Pre-Cenozoic correlations across the South Atlantic region – 'the ties that bind'

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Running Title: The Ties that Bind

The first to recognise the complementary shapes of Africa and South America and to suggest that these continents were once joined together was Dutch scientist Ortelius in 1596. He was followed in 1620 by Elizabethan philosopher Sir Francis Bacon, who asserted that the similarity of their shapes could not be accidental. Nearly 200 years later, German naturalist von Humboldt described how the two continents may have fitted together, and in 1860 French geographer Antonio Snyder produced the first map that showed South America and Africa in close contact (e.g., Blankett 1965). By 1915 the German meteorologist Alfred Wegener had amassed enough data to publish a comprehensive scientific argument for the past conjunction of these two continents on the basis of similarities in the Palaeozoic–Mesozoic geology on each side of the South Atlantic, and then boldly proposed that 'horizontal displacements of the continents' (Horizontal verschiebungen der Kontinente) caused their subsequent separation (Wegener 1915).

Wegener's original hypothesis of 'continental displacement' (Krause & Thiede 2005) was severely criticized, especially by geophysicists (Oreskes 1999). Nevertheless the concept was successfully transformed into the continental drift hypothesis through the support of, amongst others, two prominent geologists working in South America and Africa, respectively: Argentine Juan Keidel (1916) recognised the geological similarities between the Sierra de La Ventana Fold Belt in Argentina and the Cape Fold Belt in South Africa, whilst South African Alex du Toit (1927), following his extended visit to South America in the 1920s, first correlated in detail the litho- and bio-stratigraphy of the Palaeozoic and Mesozoic Karoo sequences of southern Africa across the Atlantic into Brazil and Argentina, and then summarized these findings in his book *Our Wandering Continents* (1937) (Fig. 1). By the early 1960s, advances in palaeomagnetism and the discovery of apparent polar wander paths finally helped to place Wegener’s concept of continental drift on more robust geophysical footing. This period culminated in a well-known Royal Society symposium on continental drift at which the first computer-controlled fit between Africa and South America was presented (Bullard *et al.* 1965). Very shortly thereafter, following the discovery of sea-floor spreading, the emergence of plate tectonic theory rapidly embedded Wegener’s continental drift and evolved into a truly new field of solid earth geodynamics (Oreskes 2001). All this stimulated new geological and geochronological research to evaluate and test different South America–Africa reconstructions that had been proposed by then. A comparative survey of ages and structures of the basement rocks on each side of the Atlantic Ocean between Brazil and West Africa was well on the way before the 1970s (e.g., Hurley *et al.* 1967; Almeida & Black 1968).

Similar contributions of this type followed rapidly and a major international programme focussed on cross-Atlantic correlations was initiated with UNESCO support (International Geological Correlation Programme, Projects Nos 108 and 144, 1975–1984). Significant syntheses resulting from this new geological research were published over a period of more than a decade (e.g., Torquato & Cordani 1981; Porada 1989; Trompette 1994). In parallel, geophysical investigations in the southern oceans revealed with increasing detail the magnetic character of the oceanic crust of the South Atlantic: key magnetic anomalies could be correlated on either side of the mid-ocean ridge with great confidence (Rabinowitz & LaBrecque 1979). Using this marine data, new geological reconstruction between these two continents became possible, and by the late 1980s, a new geological map of Gondwana was produced whose reconstruction was based purely on the available marine data at hand (de Wit *et al.* 1988). This map in turn helped stimulate a new phase of geological correlations to further refine the fit between Africa and South America (e.g., Lawver *et al*. 1999). Today, reuniting Gondwana has reached such reliable accuracy that geological features on opposite sides of the South Atlantic can be joined up with a margin of error of less than 100 km (Eagles 2007; de Wit *et al*. this volume).

