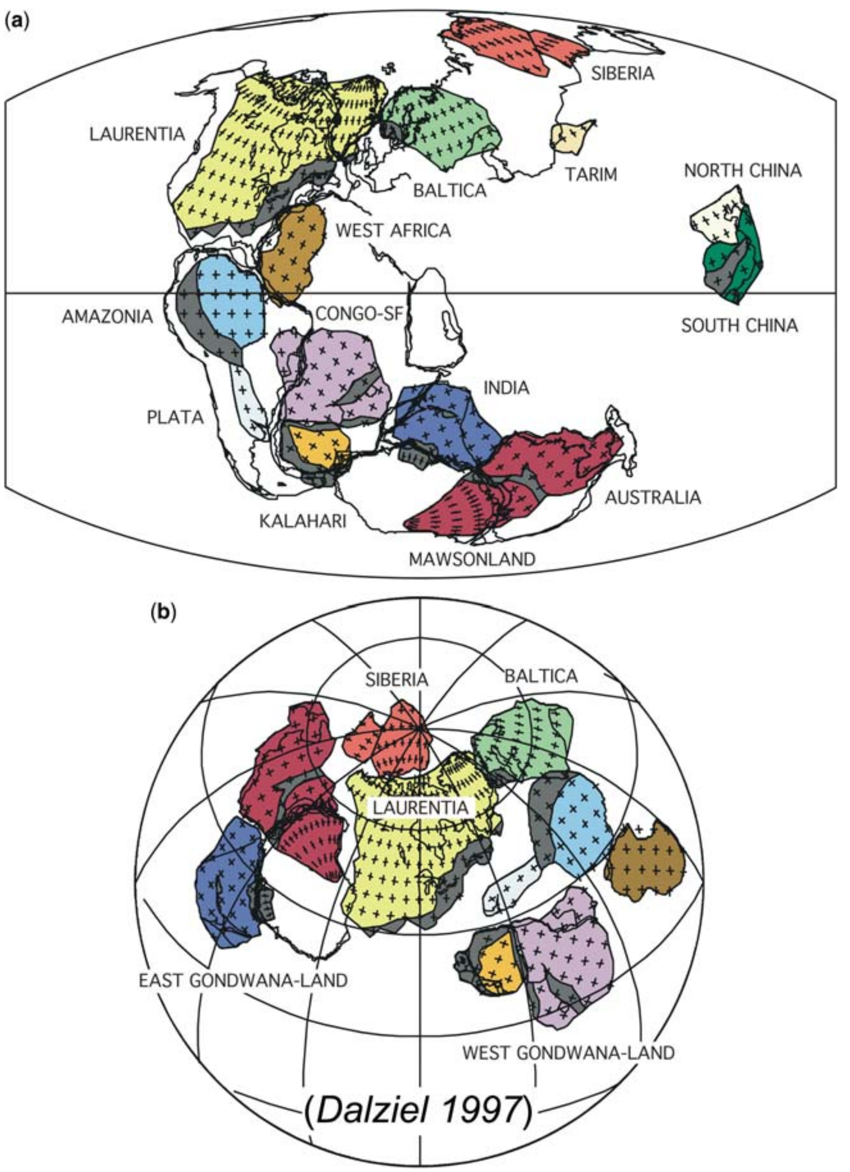

Fig. 1. (**a**) Base maps for Rodinian cratons, reconstructed to their relative early Jurassic Pangaea configuration in present South American co-ordinates. Gondwanaland fragments are reconstructed according to McElhinny *et al.* (2003); these and other Euler parameters are listed in Table 1. North and South China, although distinct cratons in Rodinia, are united in this Early Jurassic configuration as indicated by Yang & Besse (2001). Late Mesoproterozoic ('Grenvillian') orogens are shaded grey. Truncated Mercator projection. Panels (**b**–**d**) show previous Rodinia models in the present North American (i.e. Laurentian) reference frame. References are Dalziel (1997), Pisarevsky *et al.* (2003*a*) and Li *et al.* (2008).

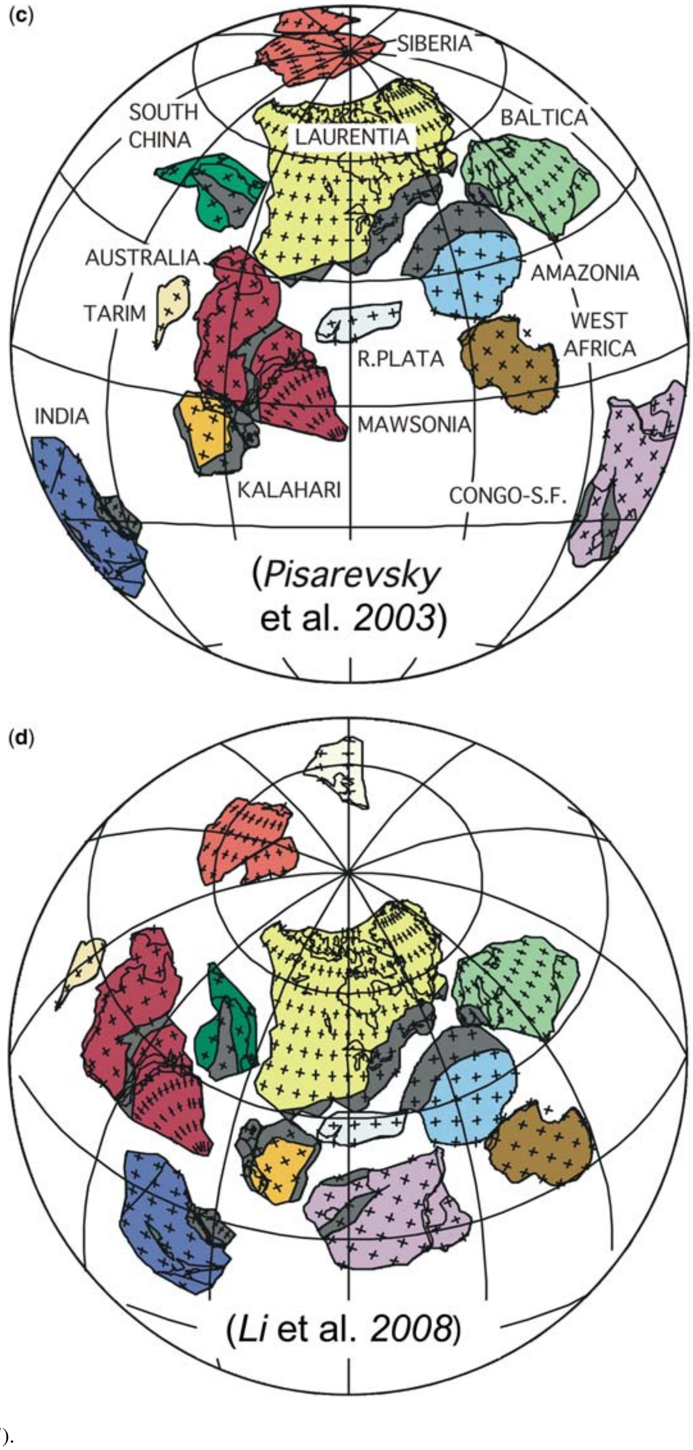

Fig. 1. (*Continued*).

Congo + São Francisco craton have been suggested to be excluded from Rodinia altogether (Kröner & Cordani 2003; Cordani *et al.* 2003).

Four general classes of options exist for how to deal with discrepant palaeomagnetic data: (1) consider potential shortcomings in those data, regarding either palaeomagnetic reliability or age constraints; (2) add loops in the APW path to accommodate the outlying poles; (3) exclude cratons from membership in Rodinia entirely; or (4) restrict the duration of that membership so that it falls between the discrepant palaeomagnetic pole ages. The standard Rodinia model (Hoffman 1991) and its relatively minor variations have been strained to the limits of temporal and spatial constraints, so that some have questioned whether Rodinia even existed at all (Meert & Torsvik 2003); and yet there is still the persistent global tectonostratigraphic evidence for late Mesoproterozoic convergence of cratons, followed by mid-late Neoproterozoic rifting and passive margin development. Given the abundance of focused studies yielding a wealth of new tectonostratigraphic, geochronological and palaeomagnetic data during the last two decades (summarized by Pisarevsky *et al.* 2003*a*; Meert & Torsvik 2003; Li *et al.* 2008), the search for Rodinia may benefit from an entirely fresh perspective. Here I introduce a novel, long-lived Rodinia that is compatible with the most reliable palaeomagnetic data from all of the dozen or so largest cratons during the interval 1300–700 Ma, with minor allowances on the ages of a single set of poles from the São Francisco craton. I show that given these palaeomagnetic data, the new reconstruction is the *only* general model of Rodinia that could have existed for this length of time with all of the largest cratons included in its assembly. The model serves as a palaeomagnetic end-member starting point for further testing and, if desired, relaxation on the assumptions of longevity or inclusion of all the largest cratons. The present analysis is thus most similar to that of Weil *et al.* (1998) in seeking a unified Rodinia model that conforms to the original concept of late Mesoproterozoic assembly and mid-Neoproterozoic dispersal, while incorporating all of the most reliable palaeomagnetic data.

Methods

Many Rodinia reconstructions have been based primarily on comparisons of the geological records among Meso–Neoproterozoic cratons. For this time interval, we can identify 13 large cratons (Fig. 1), plus many smaller terranes (e.g. Kolyma, Barentsia, Oaxaquia, Yemen). With only a dozen or so large pieces and an abundant well-preserved Meso-Neoproterozoic rock record, the Rodinia puzzle is tantalizingly solvable. Most of the geological comparisons are purely of regional extent, considering only two or three cratons (examples cited above), generally within the context of Hoffman's (1991) global model. In these geologically-based juxtapositions, palaeomagnetic data have been used in a subsidiary capacity, or ignored altogether, despite the fact that palaeomagnetism is currently the only strictly quantitative method available for reconstructing Rodinia and earlier supercontinents.

Although in a global sense Rodinia assembled in the late Mesoproterozoic and fragmented in the mid-Neoproterozoic (Hoffman 1991; Dalziel 1997; Condie 2002), thereby existing through the interval 1000–800 Ma, there are numerous indications of locally earlier assembly or later breakup. For example, only one side of Laurentia was deformed by orogeny in the late Mesoproterozoic: the Grenvillian (= proto-Appalachian) margin, and this belt did not evolve to a rifted passive margin until after 600 Ma (Cawood *et al.* 2001). Northern Laurentia experienced the *c.* 1600 Ma Forward Orogeny (Maclean & Cook 2004) followed by extensional events with associated large igneous provinces at 1270 Ma (LeCheminant & Heaman 1989) and 720 Ma (Heaman *et al.* 1992). The western margin assembled in the Palaeoproterozoic (Karlstrom *et al.* 2001; Ross 2002) and did not rift until the middle or latest Neoproterozoic (Link *et al.* 1993; Colpron *et al.* 2002). Rifting of Rodinia along these northern and western Laurentian margins, then, split the proto-Laurentian continent through terrains that had been joined for about a billion years. In these instances, if we can find the correct Rodinia juxtapositions, we have also solved part of the configuration of Nuna, which is Rodinia's Palaeoproterozoic supercontinental predecessor (Hoffman 1996). Many other examples of this type exist around the world, essentially wherever a Neoproterozoic rifted margin does not coincide with a 'Grenvillian' orogen (Fig. 1). When we test Rodinia models with palaeomagnetic data, therefore, we must in some cases consider results from rocks as old as *c.* 1800 Ma (e.g. Idnurm & Giddings 1995).

Axisymmetry of the Earth's time-averaged geomagnetic field implies that when individual palaeomagnetic poles from two continents are compared, their relative palaeolongitude remains unconstrained. This shortcoming to palaeomagnetically-based palaeogeographic reconstructions has led to illustrations of Rodinia and older supercontinents that show only a set of latitude-constrained options, further unconstrained by the unknown geomagnetic polarity states of the compared palaeomagnetic data, a degree of freedom for nearly every Precambrian reconstruction (Hanson *et al.* 2004). Among these degrees of freedom in palaeolongitude and hemispheric ambiguity, two or more cratons are juxtaposed in several allowable positions of direct contact for the specific age of pole comparison. If a similar reconstruction emerges from several adjacent time slices, then a long-lived direct connection between the cratons can be considered viable. Examples of this method, called the 'closest approach' technique, are found in Buchan *et al.* (2000, 2001), Meert & Stuckey (2002) and Pesonen *et al.* (2003).

A more powerful method of reconstructing ancient supercontinents relies on the coherent motion of all component cratons as part of that supercontinent, for the duration of their conjunction within a single lithospheric plate. Throughout the time interval when constituent cratons are assembled into a supercontinent, and if that assemblage is in motion relative to the Earth's magnetic field reference frame (due to plate tectonics or true polar wander, or both), then all elements of the landmass will share the same palaeomagnetic APW path. After the supercontinent disaggregates, the APW paths diverge (Powell *et al.* 1993), but their older segments carry a record of the earlier supercontinental motion. As we approach the problem from the present, we see that each craton's APW path contains segments alternating between times of individual plate motion and membership in successive supercontinents. When the cratons are reconstructed to their correct positions in a supercontinent, the APW paths superimpose atop one another (Evans & Pisarevsky 2008). Examples of this type of analysis are found in Weil *et al.* (1998) and Piper (2000), although both of those studies preceded important new palaeomagnetic data that disallow some of their cratonic juxtapositions. The modified Palaeopangaea reconstruction of Piper (2007) achieves broad-brush palaeomagnetic APW concordance among several cratons, merely as a result of pole averaging (e.g. Siberia), misquoted ages (e.g. Bangemall sills of Australia), or rotation parameters yielding somewhat acceptable pole matches but differing dramatically from the simple cartoon depiction of the reconstruction (e.g. Amazonia, São Francisco + Plata, West Africa and Tanzania + Kalahari) or even producing unacceptable geometric overlaps (northern Australia directly atop Kalahari, and portions of North China directly atop eastern India, in the 'primitive' or pre-1100 Ma reconstruction).

