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Restoring Pan-African–Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption

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Abstract: The concept of South America and Africa as rigid continents during the formation, growth and motion of their respective plates has frustrated reconstruction of a tight, geologically economic fit between these two fragments in their Gondwana framework. We recognize that (1) internal strains released during and following Gondwana break-up have distorted their actual shapes within Gondwana and (2) these two continents comprise mosaics of smaller microblocks, or platelets, of relatively undistorted Precambrian terrains that experienced modest, episodic relative motions along rift zones that separate them. This permits a fresh approach to quantitative reconstructions of palaeo-continents. Former geological ties forged at the time of Gondwana amalgamation, now exposed at the continental margins of the South Atlantic as piercing points, provide robust anchors for new paleo-cartographic experiments. We present two new tectonic maps of the Brasiliano and Pan-African structures of West Gondwana on which we identify ten piercing points that, if re-joined simultaneously, could facilitate quantification of a well-substantiated Gondwana fit and help retrace the evolution of its continental margins with greater accuracy than has been achieved until now. This has significant bearing on understanding the origin and evolution of passive continental margins, and the geodynamics of Gondwana break-up.

Relative rapid amalgamation of a number of continental fragments during the Late Neoproterozoic resulted in a united Gondwana supercontinent (e.g., de Wit *et al.* 1988; Unrug 1992, 1997; Trompette 1994; Brito Neves *et al.* 1999; Bizzi *et al.* 2003). Whilst accretion of smaller blocks continued along the peripheries of this supercontinent throughout the Palaeozoic (e.g., de Wit & Ransome 1992; Nance & Murphy 1996; Linnemann *et al.* 2004; Vaughan *et al.* 2005), central Gondwana became peneplained and remained relatively undisturbed until a series of Mesozoic intra-continental rifts fractured this stability (e.g., Burke & Dewey 1976; de Wit *et al.* 1988; Daly *et al.* 1989; Fairhead & Brink 1991; Reeves 1999). The precise history of Gondwana's subsequent break-up and early separation into the present day continents of the southern hemisphere is recorded in the rock record along the continental margins of South America, Africa, Antarctica, Australia and India (e.g., Tankard *et al.* 1996; Hinz *et al.* 1999; Mohriak *et al.* 2007, 2008). This history has yet to be deciphered to a degree that can differentiate cause and effect between convecting mantle and lithosphere processes, since there are significant gaps in our knowledge about the kinematics of the break-up of Gondwana (e.g., Storey 1995; Hawkesworth *et al.* 1999; Krabbendam & Barr 2000; Stern & de Wit 2004). How and why this supercontinent formed and came apart lies at the heart of understanding the geodynamics, episodic growth and break up of continents in general. A first step towards unravelling this interactive history requires a more accurate pre-break up fit for Gondwana than is presently available (e.g., Reeves 1999; Ghosh *et al.* 2004). Surprisingly, a robust fit still has to be achieved between the two continents flanking the South Atlantic Ocean, which have featured most prominently in all models of Gondwana reconstructions. This quest is unfulfilled because the internal deformations of Africa and South America since Gondwana break-up are not yet well-quantified (Fig. 1; Burke & Dewey 1976; de Wit *et al.* 1988; Fairhead & Brink 1991; Reeves 1999; Eagles 2007). Reeves (1999) partially solved this problem by recognising the need to subdivide the continents, particularly Africa, into a number of Precambrian sub-domains that were semi-independent during early Mesozoic rifting and fragmentation of Gondwana (Fig. 1c), and modelling the fit between Africa and South America using modest Euler rotations of these rigid microplates (Reeves *et al.* 2004). This model yields satisfactory fits between the fragments of former Gondwana, and deserves rigorous testing. Testing requires identification of *vertical* litho- and tectonic-markers on a number of different

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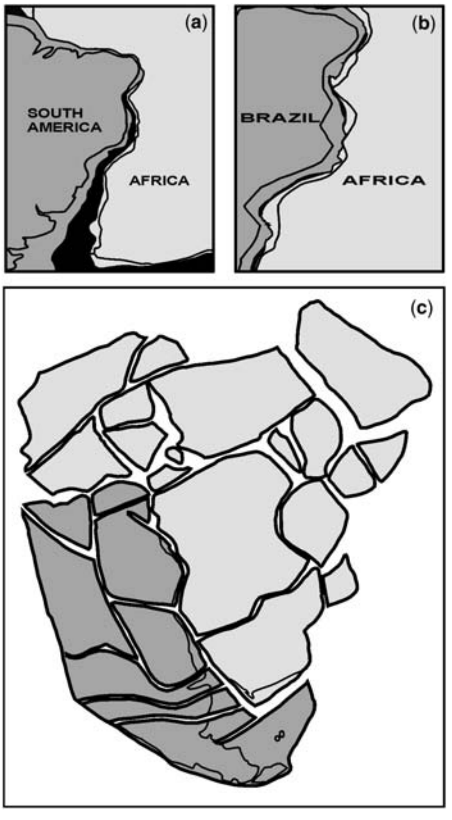

Fig. 1. Schematic representation of continental fits between South America (dark grey) and Africa (pale grey). (**a**) *c*. 120–150 Ma fit using rigid-plate rotations based on marine magnetic anomalies and transform faults (modified after Rabinowitz & La Breque 1979; de Wit *et al.* 1988). Black represents oceanic depths. (**b**) Possible tight fit of the South Atlantic continents between Nigeria and Namibia, with *c*. 60 km separation between the edges of the Precambrian blocks in Africa and South America during the earliest stages of rifting, analogous to that between Precambrian blocks along the present East African Rift with its rift-confined lakes (after Reeves *et al.* 2004). Black represents lakes. (**c**) *c*. 150–200 Ma fit of West Gondwana, schematically represented as a mosaic of Precambrian blocks separated by narrow (<50 km) rift zones. Small internal adjustments and rotations of Precambrian blocks (platelets) of central and North Africa and Brazil, to undo known Mesozoic–Cenozoic rifts and slip along major Pan-African, Brasiliano, Cretaceous and Miocene fault zones and composite tectonic lineaments (see Reeves 1999; Reeves *et al.* 2004), create a good fit along the central South Atlantic. The southernmost Atlantic is left with notable gaps because the Palaeozoic (Karoo) rift systems of southern Africa (e.g., Daly *et al.* 1989, 1992) and the Mesozoic–Cenozoic rifts of southern South America that strike at near right angles to the continental margin of South America (e.g., Tankard *et al.* 1996; Hinz *et al.* 1999), have not yet been adequately restored (e.g., Reeves *et al.* 2004; Eagles 2007).