With this firmer understanding of the relationship between Gondwana continents during the Palaeozoic and early Mesozoic, the geoscience community started to address the question of how Gondwana came to be a supercontinent in the first place; and what might have been the continental precursors to this great landmass. For this, a greater understanding of the building blocks of Gondwana was needed, a requirement that was brought into sharp focus when Canadian geologist Paul Hoffman (1991) suggested that a previous supercontinent, Rodinia, formed at about 1 Ga around the nucleus of Laurentia, the 'Grenvillian' mobile belts representing the associated accretion processes. In this model, Rodinia fragmented during the early Neoproterozoic, the resulting continental blocks drifting away from one another as new ocean basins opened up, and then colliding relatively rapidly again in a complex pattern during the later Neoproterozoic to form the backbone of Gondwana. This new bold step took continental drift much further into the past and nurtured a new concept of supercontinental 'cycles' (e.g., Nance *et al*. 1988; Murphy & Nance 1992; Rogers 1996), almost 100 years after Wegener had introduced the concept of drifting continents. At present the details of Rodinia and its transformation into Gondwana are as controversial as the concept of Gondwana was when it was first formulated (Unrug 1992, 1996; Rogers 1996; Dalziel 1997; Hoffman 1999; Meert 2003; Cordani *et al.* 2003; Mantovani & Brito Neves 2005),

Nomenclature

Differences in the way that geological concepts are used by different geoscientists and on either side of the South Atlantic warrant some discussion. West Gondwana, for example, can be subdivided into cratons, shields, and orogenic or mobile belts (Fig. 2), but there is considerable disagreement about the terms ‘craton’ and ‘shield’. Some of these disagreements stem from the fact that very recent advances in Africa (and Canada), particularly in seismology, tomography, magnetotellurics, geochemistry and mantle petrology, have redefined the shape of cratons more robustly in three and four dimensions: with this, terms such as shield and craton are taking on new meanings. The oldest pristine Archaean terrains are now known to be underlain by unusually thick and depleted mantle lithosphere that stabilised in Archaean times, resulting in a strong lithospheric profile capable of resisting major tectonic and thermal modification for over 3 billion years, except where subsequently rifted apart and broken up below a critical size. Post-Archaean terrains in Africa do not display these unusual lithospheric characteristics. Geoscientists who have focussed their studies on these Archaean regions (and their distinct differences with younger continental areas) have suggested that the term craton (or ‘tectosphere’) should be restricted to these Archaean areas (Jordan 1988; Durheim & Mooney 1994; James *et al*. 2001; Stankiewicz *et al*. 2002; Bell & Moore 2004; Fouch *et al*. 2004; Niu *et al*. 2004; Shirey *et al*. 2005; O’Reilly & Griffith 2006; Chevrot & Zhao 2007). Where cratons have been tectonically fragmented and then reworked by later thermal and tectonic events, they may lose some or all of their cratonic features, especially their thick mantle lithosphere. Such fragments can, in turn, be enlarged through subsequent accretion processes and the addition of new juvenile lithosphere, to form new stabilised regions (within which older cratons, or fragments thereof, may be tectonically embedded), and become covered by undeformed shallow marine and terrestrial sequences. It is suggested that these stable regions should be referred to as shields (de Wit *et al*., this volume). In the present volume, for example, Pedreira & de Waele describe Proterozoic (*c*. 1.8 Ga) sedimentary sequences that covered the combined São Francisco–Congo shield prior to Gondwana break-up.

Because in many regions of West Gondwana sufficient seismic/magnetotelluric data and deep mantle petrology/geochemistry are not yet available, the distinction between cratons and shields is not always possible. In this volume therefore the term craton is often used for areas that are composed of both Archaean and Palaeoproterozoic rocks, and that may even include some Mesoproterozoic belts as well, to represent crustal (albeit not necessarily lithospheric) continental units that were essentially unaffected by the late Neoproterozoic to Early Cambrian (650–500 Ma) penecontemporaneous sequence of orogenies traditionally referred to as *Pan-African* in Africa and *Brasiliano* in South America. These Neoproterozoic 'cratons' represent palaeo-continents (or cores thereof) formed during the Meso- Neoproterozoic break-up of Rodinia, such as the Congo shield in Africa and the São Francisco craton in South America.. In cases where theses 'cratons' are relatively small, or their geochronology is poorly defined, they are often referred to as 'blocks' (or crustal fragments), which may have broken off larger palaeocontinents at some earlier stage. One example in South America is the Paranapanema block, which is hidden under the Phanerozoic cover of the Paraná Basin); another, in Africa, is the Latea block of the Hoggar Massif in the Sahara (Caby 2003). Its outline is inferred from gravimetric data, borehole sampling and tectonic inferences (Mantovani & Brito Neves 2005. In contrast, small fragments of cratonic blocks on one continent may be part of a larger shield on the other continent, for example, the small São Luís fragment in NE Brazil is probably part of the West African shield (see Klein & Moura and de Wit *et al*., this volume). The Río de la Plata craton (shield) of Uruguay and Argentina is unusual in being predominantly

