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Notes

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Abstract: The Pan-African Damara orogenic system records Gondwana amalgamation involving serial suturing of the Congo–São Francisco and Río de la Plata cratons (North Gondwana) from 580 to 550 Ma, before amalgamation with the Kalahari–Antarctic cratons (South Gondwana) as part of the 530 Ma Kuunga–Damara orogeny. Closure of the Adamastor Ocean was diachronous from the Araçuaí Belt southwards, with peak sinistral transpressional deformation followed by craton overthrusting and foreland basin development at 580–550 Ma in the Kaoko Belt and at 545–530 Ma in the Gariep Belt. Peak deformation/metamorphism in the Damara Belt was at 530–500 Ma, with thrusting onto the Kalahari Craton from 495 Ma through to 480 Ma. Coupling of the Congo and Río de la Plata cratons occurred before final closure of the Mozambique and Khomas (Damara Belt) oceans with the consequence that the Kuunga suture extends into Africa as the Damara Belt, and the Lufilian Arc and Zambezi Belt of Zambia. Palaeomagnetic data indicate that the Gondwana cratonic components were in close proximity by *c.* 550 Ma, so the last stages of the Damara–Kuunga orogeny were intracratonic, and led to eventual outstepping of deformation/metamorphism to the Ross–Delamerian orogen (*c.* 520–500 Ma) along the leading edge of the Gondwana supercontinental margin.

Understanding supercontinent reconstruction requires detailed knowledge of the orogens that bind the former continental fragments together. Apart from knowledge of palaeomagnetic poles for the constituent cratonic masses, this includes the component lithofacies, the gross crustal architecture, the geometry of the major fault and shear zones as well as the thermal and temporal aspects of deformation, metamorphism and magmatism. For West Gondwana supercontinent construction (Fig. 1) this requires understanding of Brasiliano/Pan-African orogenesis, as West Gondwana is made of a mosaic of cratons linked by a complex set of Pan-African/Brasiliano fold belts (Fig. 2).

The Pan-African Damara orogen of Namibia (Fig. 3) reflects part of the West Gondwana suture. It provides connection between the Brasiliano orogens of South America through the Ribeira and Dom Feliciano belts of southern Brazil (Fig. 2) and is related to convergence between the Río de la Plata and the Congo and Kalahari cratons of South America and Southern Africa (e.g., Prave 1996). The Damara orogen consists of three component arms that define a three-pronged orogenic system or collisional triple junction (Coward 1981, 1983; Hoffman *et al.* 1994). These component fold belts are the NNW-trending northern coastal arm or Kaoko Belt, the S-trending southern coastal arm or Gariep Belt and the ENE-trending Inland Branch or Damara Belt (e.g., Kröner 1977; Martin & Porada 1977*a*, *b*; Miller 1983*a*). The Damara Belt extends under cover into Botswana and ultimately links with the Lufilian Arc and the Zambezi, Mozambique and Lurio belts (see Goscombe *et al.* 2000; Hanson 2003).