Precambrian blocks along both continental margins of the South Atlantic that can be matched and reconnected with confidence. Many former contiguous Neoproterozoic faults and shear zones that now cut continental margins on both sides of the ocean provide ‘piercing points’ that could fulfil this requirement (e.g., Reeves & de Wit 2000). Vertical or subvertical structures should be insensitive to present-day erosion level.

We present a west South America–Africa map with a compilation of Neoproterozoic structural and tectonic data from the *c*. 200 million year period during which the continental fragments that comprise west Gondwana amalgamated along five major orogenic systems, each comprising a number of tectonic belts (Fig. 2). On this map, we identify ten key piercing points along the circum-South Atlantic that need improved aeromagnetic characterization and accurate dating, so that they can be reconnected simultaneously to yield a yet more satisfactory finite fit.

The time period in question spans the late Neoproterozoic, at the very end of the Precambrian, between about 750 and 550 Ma, albeit with some events that ‘spill-over’ into the early Palaeozoic. The geological activity in that time period within South America is generally referred to as ‘Brasiliano’ (e.g., Hurley *et al.* 1967; Trompette 1994; Brito Neves *et al.* 1999; Bizzi *et al.* 2003; Van Schmus *et al.* 2007) and in Africa as ‘Pan-African’ (e.g., Kennedy 1964; Clifford 1970; Cahen & Snelling 1984; de Wit *et al.* 1988, 2001; Black & Liégeois 1993; Stern 1994; Trompette 1994; Meert 2003; Johnson & Woldehaimanot 2003; Collins & Pisarevsky 2005). Although we restrict ourselves to regions that flank both sides of the South Atlantic Ocean, we extend our tectonic analyses eastward to include a larger part of west Gondwana, especially in Africa, to fully appreciate the extent that late Neoproterozoic geodynamics affected this region, and how Neoproterozoic tectonic inheritance influenced the shaping of the South Atlantic during subsequent Phanerozoic events.

Previous work

The first quantitative reconstruction between South America and Africa was the early computer model of Bullard *et al.* (1965) that economized overlap of continental crust whilst maintaining an optimally aesthetic fit. More reliable plate tectonic rotations using marine magnetic anomalies and fracture zones (e.g., Rabinowitz & LaBrecque 1979; de Wit *et al.* 1988; Lawver *et al.* 1999; Scotese 2000; Eagles & König 2007) and satellite-derived ocean floor topography (Smith & Sandwell 1997) followed. This arsenal of data has not, however,

ever achieved a complete satisfactory closure of the South Atlantic, and has continued, therefore, to call for greater geological and geophysical understanding and input from the surrounding continental margins (e.g., Reeves 1999; Bauer *et al.* 2000; Eagles 2007; Fig. 1).

One issue is exactly *which* conjugate continental outlines should be matched. Bullard *et al.* (1965) matched the 500 fathom (*c.* 1000 m) isobaths as a rough estimate of the likely limits of the (extended) continental crust. Coastlines are ephemeral geologically but easily recognizable in illustrations. Yet they mostly fall within the transition zone from true continental to true oceanic crust. For much of Gondwana, including the South Atlantic margins, we favour using the limit of the extant Precambrian geology. This can sometimes be seen in outcrop or inferred (where below shallow cover) from aeromagnetic surveys. Inboard of this limit we assume the Precambrian rocks within each platelet are essentially undistorted and unextended by Gondwana break-up processes. Outboard, as far as the boundary with true oceanic crust, we expect to find laterally extended (remnants of) crust that existed at the end of the Precambrian (Pan-African/Brasiliano). We favour assembling these Precambrian 'outcrop' limits with their margins essentially parallel. The optimum separation in the reconstructions or, in other words, the width of Precambrian crust that has been extended into the transitional crust of the two continental margins, is unknown. Numerous experimental geometrical reassemblies suggest that only 50–100 km (divided between the two margins) has been lost in this way (Fig. 1; Reeves *et al.* 2002).

Testing different reconstruction models for independent verification over the last 40 years has relied mostly on geochronology of onshore geology along both sides of the Atlantic. This approach was first pioneered using K–Ar and Rb–Sr dating techniques in NE Brazil and West Africa, by Hurley and co-workers (Hurley *et al.* 1967; Hurley 1972, 1974), and other parts of Africa and Brazil using, for example, the extensive data sets of Cahen & Snelling (1966, 1984) and Cordani (see Cordani *et al.* 1988 for a review). Although correlations verified the concepts of continental drift/plate tectonics, they lacked the accuracy required to convincingly correlate between individual stratigraphic marker horizons, intrusions or tectonic structures on either side of the Atlantic. It was not until the 1990s when precise U–Pb dates became widely available that attempts to test correlations and to quantify the fits and kinematic history of Gondwana break-up was attempted using, for example, well-dated continental shear zones that were active only during the formation of Gondwana (e.g., of Pan-African and Brasiliano age; Daly *et al.* 1989; de Wit *et al.* 2001). The combination of this analysis with data from magnetic anomalies and transform faults in the Indian Ocean to reconnect subvertical shear zones along the margins of India, Madagascar and Africa was attempted by Reeves, and a refined fit between East and West Gondwana to accuracies within tens of kilometres was derived (e.g., Reeves 1999; Reeves & de Wit 2000; Reeves *et al.* 2002, 2004). A prerequisite to ensure the accuracy in this technique is to join only conjugate points along opposite continental edges defined by intersection of *subvertical* shear-zones, faults, and dykes. This approach avoids unknown differential uplift and erosion on the separate fragments subsequent to their separation. Using piercing points along the continental margins of once-conterminous *shallow* dipping thrusts, suture zones or sills, creates uncertainties of several hundreds of kilometres when rejoining them along continental margins that have been eroded to different crustal levels since their separation. In the latter case additional detailed thermochronology is needed to resolve precise 3D correlation between such piercing points (e.g., Reeves & de Wit 2000), a required approach that is still frequently violated (e.g., Collins *et al.* 2007).