Palaeoproterozoic in age, with very little evidence of Archaean crust – Pazos *et al*. (this volume) review the evidence for Neoproterozoic glaciation of this craton. In Africa, its closest equivalent is the Kalahari shield or the Angola block which, in turn is part of the Congo shield. Clearly then, usage of these different terms for continental lithosphere fragments is confusing. Sorting out these Trans-Atlantic 'geo-dialects' should be an important quest for future correlation programmes.

Orogenic or mobile belts (also referred to as fold belts, orogens or simply belts) are elongated areas characterized by deformation and/or metamorphism, in the present case mostly related to the Brasiliano/Pan-African orogenies (Fig. 2). They usually contain deformed sedimentary and/or volcanic rocks of Neoproterozoic age, but may contain considerable fragments and slices of older reworked shields or cratons. They may have resulted from collision, transcurrent lithospheric shear zones or progressive accretion of terranes along an active continental margin, but terminal collision is required to explain their position in the interior of West Gondwana. A recent review of the long-term (Neoproterozoic–Palaeozoic) evolution of the accretionary orogenic belts along the proto-Pacific margin of West Gondwana is given by Vaughan & Pankhurst (in press), but the present book is more concerned with the regions within that part of the supercontinent related to initial assembly, which is usually considered to have been completed by mid-Cambrian time. It should also be noted that many of the papers in this book relating to the geology of Brazil represent updated summaries of information presented in the excellent book published for the 31st International Geological Congress in Rio de Janeiro (Cordani *et al*. 2000): this is now available more widely on-line – see below.

The term 'orogenic cycle', frequently used in the literature on evolution of the Brasiliano/Pan-African belts, meaning to include an initial stage of continental break-up and a final stage of accretion and collision, is largely avoided here for two reasons. First, because in many cases the word ‘cycle’ is used for the latter part of a full Wilsonian cycle (e.g., that part related to the contractional or orogenic phase), in which case ‘orogeny’ is preferable. Second, because the concept of the Wilson Cycle with continental break-up followed by collision along the same line of rifting seems not to apply to many orogens under discussion. That is, continents may break up at different times and come together in completely different configurations, possibly on the other side of the Earth. Adherence to the Wilson Cycle concept would appear to be more the exception then the rule. Of course, if the concept of a cycle is understood on a more global scale, as the cycle of formation and destruction of supercontinents (e.g., Nance *et al*. 1988; Murphy & Nance 1992), in this case from Rodinia to Gondwana, then the idea of a supercycle might still be useful.

Instead of ‘Brasiliano/Pan-African orogeny’ some authors use Brasiliano/Pan-African event or thermo-tectonic event (e.g., de Wit *et al*., 2001, following Kennedy, who first used the expression in Africa in 1964). Since orogenic activity within the whole Gondwana region can now be differentiated using modern geochronology and thermochronology, Pan African and Brasiliano tectonics are beginning to be recognised as complex and diachronous, and several local orogenies are now identified within the major ones (e.g., the Buzios orogeny within the Ribeira–Araçuai orogenic belt, Schmitt *et al.* 200; see also Brito Neves *et al*. 1999 and Campos Neto 2000 for syntheses of continental-scale details of the Brasiliano orogeny).

Within the various orogenic belts described in this book many terranes are defined, either exotic or suspect. The precise meaning of this term has been discussed elsewhere in the literature (Coney *et al.* 1980; Howell 1989; Coombs 1997; Vaughan *et al.* 2005) but we should emphasize here that in many cases of contrasting areas of

Precambrian rocks, the existing data concerning ‘terrane’ demarcation and comparison with adjacent areas are relatively scarce and that in several cases these terranes may need to be redefined in the future. Alternatively the term domain may be used for these poorly defined “possible” terranes.

In summary, much remains to be learned about the details of Brasiliano and Pan African geology and the various pre-Gondwana basement blocks, before the paleo-geodynamics of Gondwana formation can be fully understood and described. It is therefore perhaps wise that many Gondwana geologists for the moment ‘agree to disagree’ about the details of their terminology.