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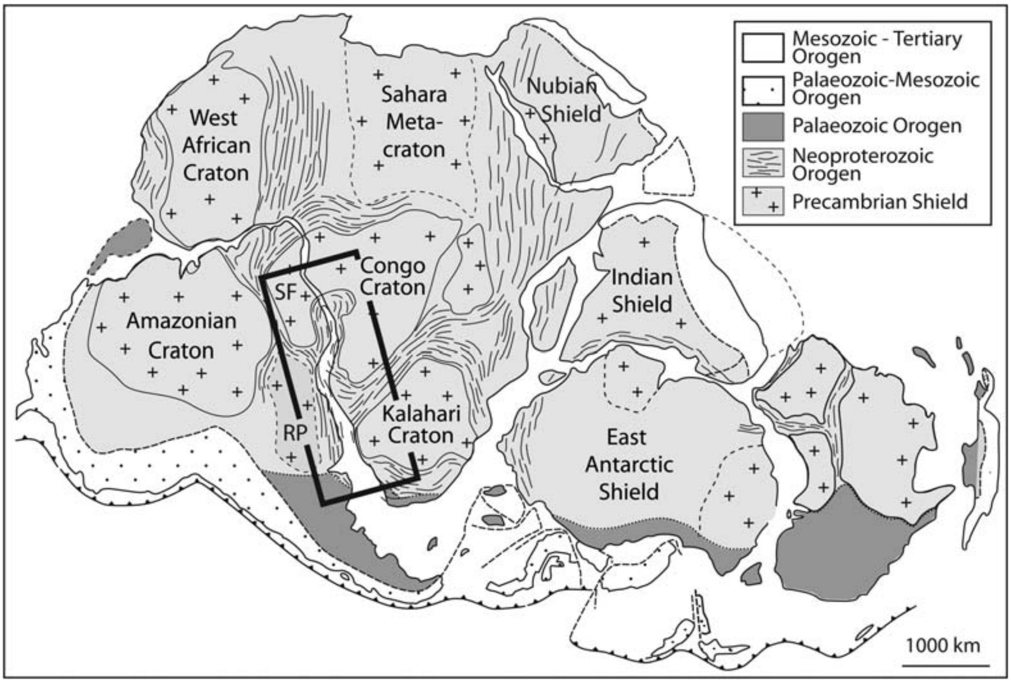

Fig. 1. Map of Gondwana showing the positions of the cratonic nuclei and the orogenic belts that weld the supercontinent together. The younger orogens occur along the supercontinent margins. The map region shown in Figure 2 is outlined by the heavy-lined box. SF, São Francisco Craton; RP, Río de la Plata Craton.

Questions remain regarding the timing and circumstances of accretion of the cratonic continental fragments, the relative positions of the cratonic fragments over time, and the presence and widths of ocean basins between the fragments. Tectonic scenarios range from ensimatic models with ocean basins that developed with oceanic lithosphere (e.g., Barnes & Sawyer 1980; Kasch 1983*a*; John *et al.* 2003) through to ensialic models of failed Cambrian intracratonic rifting (e.g., Martin & Porada 1977*a*, *b*; Trompette 1997). Despite similar questions and discussions in the detailed works on the Damara orogen published in the early 1980s (e.g., Martin & Eder 1980; Miller 1983*b*) the nature, size and substrate to the respective ocean basins, their tectonic settings of ocean closure, and the presence, or lack of subduction systems, as well as the directions of subduction, are still uncertain.

This paper revisits these issues in the light of the most recent geological, geochronological and thermochronological data for the Damara orogen. As part of this analysis the paper investigates the geological components of the Damara orogen and summarises the most recent data on (1) the structural style and crustal architecture, (2) the metamorphism, (3) geochronological and thermochronological constraints and (4) deformation kinematics. It is a review paper that attempts to link these data with the time-equivalent belts of South America. It also updates and revises the tectonic evolution of the various belts that make up the Damara orogen, particularly in the context of Gondwana amalgamation.

Background

Connections between the orogenic components of Africa and South America were first recognised by du Toit (1937), as part of his Samfrau orogenic Zone of Permo-Triassic age. Porada (1979, 1989) investigated more fully the genetic links between the different parts of the Pan-African Damara orogen and the Brasiliano Ribeira orogen with a detailed review of Damara orogen geological relationships, including regional stratigraphy, structure and metamorphism.

Porada (1989) argued that the Damara orogenic system originated as a three-pronged continental rift system at *c.* 1000 Ma, where the Damara Belt was considered as a failed rift or aulocogen. This scenario includes two episodes; the Katangan at 900–750 Ma and the Damaran at 750–500 Ma. More recently, Trompette (1997) argued for West