A Brasiliano/Pan-African tectonic map

Our new tectonic map is presented in Figure 3 (fold-out) and its simplified geological counterpart in Figure 4. The map shows the major shear zones and suture zones of Pan-African age, taken from the Geological Map of Gondwana (de Wit *et al.* 1988), converted to GIS format in 1992, and updated where appropriate, using reports from the peer-refereed geological literature and from published geological maps. Where such structural data are not available, other information is sometimes substituted, for example, the trend of foliations in parts of Libya, Sudan, Chad, CAR, DRC and Uganda. Local maps and compilations are used for this alternative data (e.g., Gsell & Sonet 1960; Sonet 1963; Vail 1976; El-Makhrouf 1978; UNESCO 2000). Fault, shear zone and geochronological data used for the purpose of identifying 'piercing points' are summarized in specific sections below. The Brasiliano data are originally also from the Geological Map of Gondwana, but are extensively edited using the new digital compilations published by the geological survey of Brazil (Bizzi *et al.* 2003).

Our maps are compiled using ESRI GIS and Mapping Software (http://www.esri.com/software/arcview/) that allows a variety of displays. Figures from publications in journals and books had to be

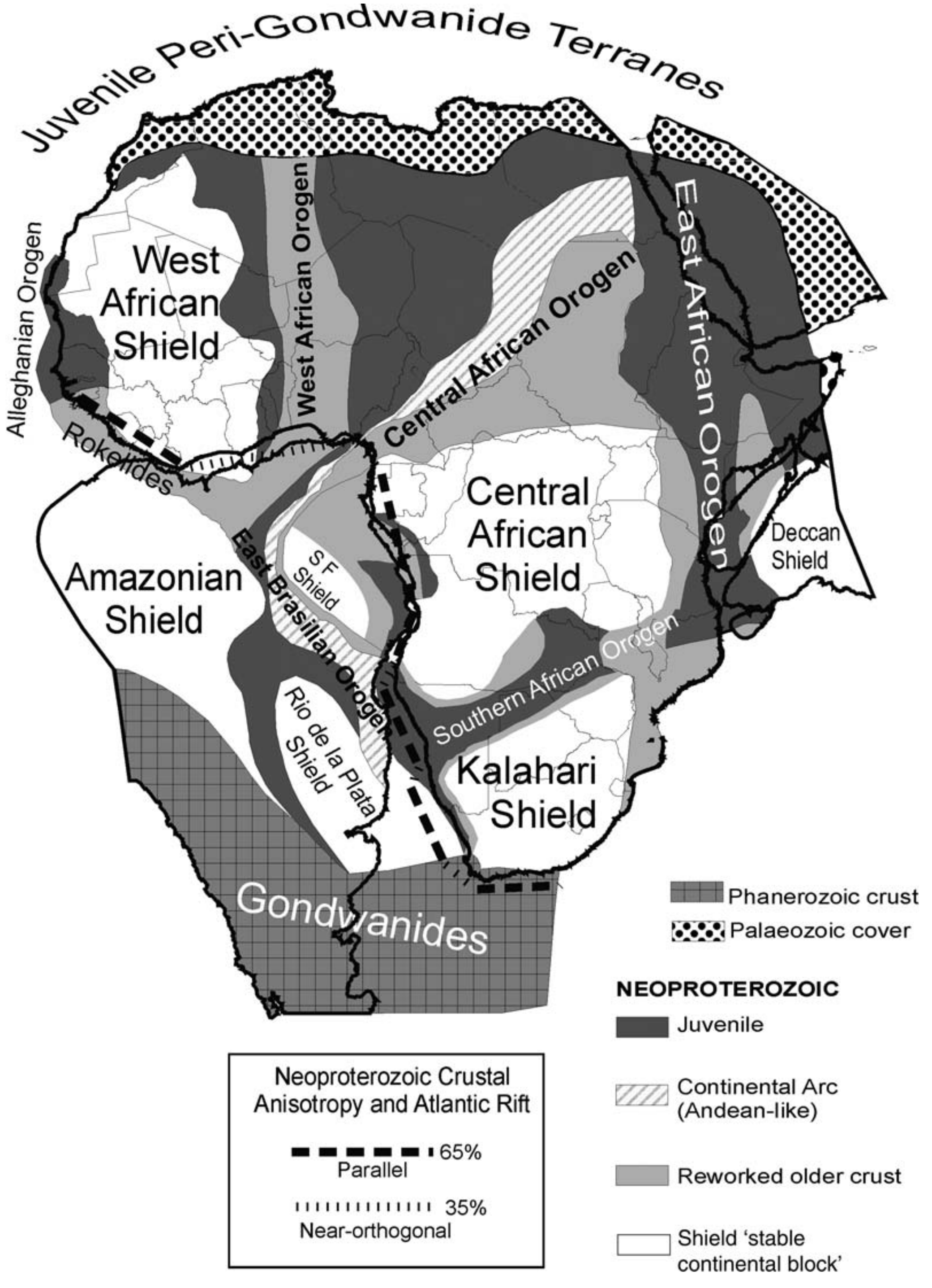

Fig. 2. (*Continued*).

scanned and imported into our GIS database. In this process keeping cartographic accuracy is essential. When co-ordinates and projections were provided in a published map, it was easy to geo-reference the figure to ensure placing it at the correct location. Often, however, the projection was not given and co-ordinates were 'eyeballed in' on the map. We have also come across several publications where the co-ordinates provided were incorrect. Fortunately, virtually all figures included an accurate map of the rivers draining the area—these constitute an essential reference point when doing field work in remote parts of Africa. With the AEON Africa River Database at our disposal (which includes a detailed digitized drainage map of Africa, see Stankiewicz & de Wit 2006; de Wit & Stankiewicz 2006, for details), judicious trial-and-error usually allows accurate positioning of even the poorest maps.