Supercontinental origins

The opening of the southern Atlantic Ocean in the Early Cretaceous separated South America from Africa along a line that, south of 12°S, largely follows Neoproterozoic to Cambrian suture belts, but also cuts older cratons and Palaeozoic–Mesozoic sedimentary basins. A best fit of the continents along the 1000 m depth contour shows wide areas where crustal rocks are covered by Mesozoic and Cenozoic shelf sediments, whose disposition has in some cases been disturbed by break-up tectonics (Mohriak *et al*. this volume), hampering the correlation of older tectonic units across the continents. However, since these older units are mostly cratons, shields and Neoproterozoic mobile belts formed during Gondwana assembly, their detailed comparison and correlation across the present Atlantic Ocean is a crucial step in both the accurate reconstruction of Gondwana and constraining the processes by which it was formed.

The lithospheric nuclei that amalgamated to form Gondwana, were essentially fragments of Rodinia. In South America the Brasiliano orogeny records a series of subduction magmatism, accretion and collisional events from 880 to about 530 Ma (Brito Neves *et al*., 1999; Campos Neto 2000). In Africa, the major accretions and collisions of the Pan-African orogeny occurred over a shorter time span, between about 650 and about 530 Ma. Collectively these orogenic events led to the final formation of West Gondwana (Unrug 1996; Brito Neves *et al*. 1999; Meert 2003). The detailed identification, recognition and correlation of tectonic terranes and domains within the various belts and provinces are some of the major issues discussed in this book, together with the ways in which later events that occurred once the supercontinent had achieved stability can be correlated across the Atlantic. Not all these issues are resolved yet in a satisfactory way, and these therefore will need further study in the future.

The assembly of East Gondwana probably resulted from prolonged and/or progressive Pan-African collisions between India, Africa, and East Antarctica–Australia along orogenic belts running from the Arabia-Nubian shield, through the Mozambique belt, to East Antarctica (e.g., Jacobs & Thomas 2004). This process began at 650 Ma or slightly earlier, terminating in some places with a Cambrian-age orogeny at 535–520 Ma (e.g., Meert 2003; Boger & Miller 2004), but this late phase elsewhere may be related to a post-orogenic exhumation history (e.g., de Wit *et al*. 2001). The assembly of the separate fragments that constitute West Gondwana is equally prolonged and, in general, also not well constrained, although some aspects of the puzzle are becoming clearer. Palaeomagnetic data constraining ocean-spreading during the separation of Amazonia, West Africa and Baltica from Laurentia during Rodinia break-up is reviewed by Pisarevsky *et al*. (this volume). They propose that the opening of the main branches of the intervening Iapetus Ocean were probably plume-related, but that a bimodal uncertainty in the database prevents a definitive interpretation, although Tohver *et al*. (2006) consider that some parts of West Gondwana (West Africa–Amazonian shield) may not have been part of Rodinia at all. The time interval between 880 and 650 Ma was marked by the movement of these fragments across Neoproterozoic oceans, generating magmatic arcs (e.g., the Goias magmatic arc in the Brasília Belt, Pimentel *et al*. 2004; Valeriano *et al*. this volume) and ophiolites (e.g., Pires Paixão *et al*. this volume; Pedrosa-Soares *et al*. this volume). The geological evolution of the Borborema Province of NE Brazil up to and including the collisional history recorded in the orogenic belts, and comparisons with evidence from the geological record for these events in West Africa, are reviewed in this volume by Arthaud *et al*., Santos *et al*., Van Schmus *et al*. and Dada. To the south of this, the geology and evolution of the Araguaia, Brasília, Araçuaí, and Ribeira belts, together with their probable links to the West Congo region, are treated in this volume by Pires Paixão *et al*., Moura *et al*., Valeriano *et al*., Pedrosa-Soares *et al*., Heilbron *et al*. and Schmitt *et al*. A southern palaeo-ocean, the Adamastor ocean probably existed during much of the Neoproterozoic between the south-central African shields and the south-central South American shields (Pedrosa-Soares *et al*., Gray *et al*., Basei *et al*. all in this volume) present U–Pb data for detrital zircon that elucidate the provenance of sediments deposited on ether margin of this ocean throughout the Neoproterozoic. Collisions between the South American and the African nuclei seem to have culminated at *c*. 520 Ma, essentially at the same time as a terminal event within parts of the East African–Antarctic orogen (Jacobs & Thomas 2004), as demonstrated by the evidence for Cambrian orogeny in the Ribeira Belt of eastern Brazil (Heilbron *et al*. this volume; Schmitt *et al*. this volume). Gray *et al*. (this volume) who review the history of the orogenic belts on the African side (Damara, Kaoko and Gariep) and deduce that the Adamastor Ocean closed sequentially from north to south, followed by northward thrusting of the Kalahari shield across the Damara Belt.