As discussed below, Laurentia has the most complete palaeomagnetic APW path for the interval of *c*. 1300–750 Ma that is most relevant for testing Rodinia reconstructions. In this paper I use the most reliable palaeomagnetic poles from non-Laurentian cratons to compare with the Laurentian reference APW path and thereby to constrain the possible configurations of a long-lived Rodinia. A quantitatively viable Rodinia may be found by investigating possible APW superpositions and determining whether the resulting juxtapositions are geologically reasonable for the time intervals under consideration. This method requires equal APW track lengths between coeval poles on any two given cratons; thus it is conceivable that no APW comparisons will be possible between those blocks and that they must have been in relative motion throughout the interval under consideration. Likewise, there is no guarantee that direct juxtapositions of cratons will emerge: some pole comparisons may result in substantial or complete geographic overlap between two or more cratons, which are unallowable, and others may indicate wide separations between blocks, requiring the presence of intervening blocks (or occurrence of rapid true polar wander; see Evans (2003) to legitimize the initial hypothesis of common APW.

Accurate Neoproterozoic craton outlines are important not only for correct geometric fits in Rodinia reconstructions, but they also indicate whether certain palaeomagnetic results from marginal foldbelts apply to a craton or to its allochthonous terranes. Cratonic outlines, drawn in accordance with a broad range of tectonic and stratigraphic studies that are too numerous to cite here, are generally chosen to lie within craton-marginal orogens at the most distal extent of recognizable stratigraphic connections to each adjacent block. Cratons that have split into fragments during the breakup of Pangaea (e.g. Laurentia + Greenland + Rockall, or Kalahari + Falkland + Grunehogna + Ellsworth) must first be reassembled according to seafloor-spreading data combined with geological 'piercing points.' Post-Pangaean fragments are restored to each other according to standard reconstructions (Table 1), with the exception of Kalahari: following restoration of the Falkland Islands (Grunow *et al.* 1991), Grunehogna is reconstructed to align the Natal and Maud orogenic fronts in the manner suggested by Jacobs & Thomas (2004), and the Ellsworth + Haag province is then rotated to fit into the Natal embayment. The Siberian craton shows restoration of a 25° internal rotation between its northwestern and southeastern (Aldan) portions, associated with development of the Devonian Vilyuy aulacogen, to resolve discrepancies in older palaeomagnetic data (Smethurst *et al.* 1998; Gallet *et al.* 2000). Craton boundaries in Antarctica are particularly uncertain, and the present analysis uses conservative estimates of minimal areas attached to each block. Smaller blocks with limited to no palaeomagnetic data, such as Precordillera–Cuyania, Oaxaquia, Barentsia, Azania and various poorly exposed blocks in South America (Dalziel 1997; Collins & Pisarevsky 2005; Fuck *et al.* 2008), are not described in

Table 1. *Pre-Mesozoic reassemblies of Rodinian cratons*

Craton fragment	Euler rotn.			Reference
	°N	°E	°CCW	
Rotations to Laurentia				
Greenland	67.5	241.5	−13.8	Roest & Srivastava 1989
Rockall Plateau	75.3	159.6	−23.5	Srivastava & Roest 1989; Royer *et al.* 1992
Rotations to Kalahari				
Falkland Islands	−45.3	349.2	156.3	Grunow *et al.* 1991
Grunehogna	−05.3	324.5	58.6	After Jacobs & Thomas 2004
Ellsworth-Haag	−48.9	102.8	82.8	Geometric fit
Rotation to Congo				
São Francisco	46.8	329.4	55.9	McElhinny *et al.* 2003
Rotation to West Africa				
São Luis	53.0	325.0	51.0	McElhinny *et al.* 2003
Rotations to India				
Enderby Land	−04.8	016.6	93.2	McElhinny *et al.* 2003
Eastern Madagascar	18.8	026.3	62.1	McElhinny *et al.* 2003
Southern Somalia	28.9	040.9	64.8	McElhinny *et al.* 2003
Rotation to Australia				
Terre Adélie	01.3	037.7	30.3	McElhinny *et al.* 2003
Reconstruction of Siberia				
NW Siberia to Aldan shield	60.0	115.0	−25.0	Fit pre-Devonian poles from Smethurst *et al.* 1998; Gallet *et al.* 2000

detail but are mentioned below where appropriate. Cratons and palaeomagnetic poles are rotated to geometric accuracy via the software created by Cogné (2003). All calculations assume a geocentric axial-dipolar magnetic field, recently verified for the Proterozoic using a compilation of evaporite palaeolatitudes that gave subtropical values as expected (Evans 2006) and a planetary sphere of constant radius.

Laurentia

Reliable Precambrian palaeomagnetic data are currently so sparse that in only a few instances can we assemble poles into coherent APW paths. In the Rodinia interval, only Laurentia has a well-established path, with ages of *c.* 1270–1000 Ma and tracking younger, with imprecise cooling ages from the Grenville Province (Fig. 2; Weil *et al.* 1998; Pisarevsky *et al.* 2003*a*). The APW path shown in Figure 2 also includes the 1750 Ma grand mean of Irving *et al.* (2004) and representative 'key' poles from *c.* 1450 Ma, as listed by Buchan *et al.* (2000). Although this is not a complete set of data from the 1750–1270 Ma interval, it adequately represents the general trend with which the most important poles from other cratons may be compared. The sense of vorticity of the Grenville APW loop, at *c.* 1000 Ma, has been debated (Weil *et al.* 1998). The present compilation follows Pisarevsky *et al.* (2003*a*) in selecting the most reliable ($Q > 3$ in the scheme of Van der Voo 1990) results from late Keweenawan sedimentary rocks, in stratigraphic order, which generates a southward leg of the loop at *c.* 180° longitude, followed by the well-dated Haliburton 'A' pole at 1015 ± 15 Ma (Warnock *et al.* 2000), and then by a northward leg at <180°E longitude. This clockwise sense of the Grenville loop is compatible with the earlier interpretation of Hyodo & Dunlop (1993) but not that of Weil *et al.* (1998). Another set of reliable Laurentian poles is determined for the interval 780–720 Ma, summarized by Buchan *et al.* (2000) and Pisarevsky *et al.* (2003*a*), plus more recent data from stratified successions in western United States (e.g. Weil *et al.* 2004, 2006). Within the intervening 200 Ma gap of no 'key' poles, a recent result from poorly dated but palaeomagnetically stable sedimentary rocks in Svalbard (including a positive soft-sediment slump fold test guaranteeing primary remanence)

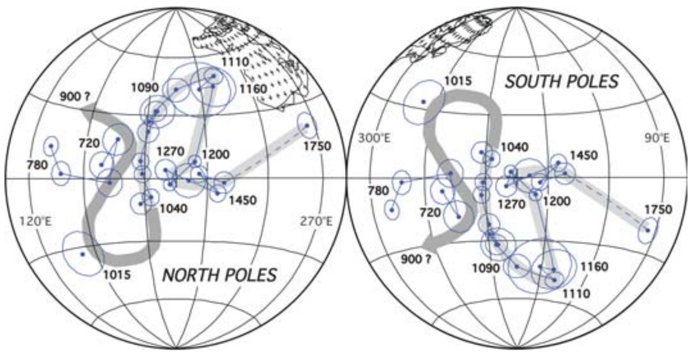

Fig. 2. Apparent polar wander path for Laurentia between 1270 and 720 Ma (poles listed in Table 2), which is used as a reference curve for superimposing 'key' poles from other cratons during the Rodinian interval (Buchan *et al.* 2001). Note the large age gap between 1015 and 780 Ma, which is hypothesized here to include a large APW loop at 800 Ma as observed from other cratons (see text and Figs 8 & 10) and from recent high-quality data from Svalbard (Maloof *et al.* 2006).

suggests a large APW loop, hitherto unrecognized for early Neoproterozoic Laurentia (Maloof *et al.* 2006). Regarding these results, it is important to note that this loop is underpinned by data from continuous stratigraphic sections in Svalbard, thus eliminating uncertainties in the reconstruction of Svalbard to Laurentia, or local rotations, as trivial explanations for the divergent pole positions. Global correlations of this new, *c.* 800 Ma, APW loop are discussed in various sections below with the relevant data from other cratons.

Lack of data from the *c.* 1000–800 Ma interval of the Laurentian APW path renders many Rodinian cratonic juxtapositions currently untested; for example, the various reconstructions of Australia + Mawsonland against particular segments of the Laurentian Cordilleran margin (SWEAT, AUSWUS, AUSMEX) all fail palaeomagnetic comparisons at *c.* 750 Ma (Wingate & Giddings 2000) and *c.* 1200 Ma (Pisarevsky *et al.* 2003*b*), but any one of those reconstructions could be salvaged if it assembled after *c.* 1000 Ma and fragmented by *c.* 800 Ma. In this option for dealing with the discrepant palaeomagnetic data as described above, only Li *et al.* (1995, 2002, 2008) have developed a tectonically reasonable hypothesis by inserting the South China block between Laurentia and Australia. In that model, the Sibao orogen represents the suture between the Australia + Yangtze craton and Cathaysia + Laurentia in a collision at *c.* 900 Ma (Li *et al.* 2008).

Baltica

The least controversial component of the revised Rodinia reconstruction proposed herein is the placement of Baltica adjacent to eastern Laurentia, as has been suggested with minor variations throughout the last three decades (Patchett *et al.* 1978; Piper 1980; Bond *et al.* 1984; Gower *et al.* 1990; Hoffman 1991; Dalziel 1997; Weil *et al.* 1998; Hartz & Torsvik 2002; Pisarevsky *et al.* 2003*a*; Cawood & Pisarevsky 2006). The principal variations among these reconstructions are the latitude of juxtaposition along the Greenland margin and the orientation of Balitca such that various margins (e.g. Caledonide, Timanian, Uralian) are proposed to participate in the direct conjunction with Greenland (Buchan *et al.* 2000; Cawood & Pisarevsky 2006). The reconstruction favoured here is nearly identical to that proposed by Pisarevsky *et al.* (2003*a*), but with a tighter fit. Pisarevsky *et al.* (2003*a*) opted for a several hundred-kilometre gap between the present-day margins of SE Greenland and the Norwegian Caledonides, in order to account for palinspastic restoration of Caledonide shortening. These same margins, however, experienced a counteracting amount of extension during Cenozoic initiation of Atlantic Ocean opening as well as Eocambrian opening of Iapetus; the three post-Rodinian alterations to the Greenland and Baltic margins may well have nullified one another, so a tight fit is preferred here (Fig. 3).

Palaeomagnetic poles within the 1100–850 Ma interval from Baltica broadly superimpose onto the Laurentian Grenville APW loop when the two cratons are restored to their proposed Rodinian reconstruction (Fig. 3). The distribution of Baltic poles from this interval has been described in terms of a so-called Sveconorwegian APW loop, with discussions on the ages of individual poles and whether a complete loop is actually circumscribed by the data (Walderhaug *et al.* 1999; Brown & McEnroe 2004; Pisarevsky & Bylund

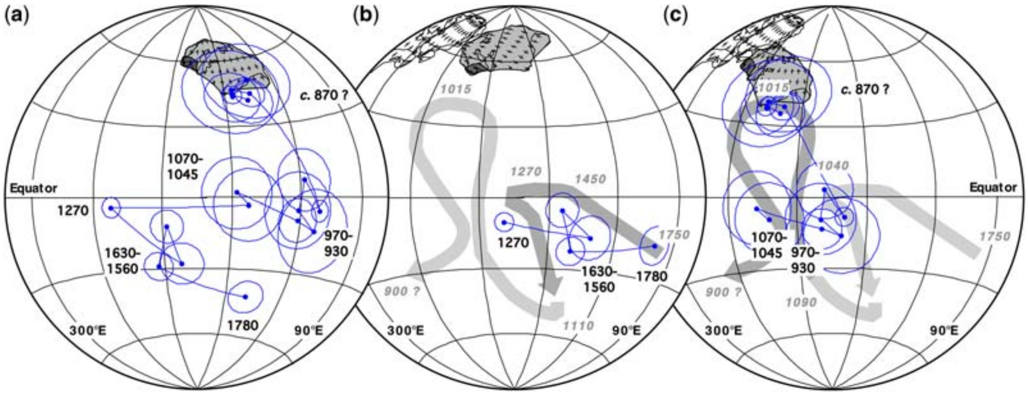

Fig. 3. Palaeomagnetic poles from Baltica (grey), compared with the Laurentian reference APW path. As with Figures 4–11, dark-grey shaded cratonic areas are late Mesoproterozoic ('Grenvillian') orogens. (**a**) Poles with their 95% confidence ellipses and ages in Ma, as listed in Table 2, plus Evans & Pisarevsky (2008) for the 1780–1270 Ma data. (**b**) Superposition of the 1780–1270 Ma poles with the pre-Rodinian APW path from Laurentia, rotating Baltica and its poles by (47.5°N, 001.5°E, +49°CCW) after Evans & Pisarevsky (2008). This pre-Rodinia configuration is essentially the same as 'NENA' by Gower *et al.* (1990). (**c**) Rodinian reconstruction (1070–615 Ma) that superimposes the Sveconorwegian APW loop atop the Grenville APW loop of Laurentia (despite recently recognized age mismatches), using the Euler rotation parameters given in Table 3.

2006). Here I tentatively adopt the simple explanation postulated by Pisarevsky & Bylund (2006) that the high-latitude Sveconorwegian poles represent a single, post-900 Ma overprint affecting the southernmost regions of Norway and Sweden, despite lack of independent supporting evidence for such an event (Brown & McEnroe 2004). As a more complex alternative, there might be several oscillatory 'Sveconorwegian' loops in the Baltic APW path, which would be geodynamically explained best by multiple episodes of true polar wander (TPW; Evans 2003). More detailed palaeomagnetic and thermochronological studies of the two cratons from this time interval are needed to resolve these questions.