Ten selected Neoproterozoic 'piercing points' to close the South Atlantic

The following piercing points (see Fig. 4 and Table 1 for their locations) are suggested as prime targets for further geochronology and geophysics to aid the reconstruction of the continental margins flanking the South Atlantic, and to facilitate a tighter fit between South America and Africa. This is by no means an exhaustive list, but serves to illustrate the approach and the requirements of the Pan-African/Brasiliano features needed to complete manifold simultaneous rotations.

(1) The Rokelide front of subvertical Neoproterozoic transpressive shear zones that delineate the southern tectonic margin of the Archaean–Eburnian age West African Shield (MacFarlane 1980) and the equivalent southern margin of the Archaean–Trans-Amazonian age São Luís fragment in northern Brazil (Bizzi *et al.* 2003; Klein & Moura 2008).

(2) The Dahomide thrust front/suture zone (including ophiolites) and the vertical Kandi Shear System that separate the West African shield from the Neoproterozoic West Saharan orogen (Castaing *et al.* 1993; Attoh *et al.* 1996; Agbossoumondé *et al.* 2004), and the equivalent tectonic boundary along the eastern margin of the São Luis fragment in NE Brazil (Bizzi *et al.* 2003). In both locations, this tectonic zone hosts a number of subvertical shear zones, and separates this Pan-African zone from Palaeoproterozoic basement (*c.* 2.0 Ga) to the west that has not been affected by Pan-African tectonothermal overprinting (e.g., the Birimian of the West African Shield and the Trans-Amazonian of São Luís). This is in contrast with all Archaean–Palaeoproterozoic basement east of the West African Shield and São Luis fragment (the Nigerian shield and the Ceará terrane of the Borborema province, respectively), which has been thoroughly remobilized by Pan-African thermotectonic processes, often densely invaded by late Pan-African and Brasiliano granites, and interleaved with minor Neoproterozoic sequences (e.g., Caby 1989; Black & Liégeois 1993; Castaing *et al.* 1993; Trompette 1994; Ekwueme & Attoh 1996; Fetter *et al.* 2003; see Fig. 4).

(3) Major subvertical crustal lineament(s) within the West Sahara orogen extending from the Tuareg shield through the Nigerian shield, flanking the Latea block (Caby 1989, 2003; Castaing *et al.* 1993; Black *et al.* 1994; Trompette 1994; Bournas *et al.* 2003; Caby & Monié 2003; Liegéois *et al.* 2003; Ouzegane *et al.* 2003; Peucat *et al.* 2003), into the Trans-Brasiliano Lineament (TBL) and associated shear zones of the Ceará terrane of NE Brazil; and the junction between the Araguaia and the western sections of the Brasília Belts (Pimental & Fuck 1992; Bizzi *et al.* 2003; Fetter *et al.* 2003; Piuzana *et al.* 2003; Neves 2003; Van Schmus 2003, 2008).

(4) Major subvertical shear zones flanking the fold belt along the eastern margin of the Tuareg shield (Caby 1989, 2003; Trompette 1994; Ferre *et al.* 2002; the most easterly is known as the Rangane shear zone, RSZ) that strike into the north–south trending Seridó Fold Belt of the Borborema province, NE Brazil (Bizzi *et al.* 2003; Van Schmus *et al.* 2003, 2008).

Fig. 2. (*Continued*) Simplified map of major Neoproterozoic–Palaeozoic orogenic systems and associated tectonic belts of Gondwana. Also shown are the extents of relatively stable continental lithosphere in the Neoproterozoic (white represents Neoproterozoic shields) and those areas where parts of these shields and other older fragments were significantly reworked during the Neoproterozoic (pale grey). The Pan-Gondwana Andean-like belt from Egypt to Argentina (*c.* 7500 km) flanks the Neoproterozoic Central African Shield (which includes its extension into Brazil as the largely remobilised São Francisco Shield). The poor fit across the southernmost Atlantic Ocean does not yet permit extending this Andean-like arc farther south beyond the coast of Argentina. Those sections of Neoproterozoic orogenic belts that trend approximately parallel to the early South Atlantic rift, are shown in dashed lines: here, rifting took place near-parallel to the Pan-African/Brasiliano tectonic fabric (*c.* 65% of the total South Atlantic rift length); sections where the Atlantic rifts cross-cuts such Pan-African/Brasiliano tectonic trends at a significant angle (*c.* 35%) are shown in dotted lines. Such conterminous ties may play important roles in creating the *en echelon* geometries and overlap of early continental rifts (e.g., Fig. 1b).

(5) The Central African Shear System (the Adamawa, Tchollíré–Banyo, Sanaga, Foumban shear zones) and the Bohorema Shear System (the Pernambuco and Patos shear zones in Brazil). These essentially vertical major mylonitic systems stretch from NE Brazil into Central Africa (e.g., Poidovin 1985; de Wit 1988; Daly *et al.* 1989; Neves 2003; Van Schmus *et al.* 2008), through Cameroon, northern Gabon to the Central African Republic and Chad (Poidovin 1985; Rolin 1995; Toteu *et al.* 2001, 2004; Ngako *et al.* 2003). There is no consensus as to how precisely the individual shears link up, despite the long history of study (compare, for example, Poidovin 1985; de Wit *et al.* 1988; Daly *et al.* 1989; Castaing *et al.* 1993; Trompette 1994; Neves 2003; Van Schmus *et al.* 2008, and Fig. 3). They are well-defined positionally in NE Brazil from geological mapping and aeromagnetic surveys; detailed aeromagnetic mapping of Nigeria currently underway may throw new light on the precise location of their continuation into Africa.