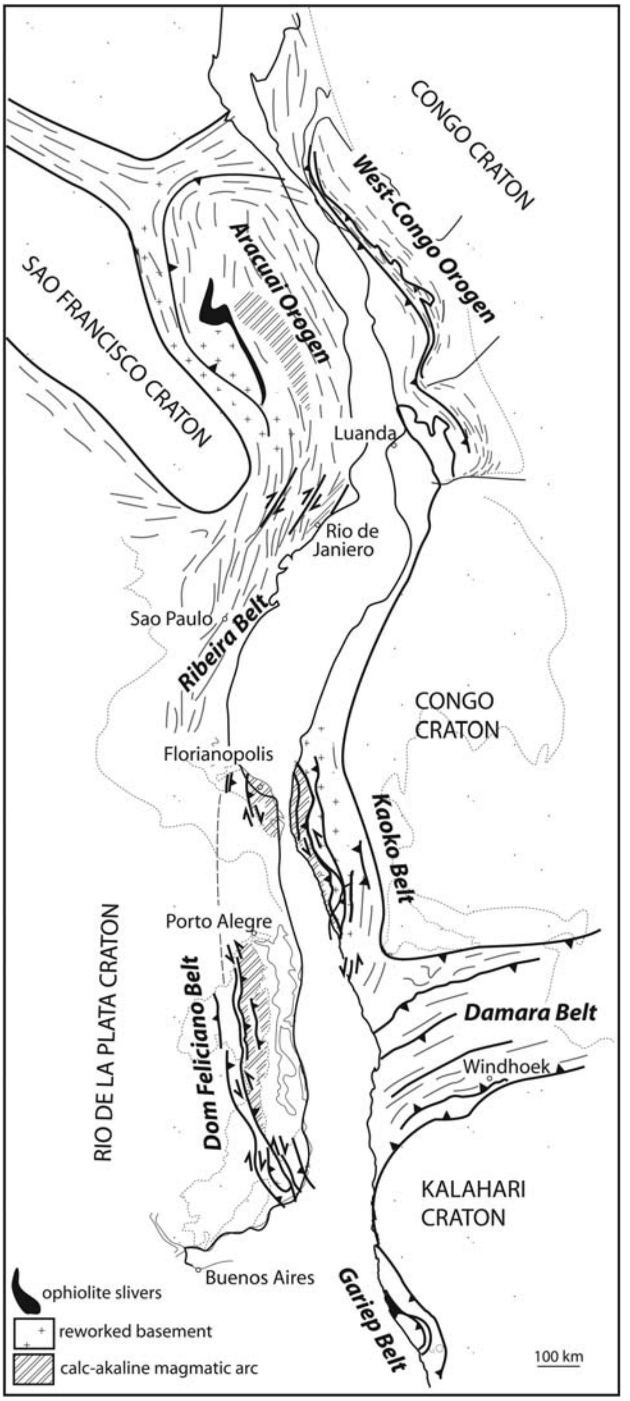

Fig. 2. Map of the Brasiliano and Pan-African orogens defining the amalgamation sutures of West Gondwana between the South American and African cratonic nuclei. The composite orogenic system is made up different component belts and orogens, including from north to south the Araçauí–West Congo orogen, the Ribeira Belt, the Dom Feliciano–Kaoko Belts and the Gariep Belt. Geological relationships including fault traces from the Araçauí orogen are from Pedrosa-Soares *et al.* (2001), the Ribeira Belt from Heilbron & Machado (2003), the Dom Feliciano Belt from Basei *et al.* (2000) and Frantz & Botelho (2000), and the Kaoko Belt from Goscombe *et al.* (2003*a*, *b*; 2005*a*, *b*).

Gondwana supercontinent aggregation from 900 to 600 Ma, involving a two-stage evolution with intracratonic rifting (ensialic) at *c.* 600 Ma followed by basin closure at 520 Ma.