The proposed reconstruction of Baltica adjacent to SE Greenland at *c.* 1100–600 Ma, like that of Pisarevsky *et al.* (2003*a*), brings the Sveconorwegian orogen in southern Scandinavia close to the Grenville orogen in Labrador with minor right-stepping offset (Gower *et al.* 2008). It also unites the loci of precisely coeval 615 Ma Long Range dykes in Labrador (Kamo *et al.* 1989; Kamo & Gower 1994) and Egersund dykes in southernmost Norway (Bingen *et al.* 1998). Palaeomagnetic results from both of these dyke swarms have yielded scattered results spanning a wide range of inclinations, rendering palaeolatitude comparisons difficult (Murthy *et al.* 1992; Walderhaug *et al.* 2007); however, they are as consistent with the reconstruction introduced here as they are for that of Pisarevsky *et al.* (2003*a*) and Li *et al.* (2008), and this general class of reconstructions is superior to all other proposed Rodinian juxtapositions of Laurentia and Baltica (Cawood & Pisarevsky 2006).

Palaeomagnetic poles from Baltica and Laurentia during the preceding interval *c.* 1750–1270 Ma are incompatible with the preferred *c.* 1100–600 Ma reconstruction, and suggest instead a modified fit with Baltica's Kola–Timanian margin adjacent to East Greenland (Fig. 3). This fit is essentially the geologically-based Northern Europe + North America (NENA) reconstruction of Gower *et al.* (1990), confirmed palaeomagnetically by Buchan *et al.* (2000) and Evans & Pisarevsky (2008) for the pre-Rodinian interval. Relative to Laurentia, Baltica rotated clockwise *c.* 70° about an Euler pole near Scoresby Sund, some time between 1270 and 1050 Ma, in approximately the same sense as was first proposed by Patchett *et al.* (1978) and Piper (1980). New palaeomagnetic results from the 1122 Ma Salla Dyke in northern Finland are more compatible with a pre-rotation reconstruction than a post-rotation reconstruction, suggesting that the rotation occurred after, or even coincident with, dyke emplacement at *c.* 1120 Ma (Salminen *et al.* 2009). The proposed rotation is consistent with the broad-scale tectonic asymmetry of Baltica (orogeny in west, rifting in east) through the Mesoproterozoic interval (Bogdanova *et al.* 2008). Below it will be shown how this rotation created a broad gulf along the edge of the Rodinia-encircling ocean, Mirovia (McMenamin & McMenamin 1990), which became an isolated sea following further Rodinian amalgamation.

Australia + Mawsonland

The semi-contiguous Albany–Fraser and Musgrave belts are commonly considered as part of a late Mesoproterozoic suture zone among three constituent Australian cratons (western, northern and southern; Myers *et al.* 1996), or between a previously united western + northern craton (Li 2000) and the southern, 'Mawson Continent' (Cawood & Korsch 2008). The latter entity extends from the Australian Gawler craton *s.s.* into Terre Adélie in Antarctica, and possibly as far south as the Transantarctic Mountains near the Miller Range (Goodge *et al.* 2001; Fitzsimons 2003; Payne *et al.* 2009). Here the term 'Mawsonland' is formally introduced as a more succinct synonym to 'Mawson Continent.' The Albany–Fraser belt is truncated on its western end by the late Neoproterozoic Pinjarra orogen (Fitzsimons 2003) and on its eastern end by the Palaeozoic Lachlan–Thompson accretionary orogen (Li & Powell 2001), although some local vestiges of Mesoproterozoic orogeny or magmatism are documented in northern Queensland (Blewett & Black 1998) and around Tasmania (Berry *et al.* 2005; Fioretti *et al.* 2005). These truncations can provide important piercing points for Rodinia reconstructions, because the Albany–Fraser–Musgrave orogen contains, along its entire length, two episodes of tectonomagmatic activity dated at *c.* 1320 and *c.* 1200–1150 Ma (White *et al.* 1999; Clark *et al.* 2000). Early consolidation of the Australia + Mawsonland continent allows it to be considered as a single entity in post-1200 Ma Rodinia reconstructions.

Two important ('key') palaeomagnetic poles are available for the *c.* 1100–750 Ma Rodinian interval: the Bangemall basin sills at 1070 Ma (Wingate *et al.* 2002), and the Mundine Well Dykes at 755 Ma (Wingate & Giddings 2000). The latter result is supplemented by a pole from oriented borehole core of the Browne Formation (estimated age *c.* 830–800 Ma), which is the only result among several reported by Pisarevsky *et al.* (2007) with adequate statistics on the mean direction. Other palaeomagnetic poles from Australia during the Meso–Neoproterozoic interval are problematic, as discussed by Wingate & Evans (2003): they suffer from any combination of poor geochronology, lack of tilt control, and unknown timing of the magnetic remanence acquisition. Similarly, a more recent result from the Alcurra dykes in the Musgrave belt (Schmidt *et al.* 2006) also suffer from lack of tectonic control, either relative to the palaeohorizontal or in the sense of vertical-axis rotation of the Musgrave region. The principal conclusion of the latter study, that Australia did not assemble until after 1070 Ma, should be treated with caution until further palaeomagnetic studies of Australia's constituent cratons are undertaken.

The great-circle angular distance between the two key poles (32.5°) is identical within error of the angular distance between the two age-correlative interpolated positions on the Laurentian APW path, and this permits the working hypothesis that both cratons could have been part of a single Rodinia plate throughout the intervening time interval. Under this assumption, these two poles can be superimposed on the Laurentian APW path in two options, depending on choice of geomagnetic polarity (Fig. 4). One option points the Albany-Fraser orogen directly into the centre of the northern margin of Laurentia (Fig. 4a), which appears incompatible with the lack of an equivalently aged orogen. Although Hoffman (1991) depicted the Racklan

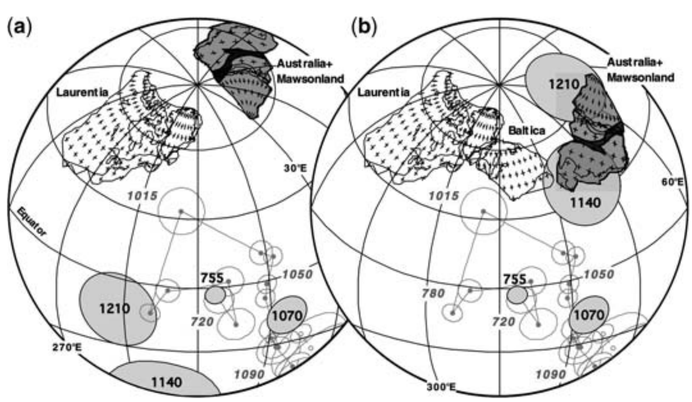

Fig. 4. Superposition of 'key' poles from Australia, at 1070 and 755 Ma (Table 2), and the Laurentian APW path (in the North American reference frame) according to one polarity option (**a**) that produces pronounced geologic mismatches between Western Australia and northern Canada, and the alternative, allowable polarity option (**b**) indicating the preferred position adjacent to the Uralian margin of Baltica. Euler parameters for the rotation of Australia and its poles to Laurentia are (−21.8°N, 318.4°E, +155.3°CCW) in panel (A), and (−12.5°N, 064.0°E, +134.5°CCW) in panel (B).

orogeny in that region as a Mesoproterozoic event, subsequent work indicates a Palaeoproterozoic age for that and related events (Thorkelson *et al.* 2001; Maclean & Cook 2004). There is a poorly understood post-Racklan orogenic event in Yukon (Corn Creek orogeny; Thorkelson *et al.* 2005), but its precise timing and regional extent are unknown. Similarly, although Hoffman (1991) and Dalziel (1997) extended the Grenville orogen northward along the margin of East Greenland, more recent work in that area – plus the once-contiguous eastern Svalbard – dates the 'Grenvillian' tectonomagmatic activity at *c.* 950 Ma (Watt & Thrane 2001; Johansson *et al.* 2005), far younger than the Albany-Fraser belt and negating that potential piercing point. The reconstruction of Australia relative to Laurentia as shown in Figure 4a is also incompatible with the only viable option for the Congo + São Francisco craton, as will be shown below.

The second option for a continuously connected Laurentia and Australia + Mawsonland in 1100–750 Ma Rodinia (Fig. 4b) requires a gap between the two cratons that is neatly filled by Baltica in the reconstruction presented above. In this fit, which juxtaposes the southern Urals and pre-Caspian depression against northern Queensland, poles from earlier ages of 1200–1140 Ma do not superimpose (Fig. 4b), requiring that the postulated connection was not established until *c.* 1100 Ma. Blewett & Black (1998) documented evidence of *c.* 1100 Ma tectonomagmatism in the Cape River province of northern Queensland, which could testify to the inferred collision with Baltica at that time – almost synchronously with Baltica's rotation as described above. Although Proterozoic geology of the pre-Caspian depression is entombed by *c.* 15 km of overlying Phanerozoic sedimentary cover (Volozh *et al.* 2003), the para-autochthonous Bashkirian anticlinorium of the southern Urals exposes the Riphean stratotype succession of the Baltic craton that can be subdivided into three unconformity-bounded successions. Angular unconformity between the Middle and Upper Riphean successions has commonly been attributed to a rift event (Maslov *et al.* 1997) but it could also be the distal expression of collisional tectonism at *c.* 1100 Ma between Baltica and Australia as proposed herein. The Beloretzk terrane, with two stages of deformation bracketing eclogitization, all between 1350 and 970 Ma (Glasmacher *et al.* 2001), could be a sliver of the proposed collision zone.

Congo + São Francisco

Sharing many tectonic similarities since the Archaean–Palaeoproterozoic, the Congo craton in central Africa and the São Francisco craton in eastern Brazil are almost universally considered to represent a single tectonic entity in Rodinian times (e.g. Brito Neves *et al.* 1999; Alkmim *et al.* 2001). The Congo craton itself is transected by a Mesoproterozoic orogen, the Kibaran belt, which divides the poorly-known western two-thirds of the craton that is largely covered by the Phanerozoic Congo basin (Daly *et al.* 1992) from the relatively well-exposed Tanzania and Bangweulu massifs (and bounding Palaeoproterozoic belts) in the east (De Waele *et al.* 2008). The Kibaran belt has been viewed as either an ensialic orogen (e.g. Klerkx *et al.* 1987) or a subduction-accretionary margin followed by *c.* 1080 Ma continental collision (e.g. Kokonyangi *et al.* 2006). At the southeastern extremity of the craton, the Irumide belt records *c.* 1100–1000 Ma deformation and magmatism (Johnson *et al.* 2005; De Waele *et al.* 2008).

Reliable palaeomagnetic data from the aggregate Congo + São Francisco craton are sparse. In this paper, two poles from Congo are used as the key tie points to the Laurentian master APW curve: the post-Kibaran (e.g. Kabanga–Musongati) layered mafic–ultramafic intrusions (Meert *et al.* 1994) and the Mbozi gabbro (Meert *et al.* 1995). The former pole is constrained by Ar/Ar dating at *c.* 1235 Ma, despite crystallization ages of the complexes as early as *c.* 1400–1350 Ma (Maier *et al.* 2007). The intrusions lie along the boundary between para-autochtonous Tanzania craton to the east, and an orogenic internal zone to the west (Tack *et al.* 1994). Using the Kabanga–Musongati pole to represent the entire Congo craton requires that the subsequent *c.* 1080 Ma deformation was ensialic rather than collisional. Despite the fact that the palaeomagnetically studied Mbozi gabbro is not directly dated, the later-stage syenites in the complex are now constrained by a 748 ± 6 Ma zircon U–Pb age (Mbede *et al.* 2004), and this may serve as an approximation of the age of palaeomagnetic remanence. In addition to these poles, the 795 ± 7 Ma (Ar/Ar; Deblond *et al.* 2001) Gagwe–Kabuye lavas have yielded a result that appears reliable yet is widely separated from the slightly younger Mbozi pole (Meert *et al.* 1995). Two groups of poles from dykes in Bahia, Brazil (D'Agrella-Filho *et al.* 2004) are also included in the aggregate Congo + São Francisco APW path. These groups of poles, with Ar/Ar ages of *c.* 1080 and 1020 Ma, suggest high-latitude positions for the Congo + São Francisco craton that appeared to negate any direct long-lived Rodinian connections with Laurentia (Weil *et al.* 1998; Pisarevsky *et al.* 2003*a*; Cordani *et al.* 2003), although collision between the two blocks at *c.* 1000 Ma was considered possible (D'Agrella-Filho *et al.* 1998). As discussed below, these poles are of crucial importance for testing the radical Rodinia revisions proposed in this paper.

Given the 1235 Ma Kabanga–Musongati and *c*. 750 Ma Mbozi poles superimposed atop the coeval Sudbury dykes and *c*. 750 Ma poles from Laurentia (Table 2), the two polarity options for this long-lived reconstruction of the two blocks are shown in Figure 5. In the first option (Fig. 5a), there is substantial overlap between the two cratons that cannot be avoided by minor adjustments to the rotations within the uncertainty limits of the poles. This implies that the reconstruction, although palaeomagnetically accurate, is not geologically possible. Other Congo + São Francisco poles are also shown in Figure 5a, to illustrate that they too fall off the Laurentian APW path in the reconstruction of this first polarity option.