Between about 520 and 500 Ma, extensive exhumation and erosion led to regional peneplanation, especially across Africa, followed by widespread deposition of siliciclastic sequences such as the Table Mountain Group of southern Africa**,** the Alto Garças Formation in Brazil, the Caacupé Group in Paraguay and their equivalents in North and West Africa (Burke *et al*. 2003; Milani & de Wit this volume). After the short-lived Ashgill glaciation a gradual transition took place to stable platform conditions, with the development of large intracratonic sedimentary basins, such as the Paraná, Parnaíba, and Amazonas basins in Brazil and the Karoo basin in southern and central Africa, reviewed in this volume by Milani & de Wit.. During this period of relatively stable internal Gondwana, lasting until Triassic desertification, Palaeozoic accretion continued along its proto-Pacific margin (e.g., Vaughan *et al*. 2005; Vaughan & Pankhurst in press).

Thus, the formation of Gondwana occurred by the assembly of quite varied fragmented cratonic nuclei from earlier supercontinents, through ocean-spreading, subduction, accretion and collisions over a period of 250–350 million years. In the process, some of the building blocks (shields and cratons) were modified in their form and structure, and even further fragmented. Local and regional orogenic belts developed quasi-simultaneously, often overprinting or cross-cutting earlier belts in a way that could have caused crustal shortening, block rotations and the opening of new basins, even after major stages of assembly were completed. The complexities of these interactions, together with poor exposure or a paucity of good data continue to impede a definitive timetable and exact reconstructions. Continued field and laboratory studies, and in particular aeromagnetic surveys are clearly necessary as called for in the final chapter of this book, in which de Wit *et al*. also propose specific geological features that in principle should help to resolve some of the details of how we should envisage West Gondwana in its essentially final form, and constrain parameters in order to model the assembly of Gondwana with greater accuracy and precision.

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Figure Captions

Figure 1. The first detailed geological comparison between Africa and South America by Alex Logie du Toit. This figure (from the A. du Toit collection, reproduced with permission from the University of Cape Town Library Archives) shows the handwritten proof corrections by du Toit for his book "Our wandering continents" published in 1927. This figure was later also published in his presidential address to the Geological Society of South Africa in 1928. Note that du Toit connected the extremities of the Cape Fold Belt and the Sierra de la Ventana Fold Belt directly through the Falkland Islands.

Figure 2. Modern view of West Gondwana in the mid Palaeozoic, with (a) the shields and cratonic fragments representing pre-existing continental masses and (b) the Pan-African/Brasiliano orogenic belts mainly formed during assembly. NB. This is a schematic representation, principally to identify the location of named structures dealt with in this volume . Deposition in the Sierra de la Ventana–Cape Fold Belt began in the Early Palaeozoic and continued up to Permian times. After Vaughan & Pankhurst (in press) and Tohver *et a*l. (2006).

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Fig 13. Suggested Continental Restoration for the South Atlantic Region under the Displacement Hypothesis:— A, Agua Suja; B, Burnier; Bv, Boa Vista; Ki, Kasai; Ko, Kaokoveld; Ks, Klein See; L, Lüderitz; N, Neuquen; P, Postmasburg; S, Salobro; Sc, Santa Catherina; Sv, Sierra de la Ventana; U, Uitenhage.