The timing of ocean basin closure has been disputed. Stannistreet *et al.* (1991) proposed that the Khomas Ocean between the Congo and Kalahari cratons (i.e., the Damara Belt) closed before the southern part of the Adamastor Ocean between the Río de la Plata and Kalahari cratons (Gariep Belt), in contrast to Prave (1996) who used sedimentological evidence to argue the opposite. Ocean closure, particularly for the Adamastor Ocean is generally accepted as being diachronous, closing initially in the north (Kaoko Belt) and migrating southwards with a 'zip closure' action (e.g., Germs & Gresse 1991; Gresse & Germs 1993; Stannistreet *et al.* 1991; Frimmel & Frank 1998; Maloof 2000). Most recent geochronology/thermochronology of the Damara orogen (e.g., Goscombe *et al.* 2005*b*; Gray *et al.* 2006) linked with existing data (e.g., Frimmel & Frank (1998) for the Gariep; Kukla (1993) and Jung & Mezger (2003) for the Damara Belt) supports closure of the northern Adamastor Ocean resulting in the Kaoko Belt, then the southern Adamastor Ocean producing the Gariep Belt and finally the Khomas Ocean, suturing along the Damara Belt.

Recent provenance studies utilising U–Pb analyses of detrital zircon populations have established linkages between the various lithostratigraphic units on both sides of the Atlantic Ocean and have helped to establish or confirm tectonic evolutionary scenarios. For example, Frimmel *et al.* (1996) argued for west-directed subduction beneath the Río de la Plata Craton, which has been supported by the provenance data of Basei *et al.* (2005). Similar detrital zircon populations in the Rocha (Dom Feliciano Belt), Oranjemund and Stinkfontein groups (Gariep Belt) establish basin/sedimentation linkages that require subduction in the southern Adamastor Ocean beneath the Río de la Plata Craton.

Recent palaeomagnetic studies and/or reviews of Gondwana palaeomagnetism (Rapalini 2006; Tohver 2006) suggest that West Gondwana was a coherent block by 550 Ma, as there is a single Apparent Polar Wander Path for its components from this time onwards, requiring continent–continent collisions for the Damara and Gariep belts at this time. However, the detailed geochronology/thermochronology presented in Goscombe *et al.* (2005*b*) and Gray *et al.* (2006) reviewed in this paper greatly refines this and allows a new revised look at the tectonics of West Gondwana amalgamation.

Damara Orogen crustal architecture: overview

Lithostratigraphy

The major geological components of the Damara orogen (Fig. 3) are the Archaean–Proterozoic basement inliers, the Damara Sequence passive margin carbonates that rimmed the ocean basins between the cratons (Otavi facies), the deeper water turbidites within the ocean basins (Swakop facies) and the foreland basin deposits (molasse) of the Mulden and upper Nama (Fish River Sub-Group) groups of northern and southern Namibia, respectively. The basement comprises continental-scale ovoid cratonic nuclei, partly contained within Namibia (Fig. 3a) and now preserved either as large inliers, the Kunene and Kamanjab inliers of the Congo Craton in northern Namibia and basement of the Kalahari Craton in the Southern Margin Zone of the Damara Belt and bordering the eastern margin of the Gariep Belt in southern Namibia (Figs 3 & 4). Basement is also exposed in the cores of smaller, elongated domes within the Central Zone of the Damara Belt and in antiformal nappes and thrust slivers in the Kaoko Belt (Fig. 4*c*).

Deposition of the Damara Sequence spanned the Neoproterozoic between at least 770 and 600 Ma (Miller 1983*a*; Prave 1996; Hoffman *et al.* 1994). The basal Damara Sequence is represented by rift-related siliciclastic rocks of the Nosib Group, comprised of quartzites, conglomerates and arenites. Quartz-syenite, alkaline ignimbrite and alkali-rhyolite units in the upper Nosib Group have U–Pb and Pb–Pb zircon ages ranging from 757 ± 1 to 746 ± 2 (Hoffmann *et al.* 1994; Hoffman *et al.* 1998: de Kock *et al.* 2000), constraining the minimum age of the Nosib Group to be approximately 750 Ma (Prave 1996; Hoffman *et al.* 1998). The overlying Otavi Group is dominated by turbiditic greywacke with pelitic schists and psammites and rare mafic schists. Within this succession are two turbiditic carbonate formations, parts of which are correlated with regional diamictite horizons that are elsewhere interpreted as 750–735 Ma and 700 Ma in age (Hoffman *et al.* 1994; Frimmel 1995; Hoffman *et al.* 1998; Folling *et al.* 1998). The uppermost Otavi Group is the widespread Kuiseb Formation, which is comprised of turbiditic greywacke and pelite schists with thin calc-silicate bands (Fig. 3).