(6) The Sergipano–Oubengides fold belt of central Africa (Fig. 4; often not shown on tectonic maps of Africa, even in relatively recent works, despite its detailed description by Poidovin 1985). There are two important components of this belt that should be considered for correlations across the Atlantic. The first concerns the near east–west striking and south-verging tectonic front with thrusts and vertical strike-slip systems that cut and remobilize the northern boundary of the Central African Shield. This shield represents a large Neoproterozoic continental fragment that stretches into South America, and comprises a mosaic of Archaean cratons (Sao Francisco (São Miguel do Aleixo system), Ntem (Yaoundé system), Congo (Nola–Bangui system) in Brazil, Gabon, and CAR/DRC) and their Palaeoproterozoic outboard margins (reworked in the Neoproterozoic—Eburnian in Africa and Trans-Amazonian in South America; Poidovin 1985; Rolin 1995; Toteu *et al.* 2001, 2004; Bizzi *et al.* 2003; Van Schmus *et al.* 2003, 2008; see Fig. 4). The second concerns the recognition that a long-lived Neoproterozoic magmatic belt, apparently of Andean-like proportions, with associated vertical shear zones, flanks the western edge of the Central African Shield (de Wit *et al.* 2005), extending southwestwards across the Sahara, from Egypt, through Darfur, Chad, Cameroon (Schurmann 1974; Kusnir 1993; Kushnir & Moutaya 1998; Tagne-Kamga 2003; Toteu *et al.* 2004; de Wit *et al.* 2005) into NE Brazil (marked by the Alto Pajeú domain; Bizzi *et al.* 2003; Van Schmus *et al.* 2008). Flanking the São Francisco craton (Riacho do Pontal domain), it continues through the Brasília Belt (Pimental & Fuck 1992; Piuzana *et al.* 2003, 2005), and possibly farther south still along the edge of the Río de la Plata craton (Dalla Salda *et al.* 1988; Bizzi *et al.* 2003), a total distance of >7500 km. This is a fundamental Neoproterozoic tectono-magmatic belt of central Gondwana. Because it thins considerably (due to Neoproterozoic tectonism) as it approaches the Atlantic coast in Cameroon (Mayo Kebi domain), and across in NE Brazil (Alto Pajeú domain), it defines a piercing point of 'golden-spike' proportions (Fig. 4). Batholiths of this belt in north-central Africa and NE Brazil are some of the only known associations with extensive *c.* 1.0 Ga Mesoproterozoic granitoids in northern Gondwana.

(7) The southern margin of the West Congo Fold Belt is enigmatic. In Angola, the (low-grade) West Congo Fold Belt is abruptly cut of by a series of steep transcurrent faults and an east–west striking granulite terrain that cut the Angolan coast at high angle (e.g., de Wit *et al.* 1988; Tack *et al.* 2001; Fig. 4). This obliquity has been interpreted by some workers to indicate a significant transcurrent fault that offsets the fold belt front eastward to join with the Neoproterozoic Lufilian arc of the Katangan fold belt in Zambia/DRC (e.g., Daly *et al.* 1989, 1992; Collins & Pisarevsky 2005). Alternatively this transfer structure may form part of a deep crustal triple junction to the west joining the subvertical coast-parallel high-grade shear belts of the Ribeira-Araçuaí Belt of Brazil (e.g., de Wit *et al.* 1988; Bizzi *et al.* 2003; Heilbron & Machado 2003; Schmitt *et al.* 2004, 2005) and in particular with the shear systems in the Cabo Frio terrane (Heilbron & Machado 2003; M. Heilbron, pers. comn. 2007).

(8) The subvertical shear zones of the Kaoko Belt (Schmitt *et al.* 2005; Goscombe *et al.* 2005; Gray *et al.* 2006; Goscombe & Gray 2007) in northern Namibia and southern Angola transgress obliquely across the South Atlantic margins towards the subvertical shear zones of the Brasiliano-age Ribeira Belt (Schmitt *et al.* 2004, 2005; Gray *et al.* 2006). Because the shear zones of these belts are strike-oblique with a low angle to the present coastlines, and because they are of similar age, identifying their respective 'partners' on each side of the South Atlantic may prove difficult.

(9) The northern extensions of vertical shear zones associated with the Alferez–Cordillera–Punta del Este shear zone (ACPESZ) in the Braziliano-age Dom Feliciano Belt (e.g., Dalla Salda *et al.* 1988; Bizzi *et al.* 2003; Basei *et al.* 2005) strike with low obliquity northwards across the South Atlantic margin to apparently project into the westernmost vertical strike-slip shear zones that cut the Pan-African age Western Kaoko batholith and, at their southernmost extremity, strike southwestwards into the South Atlantic.

(a)