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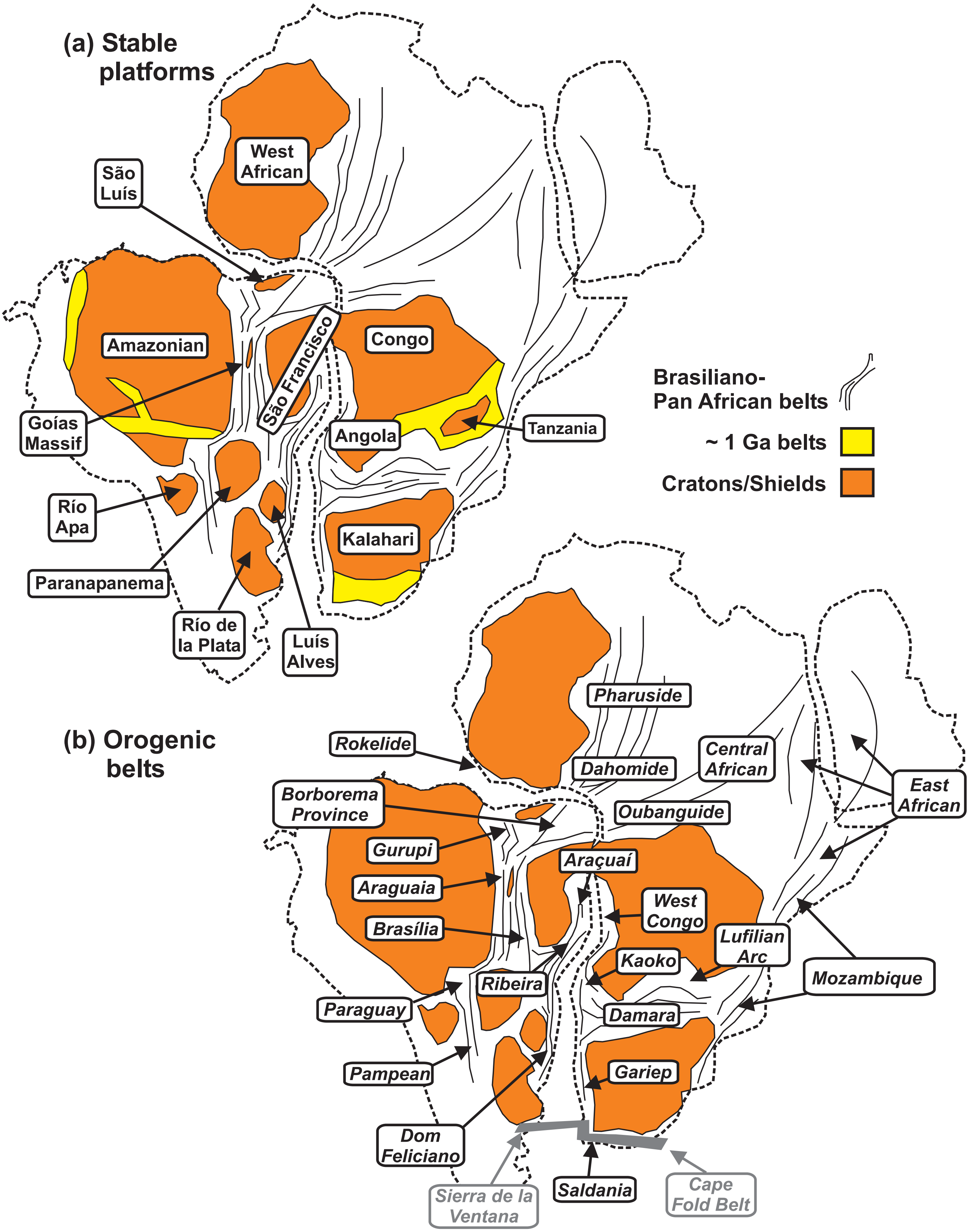
(a) Stable platforms
West African
São Luís
Amazonian
Goías Massif
São Francisco
Congo
Angola
Tanzania
Río Apa
Paranapanema
Kalahari
Río de la Plata
Luís Alves
Brasiliano-Pan African belts
~ 1 Ga belts
Cratons/Shields
(b) Orogenic belts
Pharuside
Rokelide
Dahomide
Central African
East African
Borborema Province
Oubanguide
Gurupi
Araçuaí
Araguaia
West Congo
Brasília
Lufilian Arc
Kaoko
Ribeira
Mozambique
Paraguay
Damara
Pampean
Gariep
Dom Feliciano
Saldania
Sierra de la Ventana
Cape Fold Belt