Structure

The belts that make up the Damara orogen (Fig. 3), or the arms of the collisional triple junction, have distinct structural trends and style (Figs 4 & 5).

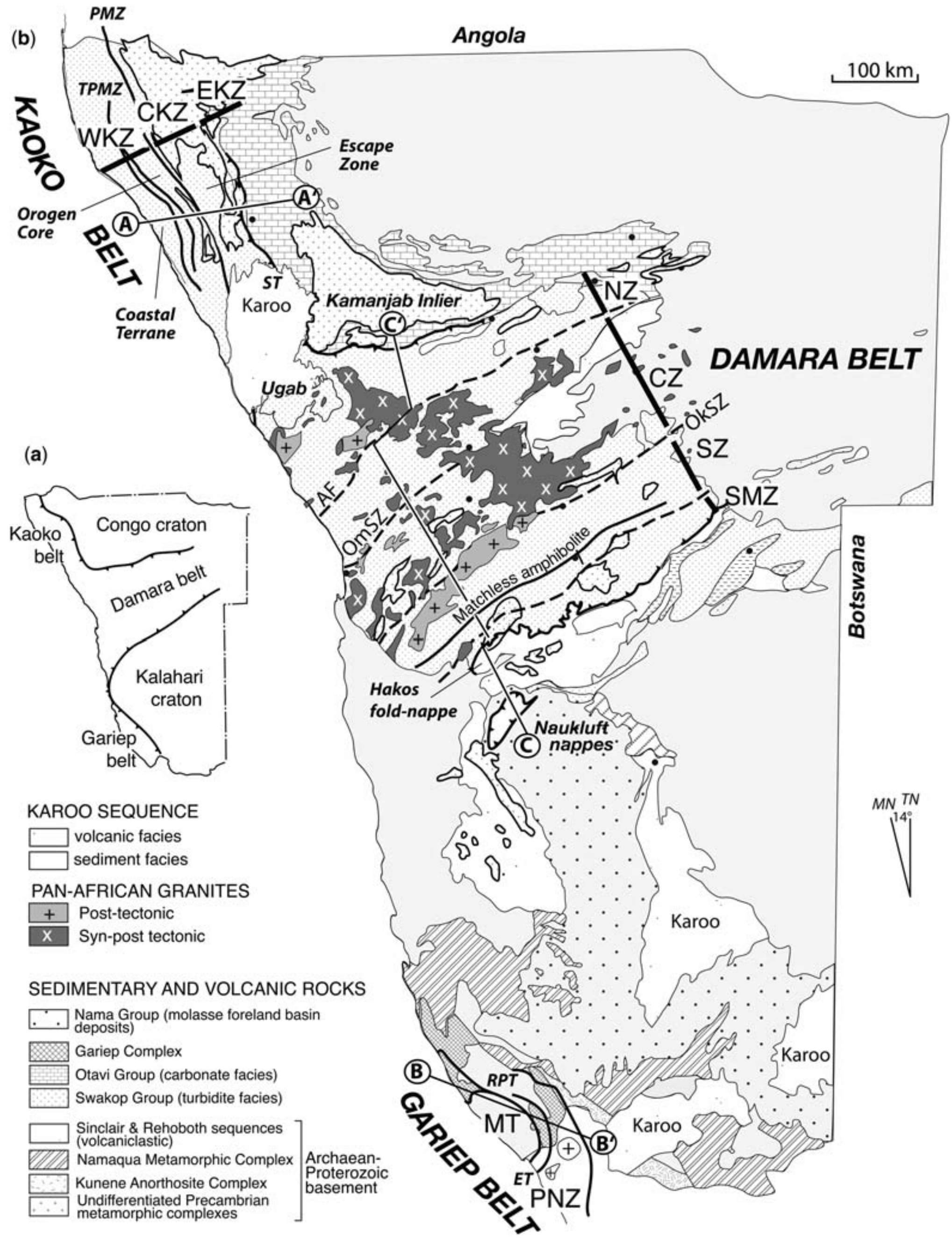

Fig. 3. Geological map of the Damara orogen showing the main geological units, the major faults, and the distribution of plutonic rocks and Swakop Group turbidites (map modified from geological map of Namibia). Inset (**a**) shows the relative positions of the component fold belts and the Congo and Kalahari cratons. The locations of profiles A–A′, B–B′ and C–C′ from Figure 4 are shown. WKZ, Western Kaoko Zone; CKZ, Central Kaoko Zone; EKZ, Eastern Kaoko Zone; TPMZ, Three Palms Mylonite Zone; PMZ, Purros Mylonite Zone; ST, Sesfontein Thrust (Kaoko Belt). AF, Autseib Fault; OmSZ, Omaruru Shear Zone; OkSZ, Okahandja Shear Zone; NZ, Northern Zone; CZ, Central Zone; SZ, Southern Zone; SMZ, Southern Margin Zone (Damara Belt). MT, Marmora Terrane; PNZ, Port Nolloth Zone; RPT, Rosh Pinah Thrust; ET, Eksteenfontein Thrust (Gariep Belt).