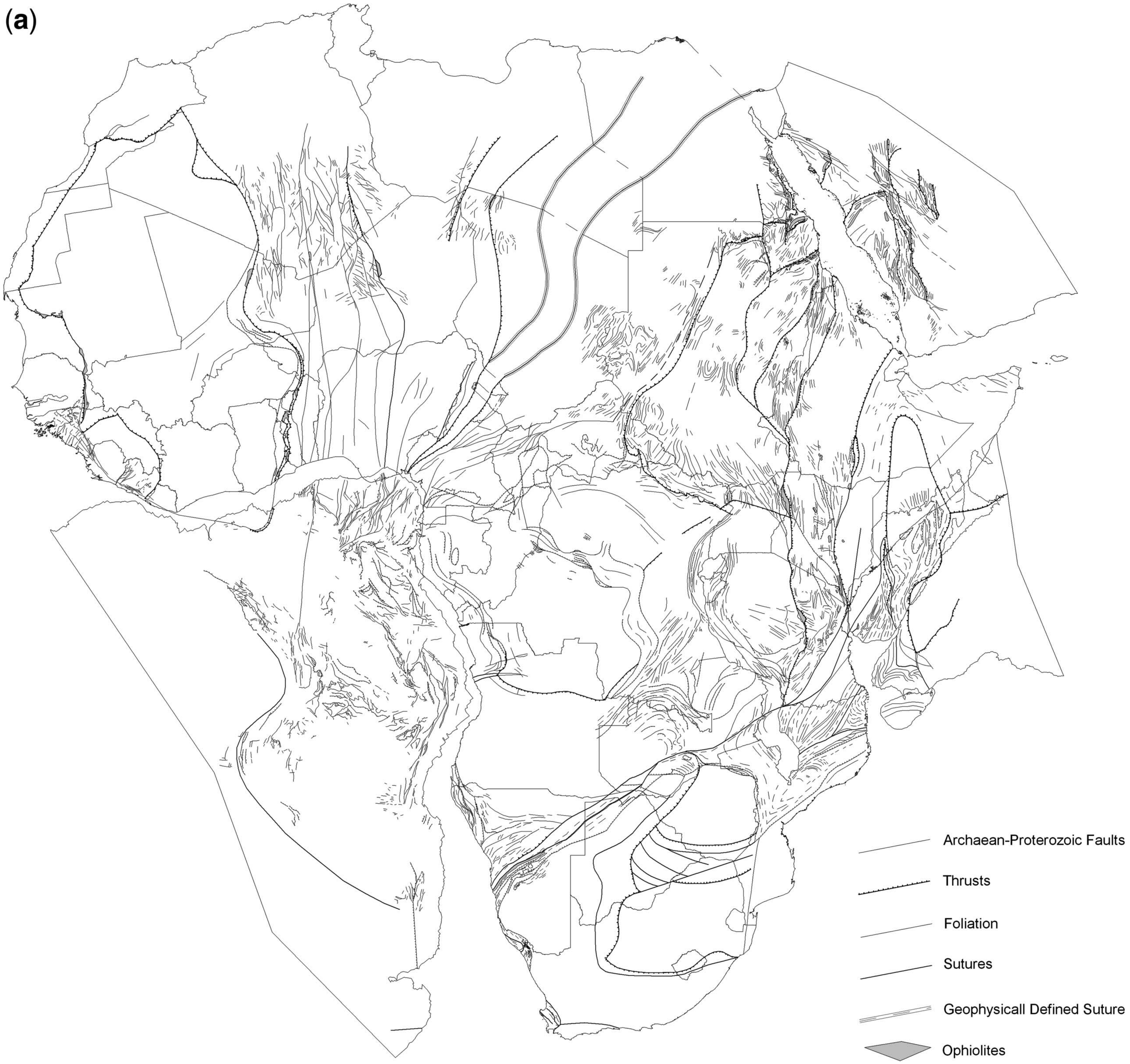

Fig. 3. (**a**) (Fold out) Tectonic Map of Brasiliano and Pan-African structures of West and Central Gondwana. Compiled between 1992 and 2006 from many sources as explained in the text. Digital format available on request.

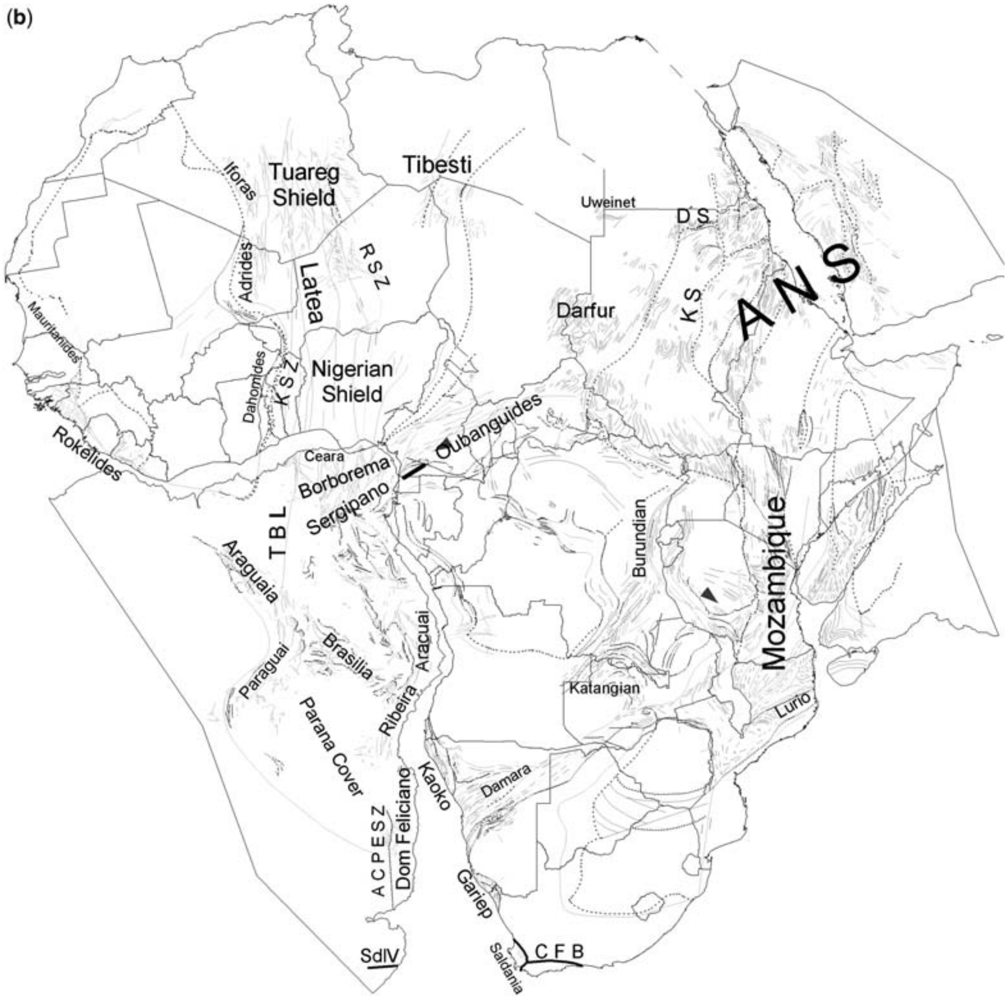

Fig. 3. (*Continued*) (**b**) Same map, reduced, as index with names and locations of the Neoproterozoic tectonic belts and major shear zones mentioned in the text.

These shear zones appear to be of identical Neoproterozoic age. (Goscombe *et al.* 2005; Gray *et al.* 2006; Goscombe & Gray 2007).