The second polarity option for superimposing the 1235 Ma and *c*. 750 Ma poles between Congo + São Francisco and Laurentia produces the juxtaposition of Arctic North America with CONgo at its DAmaride margin ('ANACONDA'). This reconstruction places the two groups of poles from Bahia dykes (D'Agrella-Filho *et al.* 2004) atop the *c*. 1100 Ma Keweenawan poles from Laurentia. This would imply that the *c*. 1080–1010 Ma Ar/Ar ages from these dykes and baked country rocks (Renne *et al.* 1990; D'Agrella-Filho *et al.* 2004) are inaccurately low, a reflection of large scatter in the raw Ar datasets and thus potentially ubiquitous Ar-loss in those rocks. Interestingly, palaeomagnetic polarity reversal asymmetries that are documented in two studies of São Francisco dykes in Bahia, Brazil (D'Agrella-Filho *et al.* 1990, 2004), precisely superimpose on reversal asymmetries among Keweenawan rocks in Laurentia (Halls & Pesonen 1982) in the ANACONDA reconstruction; this suggests a geomagnetic origin

Table 2. *Palaeomagnetic poles used in this study*

Craton/Rock unit*	Age (Ma)†	Unrot.		A95°	Pole reference
		°N	°E		
Laurentia					
Franklin–Natkusiak (FN)	*c*. 720	08	163	4.0	Buchan *et al.* 2000
Kwagunt Fm (Kw)	742 ± 6	18	166	7.0	Weil *et al.* 2004
Galeros Fm (G)	>Kw	−02	163	6.0	Weil *et al.* 2004
Tsezotene sills (Ts)	779 ± 2	02	138	7.0	Park *et al.* 1989
Wyoming dykes (Wy)	*c*. 784	13	131	4.0	Harlan *et al.* 1997
Haliburton 'A' (HA)	1015 ± 15	−33	142	6.0	Warnock *et al.* 2000
Chequamegon (C)	*c*. J	−12	178	5.0	McCabe & Van der Voo 1983
Jacobsville (J)	<F	−09	183	4.0	Roy & Robertson 1978
Freda (F)	<N	02	179	4.0	Henry *et al.* 1977
Nonesuch (No)	*c*. 1050?	08	178	4.0	Henry *et al.* 1977
Lake Shore traps (LS)	1087 ± 2	22	181	5.0	Diehl & Haig 1994
Unkar intrusions (Ui)	*c*. 1090	32	185	8.0	Weil *et al.* 2003
Portage Lake (PL)	1095 ± 3	27	181	2.0	Halls & Pesonen 1982
Upper Nth Shore (uNS)	1097 ± 2	32	184	5.0	Halls & Pesonen 1982
Upper Osler R (uO-r)	1105 ± 2	43	195	6.0	Halls 1974
Logan sills (Lo)	1108 ± 1	49	220	4.0	Buchan *et al.* 2000
Abitibi dykes (Ab)	1141 ± 1	43	209	14.0	Ernst & Buchan 1993
Upper Bylot (uB)	*c*. 1200?	08	204	3.0	Fahrig *et al.* 1981
Sudbury dykes (Sud)	1235 +7/−3	−03	192	3.0	Palmer *et al.* 1977
Mackenzie dykes (Mac)	1267 ± 2	04	190	5.0	Buchan & Halls 1990
Baltica					
Hunnedalen dykes (Hun)	*c*. 850	41	042	10.0	Walderhaug *et al.* 1999
Rogaland anorth (Rog)	*c*. 900?	42	020	9.0	Brown & McEnroe 2004
Gällared Gneiss (GG)	≪985?	44	044	6.0	Pisarevsky & Bylund 1998
Hakefjorden (Hak)	916 ± 11	−05	069	4.0	Stearn & Piper 1984
Goteborg–Slussen (Got)	935 ± 3	07	062	12.0	Pisarevsky & Bylund 2006
Dalarna dykes (Dal)	946 ± 1	−05	059	15.0	Pisarevsky & Bylund 2006
Karlshamn–Fajo (Karls)	*c*. 950	−13	067	16.0	Pisarevsky & Bylund 2006
Laanila Dolerite (Laa)	*c*. 1045	02	032	15.0	Mertanen *et al.* 1996
Bamble intrus. (Bam)	*c*. 1070	−03	037	15.0	Brown & McEnroe 2004

(*Continued*)

Table 2. *Continued*

Craton/Rock unit*	Age (Ma)†	Unrot.		A95°	Pole reference
		°N	°E		
Australia					
Mundine Well (MW)	755 ± 3	45	135	4.0	Wingate & Giddings 2000
Browne Fm (Br)	*c.* 830?	45	142	7.0	Pisarevsky *et al.* 2007
Bangemall sills (Bang)	1070 ± 6	34	095	8.0	Wingate *et al.* 2002
Lakeview dolerite	*c.* 1140	−10	131	17.5	Tanaka & Idnurm 1994
Mernda Morn mean	*c.* 1200	−48	148	15.5	this study‡
Congo					
Mbozi complex (Mb)	≥748 ± 6	46	325	9.0	Meert *et al.* 1995†
Gagwe lavas (Gag)	795 ± 7	−25	273	10.0	Meert *et al.* 1995
Kabanga-Musongati (KM)	1235 ± 5	17	293	5.0	Meert *et al.* 1994
São Francisco					
Bahia dykes W-dn (B-w)	see text	09	281	7.0	D'Agrella-Filho *et al.* 2004
Bahia dykes E-up (B-e)	see text	−12	291	6.0	D'Agrella-Filho *et al.* 2004
Kalahari					
Namaqua mean (Nam)	*c.* 1000	−09	150	18.0	Gose *et al.* 2006
Kalkpunt Fm (KP)	*c.* 1090	57	003	7.0	Briden *et al.* 1979†
Umkondo mean (Um)	1110 ± 3	64	039	3.5	Gose *et al.* 2006
India					
Malani Rhyolite (MR)	*c.* 770	75	071	8.5	Torsvik *et al.* 2001
Harohalli dykes (Har)	815/1190	25	078	8.5	Malone *et al.* 2008
Majhgawan kimb (Majh)	1074 ± 14?	37	213	15.5	Gregory *et al.* 2006
Wajrakarur kimb (Waj)	*c.* 1100	45	059	11.0	Miller & Hargraves 1994†
South China					
Liantuo mean (Li)	748 ± 12	−04	341	13.0	Evans *et al.* 2000
Xiaofeng dykes (X)	802 ± 10	−14	271	11.0	Li *et al.* 2004
Tarim					
Beiyixi volcanics (Bei)	755 ± 15	−18	014	4.5	Huang *et al.* 2005†
Aksu dykes (Ak)	807 ± 12	−19	308	6.5	Chen *et al.* 2004
Svalbard					
Svanbergfjellet (Svan)	*c.* 790?	−26	047	6.0	Maloof *et al.* 2006
Grusdievbreen u. (Gru2)	*c.* 800?	01	073	6.5	Maloof *et al.* 2006
Grusdievbreen l. (Gru1)	*c.* 805?	−20	025	11.5	Maloof *et al.* 2006
North China					
Nanfen Fm (Nan)	*c.* 790?	−17	121	11.0	Zhang *et al.* 2006
Cuishuang Fm (Cui)	*c.* 950?	−41	045	11.5	Zhang *et al.* 2006
Siberia					
Kandyk Fm (Kan)	*c.* 990	−03	177	4.0	Pavlov *et al.* 2002
Milkon Fm (Mil)	1025?	−06	196	4.0	Pisarevsky & Natapov 2003
Malgina Fm (Mal)	1040?	−25	231	3.0	Gallet *et al.* 2000
Amazonia					
Aguapei sills (Agua)	*c.* 980	−64	279	8.5	D'Agrella-Filho *et al.* 2003†
Fortuna Fm (FF)	1150?	−60	336	9.5	D'Agrella-Filho *et al.* 2008
Nova Floresta sills (NF)	*c.* 1200	−25	345	5.5	Tohver *et al.* 2002

*Abbreviations for rock units correspond to the poles depicted in Figures 2–10.
†Ages are queried where highly uncertain or estimated in part by position on the APW path. Ages are cited fully in Buchan *et al.* (2000) or Pisarevsky *et al.* (2003*a*), or the pole references, except where otherwise noted: Zig-Zag Dal – Midsommersø from Upton *et al.* (2005); Western Channel diabase from Hamilton & Buchan (2007); Mbozi complex from Mbede *et al.* (2004); Kunene anorthosite from Mayer *et al.* (2004) and Drüppel *et al.* (2007); Harohalli dykes from Malone *et al.* (2008); Wajrakarur kimberlites from Kumar *et al.* (2007); Beiyixi volcanics from Xu *et al.* (2005); Kalkpunt Formation estimated from Pettersson *et al.* (2007).
‡Combined calculation of Fraser dyke VGP (Pisarevsky *et al.* 2003*b*) with Ravensthorpe dykes of Giddings (1976) and one additional dyke at Narrogin (A. V. Smirnov & D. A. D. Evans, unpublished data).

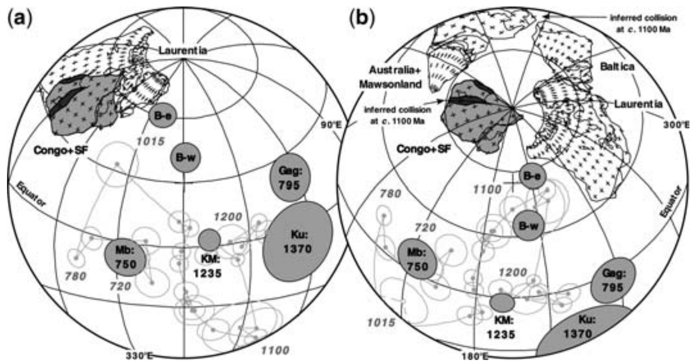

Fig. 5. Non-'key' palaeomagnetic poles from Congo + São Francisco during the interval *c*. 1370–750 Ma (Table 2). The 1235 and 755 Ma poles from Congo are used to generate two possible superpositions onto the Laurentian APW path (in the North American reference frame). One polarity option (**a**) generates a complete overlap between the two cratons and is thus not allowed, whereas the other (**b**) produces the 'ANACONDA' juxtaposition described in the text. Note that the Bahia dykes poles fall on the *c*. 1100 Ma segment of the Laurentian path, and a testable prediction of ANACONDA is that the existing Ar/Ar ages of 1080–1010 Ma from these dikes are too young (see text). Euler parameters for the rotation of Congo + São Francisco and its poles from the present African reference frame to Laurentia are (20.0°N, 334.9°E, +162.5°CCW) in panel (A), and (−24.0°N, 249.0°E, +128.5°CCW) in panel (B).

for the asymmetries (Pesonen & Nevanlinna 1981). A joint palaeomagnetic and U–Pb restudy of these dykes is currently underway (Catelani *et al.* 2007). Other poles shown in Figure 5b are from the Kunene anorthosite (Piper 1974), which with new precise U–Pb ages on consanguineous felsic rocks of 1380–1370 Ma (Mayer *et al.* 2004; Drüppel *et al.* 2007) deserves refinement with modern palaeomagnetic techniques; and the Gagwe lavas (Meert *et al.* 1995) with an updated Ar/Ar age of 795 ± 7 Ma (Deblond *et al.* 2001). If the Gagwe pole is primary, then the ANACONDA fit requires a large APW loop shared among all elements of Rodinia at *c*. 800 Ma. Such a loop has not traditionally been accepted for Laurentia, as some anomalous results of that age have been interpreted instead as suffering from local vertical-axis rotation (e.g. Little Dal lavas; Park & Jefferson 1991). However, a large APW loop in the Laurentian path at *c*. 800 Ma has now been demonstrated by high-quality palaeomagnetic results from Svalbard (Maloof *et al.* 2006; see above) and is generally supported by data from several other cratons that imply large APW shifts between *c*. 800 and *c*. 750 Ma (Li *et al.* 2004).

The ANACONDA reconstruction juxtaposes several intriguingly similar geological features among the São Francisco, Congo and northern Laurentian cratons. Extensive Palaeoproterozoic–Mesoproterozoic orogeny in the southern Angola–Congo craton (Seth *et al.* 2003) adjoins crust with a similarly aged interval of deformation in arctic Canada (Thorkelson *et al.* 2001; MacLean & Cook 2004) and suggests initial amalgamation of ANACONDA at *c*. 1.6–1.5 Ga. Post-collisional igneous activity at *c*. 1.38 Ga is recorded by the Kunene complex and coeval Hart River magmatism in Canada (Thorkelson *et al.* 2001) and Midsommersø dolerite and cogenetic Zig-Zag Dal basalt (Upton *et al.* 2005). Along the southeastern margin of Congo, potassic magmatism at 1360–1330 Ma (Vrana *et al.* 2004) correlates broadly in age with the *c*. 1350 Ma Mashak volcanics in the southern Urals (Maslov *et al.* 1997).

The ANACONDA reconstruction also identifies potential long-sought counterparts to the giant 1.27 Ga Mackenzie/Muskox/Coppermine large igneous province in Canada, with correlatives in Greenland and Baltica (Ernst & Buchan 2002). In eastern Africa, the late-Kibaran intrusive complexes described above were once thought to be of the same age (Tack *et al.* 1994), but are now known to be either older (Tohver *et al.* 2006) or younger (De Waele *et al.* 2008). Nonetheless, a dyke of similar tectonic setting in Burundi is dated by Ar/Ar at *c*. 1280–1250 Ma (Deblond *et al.* 2001), and Tohver *et al.* (2006) raise the possibility that the *c*. 1380 Ma zircons in the layered intrusions are xenocrysts. Thus, more comprehensive geochronology of this region is warranted. In Brazil, the Niquelândia and related mafic-ultramafic complexes have numerous age constraints, the most recent study suggests emplacement ages at 1250 ± 20 Ma (Pimentel *et al.* 2004). The latter intrusions lie within the late Neoproterozoic Brasilia belt, adjacent to the São Francisco craton, and in the present model are considered not grossly allochthonous relative to that craton (Pimentel *et al.* 2006). Concordance of the Laurentian and Congo + São Francisco APW paths younger than this age indicates that extension at 1270–1250 Ma failed to separate the cratons, rather than opening a postulated 'Poseidon' ocean (Jackson & Iannelli 1981).