(10) The vertical shear zones and associated aeromagnetic magnetic anomaly patterns of the triple junction between the central-southern margin of the Damara Belt, the Gariep Belt, and southern extremity of the Dom Feliciano Belt flanking the Río de la Plata Shield in Uruguay (Frimmel & Frank 1998; Basei *et al.* 2005); and possibly the NW-striking terrane boundary faults within the Saldanian Belt of the Western Cape in South Africa with the southern most extremity of the ACPESZ south of the Río de la Plata (e.g., Rozendaal *et al.* 1999). The accuracy of the latter correlation will depend on the details of Gondwana's oldest tectonic correlation across the South Atlantic (e.g., those between the Cape Fold Belt of South Africa and the Sierra de la Ventana belt of Argentina). Because these fold belts are both constructed on similar Neoproterozoic basement close to the Atlantic margin, their correct structural correlations have a direct bearing on correlating 'piercing points' in their surrounding basements. Some brief relevant comments about these two classic Gondwana belts are therefore separately summarized below.

The end-Palaeozoic Cape Fold Belt of South Africa and the Sierra de la Ventana Fold Belt of Argentina represent the once conterminous tectonic front of the Gondwanide orogen that now cuts at high

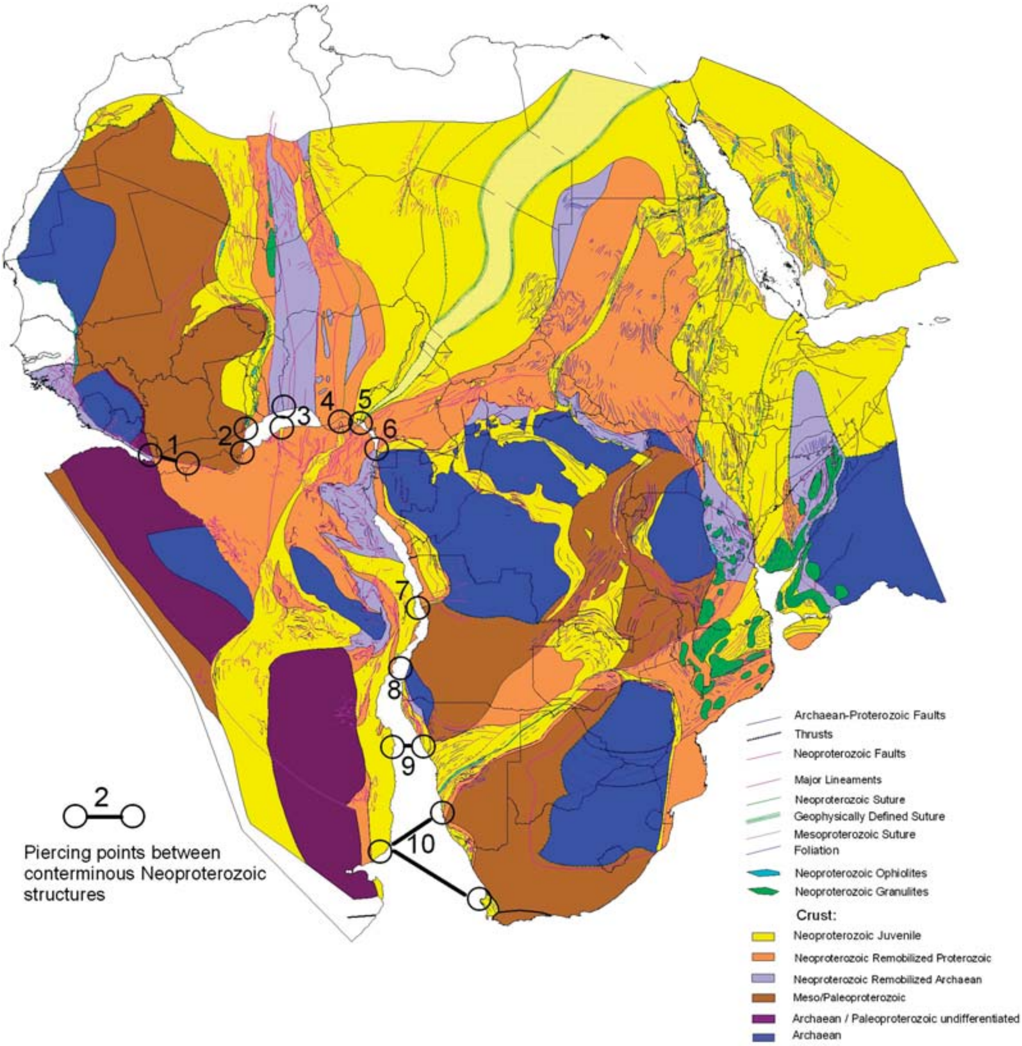

Fig. 4. A simplified geological map of West and Central Gondwana showing the major Neoproterozoic Shields with their embedded Archaean cratons, and their margins that were remobilized in the Pan-African/Brasiliano orogens. Major remobilized Archaean–Proterozoic fragments within the Neoproterozoic orogenic systems are also shown. Nine Neoproterozoic 'piercing' points between once conterminous Pan-Gondwana sub-vertical lineaments are identified along opposite sides of the South Atlantic. In addition, the mid-Phanerozoic (*c*. 250 Ma) 'piercing points' associated with the Cape Fold Belt and the Sierra de la Ventana, are also shown. The precise locations and details of these 'piercing points', which might facilitate restoring the South Atlantic margin to derive a more reliable Gondwana fit, are given in Table 1.

angle across the South Atlantic margins (Figs 3 & 4). These belts have long been correlated on lithostratigraphic grounds (e.g., Keidel 1916; du Toit 1927, 1937) and the correlation has been robustly vindicated by recent detailed geochronology (Rapela *et al.* 2003). Because the tectonic features of parts of these belts are steeply dipping, and because they formed well before Gondwana break-up, they qualify as the most southerly tectonic 'piercing points' in Africa with counterparts in South America. However, a word of caution is warranted here: the extreme western section of the Cape Fold Belt bifurcates into SW- and NW-striking tectonic branches, flanking the easternmost outcrops of the Saldanian basement of the Western Cape mentioned above (e.g., de Wit & Ransome 1992). Which branch