These magmatic loci could represent early stages of the rifting that is required by palaeomagnetic data to have rotated Baltica away from Congo and toward southern Greenland in the late Mesoproterozoic, as discussed above. Baltica's rotation, coupled with arrival of Australia at *c*. 1100 Ma as discussed above, isolated a craton-sized tract of remnant ocean at the end of the Mesoproterozoic. This 'hole', in the present revised Rodinia model, is intriguing for several reasons. First, it predicts a Mediterranean-style slab rollback to account for arc magmatism and arc-continent collision in the Irumide belt at *c*. 1050–1020 Ma (De Waele *et al.* 2008) as well as *c*. 1000–800 Ma tectonic events in Greenland (Watt & Thrane 2001) and northern Norway (Kirkland *et al.* 2006). Second, the large *c*. 800 Ma evaporite basin hosting the Shaba–Katanga copperbelt in southern Congo (Jackson *et al.* 2003) may have continued onto Laurentia as the evaporitic upper part of the Amundsen basin and its correlative units in the Mackenzie Mountains (Rainbird *et al.* 1996). This composite evaporitic basin could represent a lithospheric sag precursor to rifting and separation of ANACONDA – accompanied by the Chuos, Grand Conglomerat and Rapitan glaciogenic deposits (Evans 2000) – between *c*. 750 and 700 Ma. Finally, it demonstrates how the palaeomagnetic APW-matching method can generate a more refined palaeogeographic framework for supercontinent reconstructions; all previous models of Rodinia, using tectonostratigraphic comparisons or 'closest-approach' palaeomagnetic reconstructions, have placed the cratons together as tightly as possible – essentially ruling out even the possibility of Mediterranean-style remnant-ocean tectonism in the pre-Pangaean world.

As a final note, recall that the palaeomagnetic data from Australia were discordant in the present revised Rodinia model at *c*. 1140 Ma, requiring collision of Australia + Mawsonland to become a part of Rodinia at *c*. 1100 Ma. Proximity of Mawsonland to Tanzania in the Rodinia fit (Fig. 5b) implies convergence and inferred collision there as well. One difficulty with this inference is the lack of any direct evidence for *c*. 1100 Ma tectonism in the central Transantarctic Mountains (Goodge *et al.* 2001), despite some tenuous Nd-isotopic support for Mesoproterozoic activity there (Borg & DePaolo 1994). However, if Kokonyangi *et al.* (2006) are correct in proposing a *c*. 1080 Ma suture between Tanzania + Bangweulu and Congo cratons at the Kibaran orogen, then there is the intriguing possibility presented by this reconstruction, that Tanzania + Bangweulu was originally a fragment of Australia + Mawsonland, becoming 'orphaned' during mid-Neoproterozoic Rodinia breakup.

The juvenile Hf and Nd signatures of 1.4 Ga A-type granites preserved as clasts and detrital zircons in Transantarctic Mountains sediments (Goodge *et al.* 2008) have been used to support a connection with western Laurentia in the SWEAT juxtaposition. However, Goodge *et al.* (2008; their fig. 3a) illustrate other regions of the world with comparable magmatism of the same age: Cathaysia, eastern Congo, southern Amazonia and south-western Baltica. If the revised Rodinia position for Australia + Mawsonland (Fig. 4b) is correct, then the general proximity of 1.4 Ga A–type granite terrains in Congo and Baltica make them the most attractive candidates as the originally contiguous extensions of the Antarctic magmatic province in pre-Rodinian times.

Kalahari

As noted in a recent review of late Mesoproterozoic palaeomagnetic data from southern Africa (Gose *et al.* 2006), the two anchors of the Kalahari APW path are the *c*. 1100 Ma Umkondo grand-mean pole of highest reliability, followed by various moderately well grouped poles from *c*. 1000 Ma terranes within the Namaqua–Natal orogen. These two anchor poles permit Kalahari to have been a member of Rodinia throughout the intervening time; they are separated by about 80° or 100° of great-circle arc, depending on relative geomagnetic polarity, the larger value being similar to that separating Laurentian poles on the 'master' Rodinian APW path of the same pair of ages (Logan and Grenville loops, respectively). The precise dating of both Umkondo and early Keweenawan poles at 1108 Ma, with a pronounced geomagnetic polarity bias in both units, constrains the hemisphere option of relative reconstructions between the two cratons, such that the Grenville and Namaqua orogens cannot face each other (Hanson *et al.* 2004; Gose *et al.* 2006) as earlier proposed. In addition to this polarity constraint, if the *c*. 1000 Ma poles are aligned then Kalahari can occupy only one of two positions in relative palaeolatitude and palaeolongitude to Laurentia plus its surrounding cratons in Rodinia. The standard depiction of Kalahari's geon-10 APW path (e.g. Powell *et al.* 2001; Evans *et al.* 2002; Meert & Torsvik 2003; Tohver *et al.* 2006; Gose *et al.* 2006; Li *et al.* 2008) is shown in Figure 6a in simplified form, using the two anchor poles plus that of the Kalkpunt redbeds of eastern Namaqualand (Briden *et al.* 1979). Although Powell *et al.* (2001) suggested an age of 1065 Ma for the Kalkpunt red beds, recent U–Pb dating of a

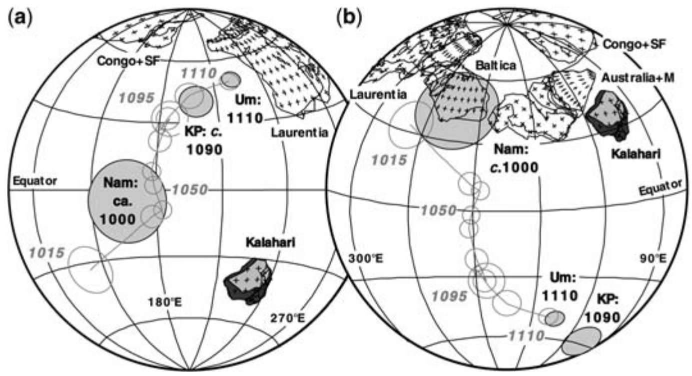

Fig. 6. Superposition of Kalahari's 1110 Ma Umkondo palaeomagnetic pole with polarity constraint tied to the early Keweenawan Logan sills pole from Laurentia (Hanson *et al.* 2004; Gose *et al.* 2006), plus younger poles from the Namaqua and Natal Provinces in various polarity options (poles listed in Table 2). Panel (**a**) shows a large distance between Kalahari and the rest of Rodinia, whereas panel (**b**) illustrates the preferred reconstruction herein. Euler parameters for the rotation of Kalahari and its poles from the present African reference frame to Laurentia, in present North American coordinates, are (81.5°N, 187.4°E, −163.4°CCW) in panel (A) and (32.5°N, 307.5°E, +76.5°CCW) in panel (B).

conformably underlying rhyolite indicates an age of only slightly younger than *c.* 1095 Ma (Pettersson *et al.* 2007). The APW arc length transcribed by this polarity option of the three poles is somewhat shorter than that of the Keweenawan APW track of Laurentia, but dating of the Namaqua–Natal poles is forgiving enough to allow for the precise mismatch. However, the reconstruction derived by this APW superposition is one in which Kalahari is widely separated from all other cratons in Rodinia – even if one were to choose more standard models involving Australia and other cratons to the SW of Laurentia. The Kalahari reconstruction shown in Figure 6a is, however, similar to that of Piper (2000, 2007), but as noted above this reconstruction produces numerous palaeomagnetic mismatches when high-quality individual results are considered rather than broad means.

The alternative polarity option for the Namaqua-Natal poles, while preserving the sanctity of geomagnetic polarity matching of Umkondo and early Keweenawan poles, produces the reconstruction shown in Figure 6b. The reconstruction juxtaposes Kalahari's northern margin adjacent to the Vostok (western) margin of Mawsonland (Fig. 6). This polarity option for Namaqua–Natal poles provides a more acceptable APW arc length relative to the Keweenawan APW track and Grenville APW loop from Laurentia, but it introduces a different problem: the Kalkpunt pole now falls on the other side of Umkondo, and reconstructs to a position slightly beyond the apex of the Logan APW loop in the Laurentian reference frame (Fig. 6b). Rather than invoke an additional APW loop, this discrepancy is perhaps best explained by local vertical-axis rotation of the Koras Group, which is only locally exposed within a region of large strike-slip shear zones (Pettersson *et al.* 2007). About 30 degrees of local rotation are required to bring the Kalkpunt pole into alignment with poles from the younger Keweenawan lavas and intrusions at *c.* 1095 Ma.

The preferred reconstruction of Kalahari shown in Figure 6b is thus the only possible way to include this craton in the Rodinia assembly as early as 1100 Ma according to existing palaeomagnetic constraints. Other published solutions involve late collision of Kalahari into Rodinia at *c.* 1000 Ma (Pisarevsky *et al.* 2003*a*; Li *et al.* 2008). The well-known Namaqua-Natal belt of southern Kalahari shows the main phases of deformation at *c.* 1090–1060 Ma (Jacobs *et al.* 2008), which is typically correlated in an opposing collisional sense to the Ottawan orogeny of the Grenville Province in Laurentia. These reconstructions, however, must either violate the geomagnetic polarity match between early Keweenawan and Umkondo poles, or invoke an implausible 180-degree rotation of Kalahari relative to Laurentia as they approached each other in geon 10.

In the preferred reconstruction here (Fig. 6b), the more proximal Mesoproterozoic margin to the Laurentian side of Rodinia is the present north-western side of Kalahari. Along that margin, a single *c.* 1300–1200 Ma orogen has been hypothesized (Singletary *et al.* 2003), and this orogen was stabilized prior to widespread large igneous province mafic magmatism at about 1110 Ma. In the revised Rodinia reconstruction presented herein, the NW Kalahari orogen is proposed to record collision between Kalahari and the Vostok margin of Australia + Mawsonland (Fig. 6). A complex collisional triple junction, suturing this orogen, the Namaqua belt and the Albany belt in Western Australia, would be partly reworked by subsequent Pan-African (Damaride) and Pinjarran tectonics, and partly buried by Antarctic ice; testing this model by correlating the details of the three collisions will be a challenging enterprise.

India, South China, Tarim

Relative to Australia, the reconstructed positions of India, South China and Tarim are similar in this Rodinia model to previously published versions (Fig. 7). The reconstruction of India to Australia essentially follows Torsvik *et al.* (2001), that of South China relative to India follows Jiang *et al.* (2003) and that of Tarim to Australia follows Li *et al.* (1996), Powell & Pisarevsky (2002) and Li *et al.* (2008). Palaeomagnetic poles from these cratons are sparse, but they provide important constraints on Rodinia configurations of these blocks and also support the existence of a large loop in the Rodinian APW path at *c.* 800 Ma. Discussing the results in detail, numerous Indian poles (reviewed by Malone *et al.* 2008) are summarized by the three depicted in Figure 7. The most reliable is from the Malani rhyolitic large igneous province of Rajasthan, with various U–Pb ages centred around 770 Ma (Torsvik *et al.* 2001; Malone *et al.* 2008). Aside from this result, which has been reproduced numerous times in the past few decades, the Indian palaeomagnetic poles from Rodinia times are questionable either in quality or in age. The oft-cited pole from Harohalli alkaline dykes was previously assigned an age of *c.* 815 Ma, based on Ar/Ar ages (Radhakrishna & Mathew 1996). However, new U–Pb zircon data from these dykes suggest a much older age of *c.* 1190 Ma (cited in Malone *et al.* 2008). If the latter age is correct, then the Harohalli dykes pole is irrelevant for the present discussion, because this portion of Rodinia is proposed herein to have assembled around 1100 Ma or younger. There is also the pole from the well-dated Majhgawan kimberlite (1074 ± 14 Ma by Ar/Ar; Gregory *et al.* 2006), which is nearly identical to poles from the nearby Rewa and Bhander sedimentary succession (Malone *et al.* 2008). The latter units have age uncertainties on the order of 500 Ma, as summarized by Malone *et al.* (2008). No field stability tests have been performed on either the Majhgawan kimberlite or the Rewa/Bhander units, so there remains the possibility that these poles represent a two-polarity magnetic overprint across north-central India. Such an interpretation could readily explain the large discordance between the Majhgawan virtual geomagnetic pole (VGP; not averaging geomagnetic secular variation due to brief emplacement of the kimberlite) and those from the nearly coeval Wajrakarur kimberlite field in south-central India (Miller & Hargraves 1994).

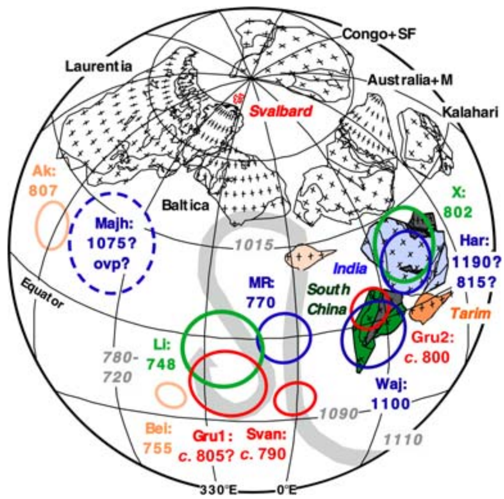

Fig. 7. Reconstruction of India (blue), South China (green), and Tarim (peach) near Australia as commonly depicted in Rodinia models. As with Figures 3–6, all cratons and poles have been rotated into the present North American (Laurentian) reference frame (Table 3). The Laurentian APW path is simplified into a curve (light grey) for clarity. Also shown are three poles (red colour) with poor absolute age control but correct stratigraphic order from Svalbard (Maloof *et al.* 2006; Table 2), rotated to a modified position north of Greenland (Table 3) for better APW matching with both the Laurentian poles from geon 7 and the proposed APW loop at *c.* 800 Ma. Palaeomagnetic poles (abbreviated as in Table 2) are shown in the colours of their host cratons. The location of Tarim poles is consistent with the craton reconstruction in darker colour; the lighter-coloured alternative Tarim reconstruction aligns the Aksu dykes pole (Ak) with *c.* 800 Ma poles from other cratons, but results in a mismatch of the Beiyixi volcanics pole (Bei); poles from this alternative reconstruction are not illustrated, for sake of clarity. Queried ages of some of the Indian poles are discussed in text.

If either of these kimberlite poles is primary, then their significant distances from the Laurentian APW path would negate the proposed reconstruction (Fig. 7) at that time. It is possible that collision between India (plus attached Cathaysia block of South China) and NW Australia occurred after 1100–1075 Ma, accounting for the reconstructed pole discrepancy.

Palaeomagnetic poles from China are more straightforward to interpret. In South China (Yangtze craton), the Xiaofeng dykes yield a high palaeolatitude at 802 ± 10 Ma (Li *et al.* 2004), and the Liantuo Formation red beds yield a moderate palaeolatitude at 748 ± 12 Ma (Evans *et al.* 2000). Similarly, the Aksu dykes in Tarim were emplaced at high palaeolatitude at 807 ± 12 Ma (Chen *et al.* 2004), and the Beiyixi volcanics were erupted at lower palaeolatitudes (Huang *et al.* 2005) at 755 ± 15 Ma (Xu *et al.* 2005). Matching these two pairs of poles from South China and Tarim, however, results in a large distance between the cratons (not shown in Fig. 7), inconsistent with their strongly compatible Sinian geological histories (Lu *et al.* 2008*a*). Figure 7 shows two alternative positions of Tarim relative to the cratons heretofore discussed. The preferred position is shown in a darker colour, along with the properly rotated pair of Tarim poles. In this position, where Tarim is directly adjacent to both South China and (present NW) India, the 755 Ma Beiyixi pole is aligned with middle-geon-7 poles from Laurentia and other cratons; however, the 807 Ma Aksu dykes pole is discordant (Fig. 7). This could suggest post-800 Ma convergence between Tarim and Rodinia, or it could also be due to unrecognized local vertical-axis rotations of the Aksu area, as suggested by Li *et al.* (2008) to be a general problem for the minimally studied Tarim block.

Alternatively, the Aksu dykes pole could be aligned with the *c.* 800 Ma pole from the coeval Xiaofeng dykes in South China; in which case Tarim reconstructs next to northern Australia (lighter shade of peach colour in Fig. 7) in the same sense as Li *et al.* (1996, 2008). The 755 Ma Beiyixi pole, however, is removed from the Rodinian APW path in this reconstruction. This would suggest either early (pre-755 Ma) rifting of Tarim from Rodinia, or local vertical-axis rotations of the Quruqtagh region where the Beiyixi volcanics are exposed. A third alternative reconstruction of Tarim – adjacent to eastern Australia, based on a proposed radiating dyke swarm at *c.* 820 Ma (Lu *et al.* 2008*a*) – is broadly compatible with the palaeomagnetic data from 755 Ma but, ironically, not *c.* 800 Ma.

The present analysis leaves the position of Tarim somewhat uncertain, but the preferred position is that described first, above, and illustrated with darker peach colour in Figure 7. The main reason for this preference is that new palaeomagnetic results from Cambrian–Ordovician sedimentary rocks in the Quruqtagh area (Zhao *et al.* 2008) are most compatible with the Gondwanaland APW path if Tarim is reconstructed near Arabia, that is separated from Australia by India and South China. If either the northern or eastern Australian juxtapositions is correct for Tarim in Rodinia, then Tarim would need to rift from that position and re-collide with East Gondwanaland in its peri-Arabian position prior to mid-Cambrian time. Neither Tarim nor northern India records Ediacaran-age orogenic activity that would document such convergence.

Although the *c.* 800 Ma poles just described are far removed from the established Laurentian APW path in the proposed reconstruction, they constitute important independent support from several Rodinian cratons that they – if not the entire supercontinent – experienced an oscillatory pair of rotations at that time. The kinematic evidence for this proposed rotation does not specify a dynamic cause, but inertial-interchange true polar wander (IITPW) events are the most straightforward explanation (Li *et al.* 2004; Maloof *et al.* 2006). When the Svalbard magnetostratigraphic data of Maloof *et al.* (2006) are considered (red colour in Fig. 7), they provide the hitherto unrecognized evidence from Laurentia for the APW loop indicated by India (if Harohalli dykes are *c.* 800 Ma), South China, Tarim and Congo (Fig. 5b). The precise reconstruction of Svalbard relative to Greenland is uncertain, but direct connection between the two areas of Laurentia are strongly supported by lithostratigraphy (Maloof *et al.* 2006). Also, because the Svalbard APW shift is recorded in several widely separated, continuously sampled magnetostratigraphic sections, local vertical-axis rotations cannot account for the directional shifts: the APW loop at *c.* 800 Ma is a genuine feature of the Laurentian palaeomagnetic database that must be included in all Rodinia models.

The reconstruction of India, South China and Tarim, adjacent to Australia as shown in Figure 7, produces some intriguing tectonic juxtapositions, in which compatible histories can be considered as predictions of the model. First, the Sibao orogen in South China (Li *et al.* 1996, 2002) appears to strike directly into northwestern India, where earliest Neoproterozoic tectonomagmatic activity is postulated to be continuous with the Delhi foldbelt in India (Deb *et al.* 2001), under Neoproterozoic sedimentary cover of Rajasthan and north–central Pakistan. If this represents a collisional orogen, then most of cratonic India should have more affinities with the Cathaysia block in South China, colliding with the Yangtze + Tarim craton during final Rodinia assembly. The Tarimian orogeny of similar age (Lu *et al.* 2008*a*) could express a poorly exposed continuation of this collisional belt.

On the other side of India, the *c.* 1000–950 Ma Eastern Ghats orogen (Mezger & Cosca 1999) and its continuation as the Rayner terrane in Antarctica (Kelly *et al.* 2002), extends east of Prydz Bay (Kinny *et al.* 1993; Wang *et al.* 2008), and according to this reconstruction splays into the Edmund foldbelt of Western Australia, which deformed 1070 Ma sills and their host Bangemall basin sedimentary rocks about tight NW–SE axes and led to moderate isotopic disturbance (Occhipinti & Reddy 2009). The full extent of this orogen is probably hidden under the East Antarctic icecap (including the Gamburtsev Subglacial Mountains; Veevers & Saeed 2008), and likely involves smaller Archaean–Palaeoproterozoic cratonic fragments such as the Ruker terrane (Phillips *et al.* 2006). The orogen is proposed here to involve collision with Kalahari along the latter craton's Namaqua margin at *c.* 1090–1060 Ma (Jacobs *et al.* 2008). Tectonothermal events of similar age in the Central Indian Tectonic Zone (Chatterjee *et al.* 2008; Maji *et al.* 2008) connect the Delhi and Eastern Ghats/Rayner orogens in poorly understood ways.

The reconstruction also suggests that the precisely coeval igneous events recorded on several cratons at 755 Ma are genetically related: Mundine Well dyke swarm in Australia (Wingate & Giddings 2000), Malani large igneous province in India (Torsvik *et al.* 2001), Nanhua rift and related provinces in South China (Li *et al.* 2003) and Beiyixi volcanics in Tarim (Xu *et al.* 2005). As will be shown below, western Siberia also reconstructs immediately adjacent to Tarim, and the Sharyzhalgai massif contains mafic dykes of precisely the same age (Sklyarov *et al.* 2003). The Malani region in India is proposed here as the central focus of a hotspot or mantle plume with radiating arms extending across these cratons.

North China, Siberia

Both North China and Siberia lack coherent late Mesoproterozoic ('Grenvillian') orogens, although possible vestiges can be found along the northern and southern margins of North China (Zhai *et al.* 2003; but see also discussion in Lu *et al.* 2008*b*). Similar carbonate-dominated mid-Proterozoic platform or passive-margin sedimentary successions on both cratons have inspired, along with palaeomagnetic support, hypotheses of a close palaeogeographic connection between the two blocks in Rodinia and in earlier times (Zhai *et al.* 2003; Wu *et al.* 2005; Zhang *et al.* 2006; Li *et al.* 2008). A recent U–Pb age determination of *c.* 1380 Ma on ash beds in the upper part of the North China cover succession (Su *et al.* 2008), however, shows that this succession is almost entirely older than the bulk of 'Riphean' sediments across Siberia (Khudoley *et al.* 2007). The older age of the North China succession also demonstrates that there are only two moderately reliable palaeomagnetic poles (Zhang *et al.* 2006) from the Rodinia interval: the Cuishang Formation (*c.* 950 Ma?) and the Nanfen Formation (*c.* 790 Ma?). Ages from both of these formations are very tenuous.

Pisarevsky and Natapov (2003) summarized the Meso-Neoproterozoic stratigraphic record across the Siberian craton, as well as its palaeomagnetic database. The most reliable palaeomagnetic poles define an APW trend that is supported by less reliable results; only the three most reliable are included in this synthesis, but the conclusion is not affected by incorporating the others. The present analysis does not include the high-quality Linok Formation pole from the Turukhansk region (Gallet *et al.* 2000), because it restores precisely atop that of the likely correlative Malgina Formation in the Uchur-Maya region marginal to the Aldan shield, after restoration of the Devonian Vilyuy rift in central Siberia (Table 1).

Matching of the Siberian APW path from the Uchur-Maya region with the Keweenawan APW track to Grenville loop from Laurentia results in two possibilities, because of geomagnetic polarity options. The first option (not shown) produces the typical reconstruction of Siberia with its southern margin in the vicinity of northern Laurentia (option 'A' of Pisarevsky & Natapov 2003; Pisarevsky *et al.* 2003*a*; Li *et al.* 2008; Pisarevsky *et al.* 2008), The hypothesized reconstruction of Siberia (Fig. 8) is essentially the same as 'option B' of Pisarevsky & Natapov (2003) and the first option discussed by Meert & Torsvik (2003). Both of those papers concluded that such a reconstruction would probably exclude Siberia because of the great distance from Laurentia, but the present revised Rodinia model covers this gap with Baltica, Australia, India, and North China.

Because there is scant to no evidence for a 'Grenvillian' orogen between India and North China in the proposed reconstruction (Fig. 8), a corollary of the model is that those two cratons were joined in similar fashion since their Palaeoproterozoic consolidations. Zhao *et al.* (2003) described a series of correlations between southern India and eastern North China, and proposed four possible reconstructions in which those two regions could have been directly juxtaposed. In this paper I present a fifth alternative connection (Fig. 8), which, unlike the previous four, is in agreement with the Rodinia-era palaeomagnetic poles described above. There are no reliable and precisely coeval palaeomagnetic results from the two cratons yet available (Evans & Pisarevsky 2008) to test their earlier hypothesised assembly.

Siberia is also proposed to have been connected to India and North China prior to Rodinia's amalgamation in the late Mesoproterozoic. Pisarevsky & Natapov (2003) summarized the Riphean

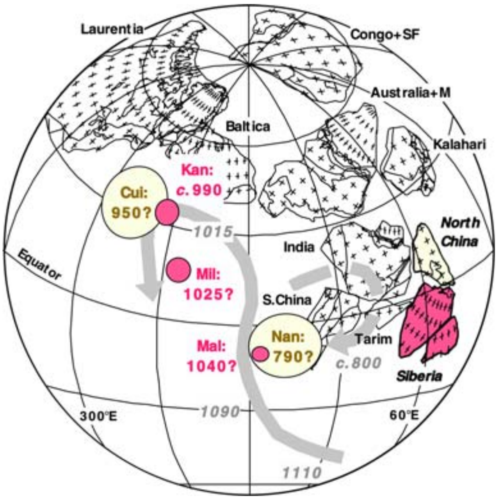

Fig. 8. Reconstruction of North China (tan) and Siberia (pink) directly adjacent to India on the outer edge of Rodinia. All cratons and their similarly coloured poles have been rotated into the present North American (Laurentian) reference frame (Table 3). The Laurentian APW path is simplified into a curve (light grey), with the additional APW loop at *c*. 800 Ma (see text and Fig. 7) indicated by the dashed segment. Among the North China and Siberia poles shown here, all but the Kandyk Formation (Kan) are poorly constrained in age.

stratigraphic architecture of the present-day margins of Siberia, demonstrating in many areas a clear thickening of strata away from the craton into deeper-water sedimentary facies. The long-lived Mesoproterozoic connections to North China and India (Fig. 8) would be inconsistent with the Siberian stratigraphic record if it could be demonstrated that the Turukhansk, Igarka, or northern Siberian margins faced the open ocean through the Meso-Neoproterozoic transition. However, in the best-documented areas of Turukhansk, there is no preserved record of substantial westward thickening of the Riphean stratigraphy as would be expected for a continent–ocean crustal transition, nor is there any preserved evidence of deep-water facies in the middle Riphean succession (Bartley *et al.* 2001; Pisarevsky & Natapov 2003; Khudoley *et al.* 2007). According to the available information, the present northwestern margin of Siberia is more likely a mid–late Neoproterozoic truncation of a more extensive Rodinian plate with widespread middle Riphean epicratonic cover.

Amazonia, West Africa, Plata

For the past 25 years, Amazonia has been the craton of choice for proposed colliders with the Grenville margin of Laurentia at the end of the Mesoproterozoic Era (e.g. Bond *et al.* 1984; Dalziel 1991, 1997; Hoffman 1991; Weil *et al.* 1998; Pisarevsky *et al.* 2003*a*; Tohver *et al.* 2006; Li *et al.* 2008). This is perhaps surprising, given how many alternative possibilities exist due to the global preponderance of late Mesoproterozoic ('Grenvillian') orogens among the world's cratons (Fig. 1). The Laurentia + Amazonia connection is broadly supported by Pb-isotopic signatures (Loewy *et al.* 2003), but without a globally comprehensive dataset such comparisons are merely indicative rather than diagnostic. If any craton-scale tectonic comparisons are to be made, then the progressively younging, accretionary character of Amazonia would fit much better *along strike* of southwestern Laurentia (Santos *et al.* 2008) rather than in the mirrored configuration of the two cratons in typical Rodinia models. The palaeomagnetic evidence in support of the Laurentia + Amazonia connection in Rodinia is not particularly strong, either. Based on new palaeomagnetic data, Tohver *et al.* (2002, 2004) and D'Agrella-Filho *et al.* (2003, 2008) have successively modified the kinematics of the putative Laurentia + Amazonia collision. If confined to such a collisional model, the data now demand two unusual kinematic features: (1) *c*. 5000 km of sinistral motion with Amazonia occupying positions adjacent to Texas and Labrador at 1.2 and 1.0 Ga, respectively; and (2) 90° of anticlockwise rotation of Amazonia relative to Laurentia, so that Amazonia appears to roll like a wheel along the Grenvillian margin during its syncollisional sinistral odyssey. Such odd kinematics could be avoided if the observations were not confined by the initial assumption of a Laurentia + Amazonia collision.