Table 1. *Piercing points for Transatlantic reconstruction of West Gondwana*

Point	Africa long.	Africa lat.	African country	America long.	America lat.	Today's distance (km)
1	8.0°W	4.5°N	Liberia	48.0°W	0.5°S	4500
2	0.5°W	5.5°N	Ghana	43.5°W	2.5°S	4900
3	3.0°E	6.5°N	Benin/Nigeria	40.0°W	3.0°S	4900
4	7.0°E	4.5°N	Nigeria	35.5°W	5.0°S	4800
5	8.5°E	4.5°N	Nigeria/Cameroon	35.0°W	6.0°S	5000
6	10.0°E	2.5°N	Cameroon/Eq. Guinea	35.5°W	9.0°S	5200
7	13.0°E	10.0°S	Angola	40.5°W	20.5°S	5800
8	12.0°E	14.5°S	Angola	45.0°W	23.5°S	6000
9	13.5°E	21.0°S	Namibia	49.0°W	28.5°S	6300
10a	15.0°E	26.0°S	Namibia	55.5°W	35.0°S	6700
10b	18.0°E	33.0°S	South Africa			6600

correlates directly with the Sierra de la Ventana, if either, will have to await detailed geophysical work along both continental margins.

Discussion

The recognition that major continents have not always responded as single rigid blocks during plate motions has led to the qualitative understanding that internal continental distortions must be better understood and quantified if continental margins around the South Atlantic (and elsewhere) are to be refitted to their correct Gondwana positions. Matching pre-drift subvertical shear zones on both sides of the South Atlantic that were conterminous just prior to rifting facilitates such an approach. There are, however, significant uncertainties in precisely correlating such structures across the Atlantic. We note, for example, that some correlations of suitable piercing points derived from sub-vertical structures differ substantially in the current literature (e.g., 2 and 3 in Fig. 4), in part because the structures have yet to be accurately dated. This underscores the point that the shear zones associated with the piercing points that we have identified require rigorous examination, geophysically and isotopically.

In addition, the internal Precambrian microplates and the edges of most cratons/shields have not yet been clearly differentiated because, in most cases, Pan-African and Brasiliano tectonothermal overprints and remobilizations have distorted their pre-Gondwana geometries (e.g., Fig. 4). Indeed there is still vigorous debate whether or not large tracts of central Africa affected by Pan-African thermotectonism constitute juvenile or remobilized earlier crusts, such as the NE extension of the Central African Shield (sometimes referred to as the Sahara metacraton or ghost craton), Tibesti and surroundings, parts of the Nigerian metacraton, and so forth (e.g., Kennedy 1964; Clifford 1970; Ghuma & Rogers 1976; Nagy *et al.* 1976; Schurmann 1976; Vail 1976; El-Makhrouf 1978; Cahen & Snelling 1984; Harris *et al.* 1984; Pelgram *et al.* 1987; Sultan *et al.* 1990, 2000; Harms *et al.* 1996; Krabbendam & Barr 2000; Kuster & Liégeois 2001; Abdelsalam *et al.* 2002, 2003). This will require a lot more careful isotopic and geophysical analysis on both sides of the Atlantic to resolve.

The fact that Neoproterozoic tectonic piercing points exists at all along the circum-continental margins of the South Atlantic corroborates findings that continental rifting does not always follow the inherent lithospheric anisotropy of the separating fragments. Indeed our geological map (Fig. 4) emphasizes that the east–west striking central South Atlantic margins cut across major Pan-African/Brasiliano tectonic belts as well as older tectonic trends on Archaean cratons and Palaeoproterozoic shields. There has been analysis in more detail for the entire Gondwana supercontinent elsewhere (Krabbendam & Barr 2000): on average about 50% of Gondwana's 25 000 km rifted margins are parallel to pre-existing structures or craton margins. Although we find this to be (significantly?) different for the circum-Atlantic margins (*c.* 65%, Fig. 2), we concur with Krabbendam & Barr (2000) that it remains to be resolved why Gondwana broke up along only one out of five of its major Neoproterozoic Gondwana orogens that cut across Central and West Gondwana (Fig. 2). Resolving this enigma will also help guide our as yet limited understanding the fundamental geodynamics of the demise of supercontinents, and the role of inherited ties between their fragments.

Conclusions

Obtaining a 'tight' reconstruction for Gondwana will remain an elusive goal unless better integration between marine geophysics and on-land geology is achieved. Reversing the oceanic crust between continental margins as they have grown apart is the relatively easy part. Recognition that the major Gondwana fragments have acted as a mosaic of platelets for part of their pre- and post-drift histories, and characterizing these smaller Precambrian fragments to aid in reconstructing their initial (and mostly aborted) rifting and rotations, is now a more challenging task. Aeromagnetic anomalies over the continents may map the boundaries between these rigid continental blocks separated by small rotations, degrees of extension and/or amounts of strike-slip motions, and can identify rift shoulders where the fossil boundaries are deeply buried (e.g., Reeves 1999; Reeves *et al.* 2004). Fitting these blocks into their pre-drift positions requires matching of geological structures that were once conterminous. One way to realize this is to re-join Neoproterozoic 'piercing points' on the conjugate margin of continental blocks that are well-dated and otherwise geophysically and geologically characterized. We have argued that for South America and Africa this might be achievable in the case of at least ten well-defined Neoproterozoic ties around the margins of the South Atlantic Ocean, and we presented a detailed map of the Brasiliano/Pan-African structures of Gondwana to facilitate the planning of such experiments. Playing back the continental motions whilst simultaneously pinning these original ties together, should result in a more robust and accurate fit from which to re-track interactive mantle–lithosphere break-up mechanisms and help quantify internal Gondwana strains that led to the break-up and separation in the first place. Involving a greater degree of such geological and geophysical control to reconstruct the Gondwana break-up history will help to correct for early Trans-Atlantic rift distortions and thus to better reconstruct the evolution of continental margins of the South Atlantic; and this in turn will improve our general understanding of the evolution of continents.

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