Figure 9 shows the available palaeomagnetic poles from Amazonia during the Rodinia interval. The Nova Floresta (NF) and Fortuna Formation (FF) poles are fully published (Tohver *et al.* 2002; D'Agrella-Filho *et al.* 2008), whereas the Aguapei sills (Agua) result is presented in abstract only (D'Agrella-Filho *et al.* 2003). This latter result is important for constraining the possible position of Amazonia in Rodinia, however, because it, like the Nova Floresta data, is from mafic igneous rocks constrained in age by the Ar/Ar method. The Fortuna Formation red beds are interpreted as gaining their diagenetic hematite remanence at *c*. 1150 Ma, according to SHRIMP U–Pb dating of xenotime (D'Agrella-Filho *et al.* 2008), but that age assignment is questioned here because the likely early-diagenetic xenotime U–Pb age may have little bearing on the timing of hematite pigmentation in the studied sandstone. The reconstruction of Amazonia relative to Laurentia shown in Figure 9 predicts a younger age of *c*. 1020 Ma for

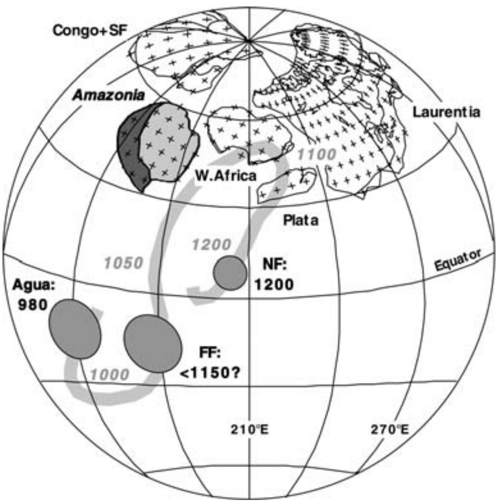

Fig. 9. 'COBRA' reconstruction of Amazonia, West Africa, and Plata near western Laurentia. Among these three cratons, only Amazonia has reliable palaeomagnetic constraints from the Rodinia time interval. Cratons are rotated into the present North American reference frame according to Table 3.

the growth of remanence-bearing hematite pigments in the Fortuna Formation.

Because the three Amazonia poles fall roughly along the same great circle, it is possible to consider the alternative polarity assignment relative to the Laurentian APW path; in that case, however, Amazonia reconstructs directly atop Australia and Kalahari (not shown in Fig. 9).

As recently reviewed by Tohver *et al.* (2006), palaeomagnetic results from the Meso-Neoproterozoic of West Africa are wholly unreliable. For the Plata Craton, Rapalini & Sánchez-Bettucci (2008) similarly show that there are no reliable Rodinian palaeomagnetic constraints. The separation between western Laurentia and Amazonia (Fig. 9), must be filled with cratonic fragments that would form the conjugate rift margin of the Cordilleran miogeocline in either mid-Neoproterzoic or terminal Neoproterozoic times (Bond 1997; Colpron *et al.* 2002; Harlan *et al.* 2003). Given that all of the other large cratons of the world have been accounted for in the present Rodinia model, the simplest placements of West Africa, Plata and smaller cratonic fragments in South America (Fuck *et al.* 2008) are within the gap between Laurentia and Amazonia (Fig. 9). These juxtapositions are collectively referred to as COBRA, named after the general link between the proto-Cordilleran rifted margin of Laurentia with the proto-Brasiliano/Pharuside rifted margins of the West Gondwanaland cratons.

COBRA unites truncated Archean and Palaeoproterozoic basement provinces among these cratons, suggesting that the amalgamation persisted from the assembly of supercontinent Nuna at 1.8 Ga (Hoffman 1996) until Rodinia fragmentation in mid-Neoproterozoic times. In this reconstruction, 2.1–2.3 Ga terranes in subsurface Yukon-Alberta (Ross 2002) continue into the Birimian (Gasquet *et al.* 2004) and Maroni–Itacaiunas (Tassinari *et al.* 2000) provinces of West Africa and Amazonia, respectively. The Archean Wyoming/Medicine Hat craton (Chamberlain *et al.* 2003) would have been contiguous with the Nico Perez terrane in Uruguay (Hartmann *et al.* 2001) and Luis Alvez craton in southern Brazil (Sato *et al.* 2003), constituting parts of an elongate collage of Archean regions extending to the Leo massif in West Africa (Thiéblemont *et al.* 2004) and the Carajas block in Brazil (Tassinari *et al.* 2000). Palaeoproterozoic accretion to the south of these provinces includes the Mojave province (Bennett & De Paolo 1987) as the orphaned edge of an extensive region of juvenile 2.2–1.7 Ga terranes in South America (Tassinari *et al.* 2000; Santos *et al.* 2000, 2003), characterized by highly radiogenic (^{207}Pb-enriched) common-lead isotopic signatures (Wooden & Miller 1990; Tosdal 1996). Detrital zircons of 1.5–1.9 Ga age in the Mesoproterozoic Belt-Purcell basin (Ross *et al.* 1992; Ross & Villeneuve 2003) find numerous potential sources in extensive granites of that age interval in South America (Tassinari *et al.* 2000). The 1.3–1.1 Ga Grenville orogen traces southwestward through Sonora (Iriondo *et al.* 2004) and, according to the COBRA hypothesis, into Brazil and Bolivia, where it bifurcates into the Aguapei and Sunsas belts (Sadowski & Bettencourt 1996). Direct juxtaposition of these provinces in Amazonia with SW North America (Santos *et al.* 2008) is not allowable palaeomagnetically, by any of the three poles discussed above, regardless of their precise ages within the Meso-Neoproterozoic interval.

COBRA is proposed to have begun rifting at 780 Ma, manifested by the Gunbarrel large igneous province in North America (Harlan *et al.* 2003), and preceding highly oblique dextral separation (Brookfield 1993) that prolonged rift magmatism to at least 685 Ma (Lund *et al.* 2003) and delayed passive-margin thermal subsidence to latest Neoproterozoic time (Bond 1997). Precise geochronology of the Gourma–Volta rift basins in West Africa, presently lacking, could provide a direct test of the proposed COBRA fit. Indications of *c.* 780 Ma mafic magmatism within a possible West African craton fragment in the westernmost Hoggar shield (Caby 2003) and along the distal western São Francisco margin in Brazil (Pimentel *et al.* 2004) may extend the Gunbarrel province into those regions. Proposing a sequence of rifts in southern South America is difficult due to Phanerozoic cover (compare Ramos 1988 and Cordani *et al.* 2003), but kinematic constraints on a COBRA–West Gondwanaland transition require some events at *c.* 780 Ma and others younger, represented by glaciogenic successions on southernmost Amazonia (Trindade *et al.* 2003) and eastern Rio Plata (Gaucher *et al.* 2003) that are correlated to the Marinoan ice age ending at 635 Ma (Condon *et al.* 2005).

Nuna to Rodinia to Gondwanaland

Any palaeomagnetic reconstruction of a supercontinent requires concordance of data from constituent cratons into a coherent aggregate APW path. Such a path for the proposed long-lived Rodinia model is shown in Figure 10. The numerous loops and turns could raise objection due to the implied complexity of the supercontinent's motion through its nearly 400 Ma of existence. Nonetheless, all of the loops are generated simply by joining the Laurentian and Baltic APW paths in the proposed reconstruction (Fig. 3). The Laurentia + Baltica juxtapositions, before and after 1100 Ma, are the least controversial aspect of the present Rodinia model, so the APW complexity of Rodinia will be implied by any alternative model incorporating

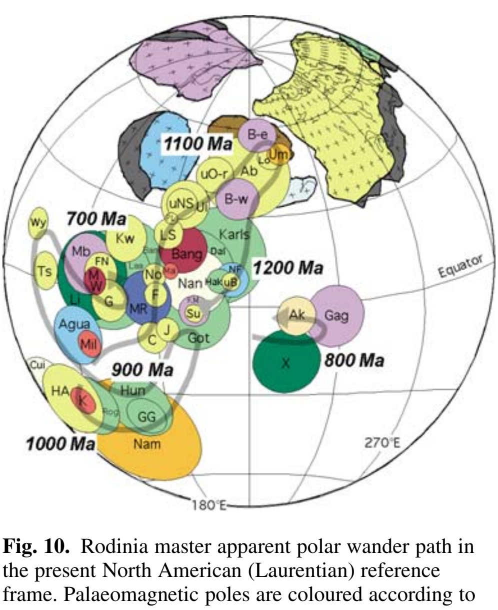

Fig. 10. Rodinia master apparent polar wander path in the present North American (Laurentian) reference frame. Palaeomagnetic poles are coloured according to the host cratons as depicted here and in Figure 1, and are tabulated with abbreviations in Table 2. Late Mesoproterozoic ('Grenvillian') orogenic belts are shaded grey.

these relationships. Adding all other cratons' reliable palaeomagnetic data from 1100–750 Ma, in the 'radically' revised Rodinia proposed herein, has resulted in no additional APW loops.

The complexity of Rodinia's aggregate motion is largely due to oscillatory swings in the APW path between 1200 and 900 Ma, and the newly recognized 800 Ma loop. The 1100–1000 Ma segment, in particular, covers >10 000 km, thus averaging rates of latitudinal motion exceeding 10 cm/yr. This would be fast enough for oceanic plates of the modern world, but it is exceptionally fast for a plate containing a supercontinent, presumably with numerous lithospheric keels, to slide over the asthenosphere. An alternative explanation for the majority of Rodinia's motion, and one which more easily accommodates its oscillatory nature, is that of TPW. Evans (2003) incorporated Rodinia's latitude shifts as due to oscillatory TPW about a prolate axis of the geoid inherited from the previous supercontinent, Nuna (a.k.a. Columbia).

Because the Siberian craton is surrounded on many sides by *c.* 1700–1500 Ma rifted passive margins (Pisarevsky & Natapov 2003), it is likely to have lain near the centre of Nuna. In contrast, Figure 11 shows Siberia at the edge of Rodinia. This would suggest that the kinematic evolution between Nuna and Rodinia was partly 'extroverted' (Murphy & Nance 2003, 2005). However, proximity of the Amazonia, West Africa, Congo + São Francisco and Plata cratons in the proposed Rodinia (Fig. 11) suggests long-lived connections from the Palaeoproterozoic (similarities noted by Rogers 1996, and inspiration for his conjectured 'Atlantica' assemblage of that age), rearranging only moderately to form portions of Rodinia and Gondwanaland. The relationships among this group of cratons, as well as the longstanding proximity between Laurentia and Baltica (through nearly the entire latter half of Earth history) suggest a more 'introverted' kinematic style of supercontinental evolution.

According to the Rodinia model proposed herein, assembly took place rapidly at *c.* 1100 Ma, although there are earlier collisions of cratons that persisted into Rodinia time. Table 3 lists the postulated ages of assembly for each craton for the rotation parameters given relative to Laurentia. Some of the proposed connections date from the time of cratonization, typically the Palaeoproterozoic amalgamations of Archean craton, set within and among juvenile terranes. The relevant cratons in this category are those (West Africa, Plata, Amazonia) proposed to reconstruct near Laurentia's proto-Cordilleran margin, where mid–late Neoproterozoic rifting cut across truncated basement fabrics. The hypothesized one-billion-year shared history of these blocks constitutes a powerful

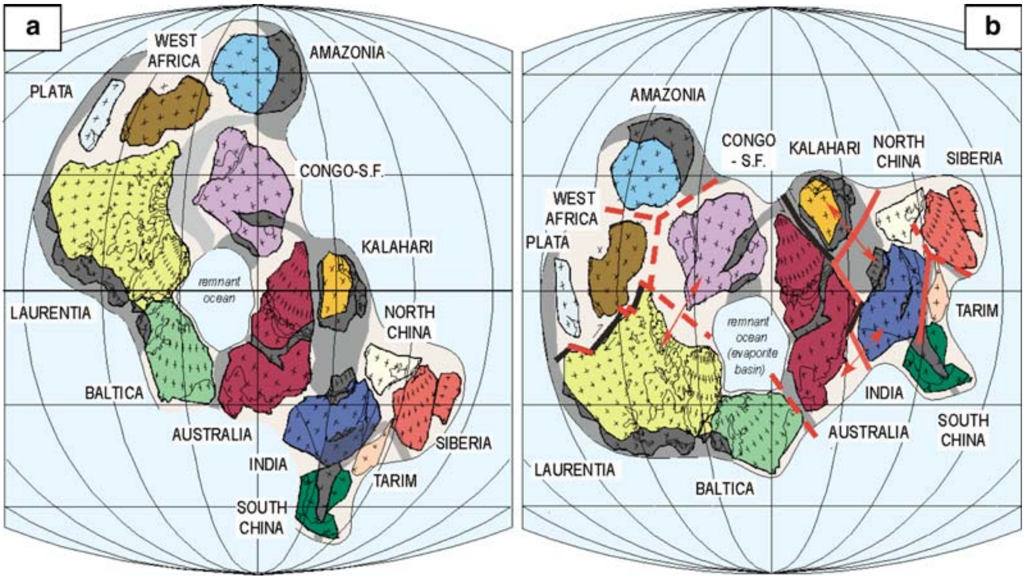

Fig. 11. Rodinia radically revised, reconstructed to palaeolatitudes soon after assembly and shortly prior to breakup. (**a**) 1070 Ma reconstruction showing extents of late Mesoproterozoic ('Grenvillian') orogens, both exposed and inferred (dark grey), and the earlier collision between Laurentia and Congo (light grey). The figure is slightly anachronistic, as several blocks are proposed to have collided at 1050 Ma, and South China and Tarim could have joined as late as *c*. 850 Ma (Table 3); however, palaeogeographic reconstructions for those younger ages would involve substantial components of Rodinia over the poles, rendering the Mollweide projection uninformative. (**b**) 780 Ma reconstruction showing incipient breakup rift margins (red) and transform offsets (black). Ridge segments are dashed where not precisely constrained in location.

prediction for future palaeomagnetic tests among these data-scarce blocks.

Because Table 3 lists all rotations relative to Laurentia, it does not provide information on relationships between non-Laurentian cratons or portions thereof, yet some of these may have similarly ancient connections. For example, as discussed above, one hypothesis resulting from the proposed configuration of Congo and Mawsonland, is that the Tanzania–Bangweulu block was originally part of Mawsonland and transferred to Congo via collision at *c*. 1100 Ma and rifting in the mid-Neoproterozoic. Palaeomagnetism of the three Palaeoproterozoic blocks (Congo, Tanzania, Mawsonland) can ultimately test this proposition. Another example is the proposed Palaeo-Mesoproterozoic connection among India, North China, and perhaps also Siberia.

Where Table 3 presents a range of ages, these are set by the limits of palaeomagnetic concordance versus discordance when rotated by the given Euler parameters. Parenthetical values indicate a best estimate based on geological histories of either collision or rifting, or by 'piggy-back' of an intervening collision or rift with Laurentia. The identical-aged *c*. 1050 Ma onset of proposed Euler reconstructions listed for India, North China and Siberia are an example of this latter case; all these cratons are proposed to have sutured, as a unified plate, to the Rodinia assemblage along the Eastern Ghats–Rayner orogen.

Although this model of Rodinia includes widespread assembly of the supercontinent at 1100–1050 Ma, probably the most contentious of its implications is that all the large cratons are accounted for, and there are no sizable blocks left to play colliding roles in any of the Sveconorwegian, Grenville and Sunsas orogens. Instead, these three orogens are placed along strike of each other, facing the Mirovian Ocean. All three orogens are characterized by an extensive prehistory of accretionary tectonism along the same margins, with successively younger age provinces progressing outward from Archaean cratonic nuclei. The great width and longevity of these three accretionary systems is reminiscient of Panthalassan or circum-Pangaean orogens of the Phanerozoic. The model proposed here requires originally farther oceanward extents of the three orogens as younger juvenile material would have accreted during the early Neoproterzoic. Then, mid-Mirovian spreading ridges would have propagated into the orogens and

Table 3. *Rotation parameters to Laurentia: Rodinia radically revised*

Craton	Maximum age	Minimum age	Euler rotn.		
			°N	°E	°CCW
Baltica[†]	1120–1070	615–555 (610)	81.5	250.0	−50.0
Australia	1140–1070	≤755 (720)	−12.5	064.0	134.5
Congo (ex.Tanz)	≥1375 (1500)	755–550 (720)	−24.0	249.0	128.5
Kalahari	1235–1110	≤1000 (790?)	32.5	307.5	76.5
India	1100–770 (1050)	≤770 (750)	04.0	066.0	93.0
South China	≥800 (850)	≤750 (750)	17.5	067.0	178.0
Tarim	≥755 (850?)	≤755 (750)	−41.5	161.0	57.0
Svalbard	cratonization	Devonian?	86.0	120.0	−48.0
North China	≥950 (1050)	≤790 (750?)	42.0	072.0	−113.0
Siberia (Aldan)[‡]	≥1040 (1050)	≤990 (750?)	32.5	002.5	−91.5
Amazonia	≥1200 (crat.)	≤980 (630?)	63.0	313.0	−139.0
West Africa	cratonization	(≤780)	−54.0	246.5	115.0
Plata	cratonization	(≤780)	−18.5	239.0	125.5

[†]Alignments are similar to those discussed in Buchan *et al.* (2000) and Pisarevsky *et al.* (2003*a*).
[‡]Reconstruction is similar to option 'B' of Pisarevsky & Natapov (2003) and that presented by Meert & Torsvik (2003).

removed the outboard, youngest terrains as 'ribbon' continents. The protracted record of tectonism in the Scottish Highlands, inlcuding the Knoydartian orogeny at *c.* 850–800 Ma with further phases possibly as young as *c.* 750–700 Ma (reviewed by Cawood *et al.* 2007) could represent the only intact remnants of a once-extensive accretionary orogenic belt that lay outboard of the present Grenville orogen.

The present location of these postulated ribbon terrains is unknown, but the kinematic histories of more recent examples suggest that they would either be transported strike-slip along the circum-Mirovian subduction girdle around Rodinia (such as present-day Baja California or the more extreme possibility of thousands of kilometres in a 'Baja–British Columbia' evolution), or separated far into Mirovia toward an unprescribed fate (such as present Zealandia). Using these analogies, we might expect to find them today as dismembered basement units within the Avalonian–Cadomian orogen (Evans 2005; Murphy *et al.* 2000; Keppie *et al.* 2003) or Borborema–Pharuside strike-slip-dominated orogenic system (Caby 2003), or perhaps partly to completely recycled into the mantle by subduction-erosion (Scholl & von Huene 2007).

Figure 11b shows the incipient breakup of Rodinia at 780 Ma, according to the revised Rodinia model. A first stage of disaggregation at *c.* 780–720 Ma around the western and northern margins of Laurentia, liberated the Congo, West African, Amazonian and Plata cratons that would eventually recombine to form West Gondwanaland between *c.* 640 and *c.* 530 Ma (Trompette 1997; Brito Neves *et al.* 1999; Piuzana *et al.* 2003; Valeriano *et al.* 2004; John *et al.* 2004; Tohver *et al.* 2006). Although the interval between rifting and collision in the Brasiliano foldbelts was brief ('young, short-lived' orogenic cycle of Trompette 1997), the predominant strike-slip component of motion during assembly allowed those belts to contain oceanic (Mirovian) terranes as old as *c.* 900–750 Ma (Pimentel & Fuck 1992; Babinski *et al.* 1996). The prominent dextral shear zones of the Borborema Province in northeastern Brazil, continue into west–central Africa (Vauchez *et al.* 1995; Cordani *et al.* 2003). These bound enigmatic terranes recording unusual 'Grenvillian' tectonothermal events that are otherwise largely absent in cratonic South America (Fuck *et al.* 2008), bearing witness to the large amount of strike-slip offset accommodating the assembly of West Gondwanaland.

On the other side of the proposed Rodinia, the kinematic evolution toward East Gondwanaland follows more conventional reconstructions, which comes as little surprise because the relative positions of Australia, India, South China, and Tarim are similar to those earlier models. India migrated sinistrally along the Pinjarra orogen to arrive at its Gondwanaland position relative to Australia by *c.* 550 Ma (Powell & Pisarevsky 2002). South China and Tarim would have lain along the same tectonic plate during that time, arriving at acceptable positions for their palaeomagnetic reconstruction into Gondwanaland (Zhang 2004; Zhao *et al.* 2008). In the palaeogeographic co-ordinate system of 780 Ma (Fig. 11b), Siberia would have rifted to the east, separating from East Gondwanaland fragments. It is debatable whether North China was part of Palaeozoic Gondwanaland; if not, it too may have rifted far away with Siberia. Kalahari would have migrated to the north in the reconstructed co-ordinate system of Figure 11b, joining the West Gondwanaland cratons as they drifted away from Laurentia + Baltica. Final disaggregation of Rodinia occurred *c.* 610–550 Ma, the age of extensive mafic magmatism in eastern Laurentia (reviewed by Cawood *et al.* 2001; Puffer 2002) and Norway (Svenningsen 2001).

Global palaeogeography at the end of the Neoproterozoic Era remains one of the most challenging problems in palaeomagnetic reconstruction, more difficult even than the quest for Rodinia. This is due to four factors: (1) lack of high-precision biostratigraphy in the Precambrian to correlate successions and to date palaeomagnetic poles from sedimentary rocks; (2) scarcity of datable volcanic successions on the large cratons, relative to geon 7; (3) likelihood that most cratons were travelling independently during the transition between Rodinia and Gondwanaland, thus disallowing the APW superposition method used in this paper; and (4) abnormally high dispersion of palaeomagnetic poles from each craton indicating either rapid plate tectonics, rapid TPW, or a non-uniformitarian geomagnetic field during that time. The most complete model incorporating the global tectonic record and palaeomagnetic data is by Collins & Pisarevsky (2005), but this model still needed to resort to separate options of a low- versus high-latitude subset of the Laurentian palaeomagnetic data. If TPW is responsible for the large dispersions in palaeomagnetic poles, which if read literally would typically imply oscillatory motions conforming to the IITPW model of Evans (2003), then there is some hope to produce reconstructions using the long-lived prolate nonhydrostatic geoid as the reference axis, rather than the geomagnetic-rotational reference frame (Raub *et al.* 2007). This alternative method, however, produces reconstructions that are highly sensitive to small errors in magnetization ages, depending on the rapidity of the putative TPW oscillations. Regardless of which class of interpretations will ultimately prove valid, questions such as the widths of Iapetan separation following Rodinian juxtaposition of Amazonia with eastern Laurentia (e.g. Cawood *et al.* 2001), must be considered premature until more precisely dated palaeomagnetic poles are obtained.

Concluding Remarks

Nearly two decades have elapsed since McMenamin & McMenamin (1990, p. 95) coined the name ‘Rodinia’ for the late Proterozoic supercontinent and ‘Mirovia’ for its encircling palaeo-ocean. Within a year of these monikers’ establishment, a general model for Rodinia was conceived (Hoffman 1991), which, despite numerous challenges from both tectonostratigraphy and palaeomagnetism, has remained largely intact in the latest consensus model (Li *et al.* 2008). However, in order to accommodate the palaeomagnetic data in particular, this latest model has shortened the duration of Rodinia’s existence to merely 75 Ma (900–825 Ma). Such brevity is acceptable and actualistic in terms of the short-lived Pangaea landmass, but it appears at odds with Hoffman’s (1991) original implication of globally widespread 1300–1000 Ma orogens and *c.* 750 Ma rifted margins, as representing Rodinia’s assembly and breakup, respectively.

Herein, I have proposed a Rodinia model that is both long-lived according to the original concept, and compatible with the most reliable palaeomagnetic data from the Meso-Neoproterozoic interval, with minimal number of APW loops. My model is a radical departure from all previous models (e.g. Li *et al.* 2008). Which existing Rodinia model, if any, will approximate the ‘true’ form of the Neoproterozoic supercontinent? As Wegener [1929 (1966, p. 17)] wrote: ‘the earth at any one time can only have had one configuration.’ How will we test the current Rodinia models and achieve a long-lasting consensus that converges toward the true palaeogeography?

Dalziel (1999) identified six criteria for validity of a ‘credible’ supercontinent: (1) account for all rifted passive margins at the time of breakup; (2) accurately map continental promontories and embayments, that is in spherical geometry; (3) display sutures related to assembly; (4) match older tectonic fabrics where appropriate; (5) show compatibility with palaeomagnetic data; and (6) be compatible with realistic kinematic evolution forward in time toward Pangaea. The revised Rodinia model proposed herein satisfies all six of these conditions, if one allows for a special consideration involving conjugate rifted and collisional margins, as follows: the past few years of palaeogeographic reconstruction of the Mesozoic–Cenozoic world have led to increasing recogniztion of ribbon-shaped continental fragments with lengths on the order of thousands of kilometres (e.g. Lomonosov Ridge; Lawver *et al.* 2002; Lord Howe Rise/Zealandia; Gaina *et al.* 2003). Farther back in time, the Cimmeride continental ribbon formed the Permian rift conjugate to the >5000 km northern passive margin of Gondwanaland (Stampfli & Borel 2002). Tectonic shuffling and reworking of Cimmeride blocks within the Alpine-Himalayan orogenic collage has largely obscured their original geometric continuity. The Lomonosov Ridge and Lord Howe Rise/Zealandia ribbons are yet to migrate to their final dispositions within accretionary orogens, but they are unlikely to arrive in pristine form. I propose that similar effects may hamper our ability to quantify the passive margin lengths of any Precambrian continental ribbons. In the case of Zealandia, separation from Australia + Antarctica roughly followed the geometry of the Terra Australis orogen (Cawood 2005), thus ending a Wilson cycle without a continent-continent collision. In the Transantarctic Mountains, the rift propagated far enough inboard to bring some of the oldest, most internal segments of the belt (Cambrian–Ordovician Ross orogen) directly in contact with the oceanic passive margin. Would future palaeogeographers interpret this record as one of Cambrian–Ordovician continent–continent collision, followed by tectonic stability inside a supercontinent, and subsequent Mesozoic breakup of that supercontinent? This example highlights the difficulty in robustly characterizing tectonic histories of Precambrian orogens without a palaeogeographic framework. With focused effort on obtaining key geochronologic and palaeomagnetic data from the Rodinian time interval, we may be able to provide that framework.

These ideas have evolved through the last five years, benefiting from discussions with S. Bryan, P. Cawood, A. Collins, B. Collins, D. Corrigan, I. Dalziel, B. de Waele, R. Ernst, I. Fitzsimons, R. Fuck, C. Gower, P. Hoffman, K. Karlstrom, A. Kröner, Z.-X. Li, A. Maloof, B. Murphy, V. Pease, M. Pimentel, S. Pisarevsky, the late C. Powell, T. Rivers, D. Thorkelson, E. Tohver and M. Wingate. P. Hoffman, I. Dalziel, C. MacNiocaill, and R. Van der Voo provided helpful criticisms on earlier versions of the manuscript; P. Cawood and S. Pisarevsky gave expedient and constructive reviews of this iteration. This work was supported by a Fellowship in Science and Engineering from the David and Lucile Packard Foundation.

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