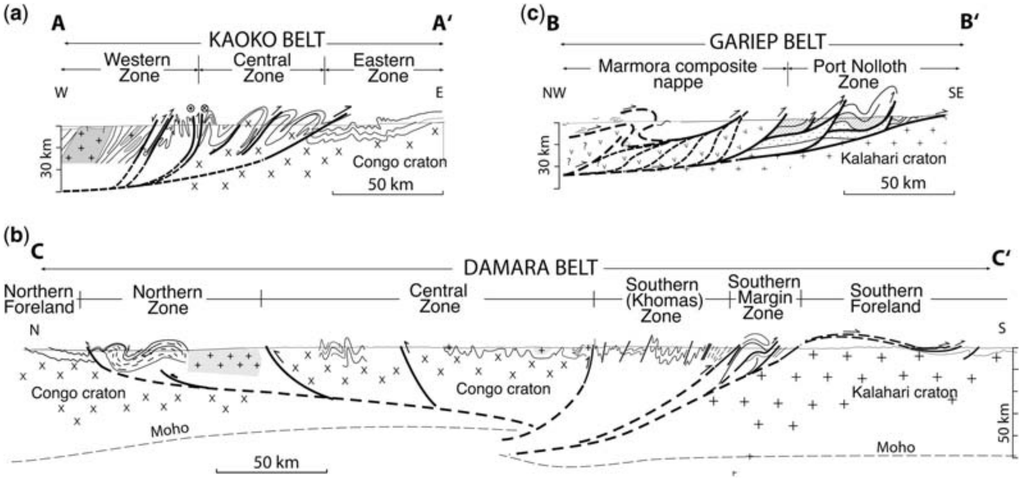

Fig. 4. Simplified structural profiles across the Kaoko, Gariep and Damara belts of the Damara orogen. (**a**) Crustal architecture of the Kaoko Belt (modified from Goscombe *et al.* 2003*a*). (**b**) Crustal architecture of the Gariep Belt (modified from Von Veh 1983 *in* Frimmel & Frank 1998). (**c**) Crustal architecture of the Damara Belt of the Damara orogen (modified from Miller & Grote 1988: profiles on Damara orogen 1:500,000 Map sheets). For location of the profiles see Figure 1. Note (a) and (c) are transpressional belts underlain by inferred west-dipping décollements and (b) shows an asymmetric orogen profile with an inferred former subduction interface, now thrust/shear zone system, penetrating to Moho depth beneath the Southern Zone.

Structural grain is NNW-trending in the Kaoko and Gariep Belts, but is ENE-trending in the Damara Belt (Fig. 5). Both coastal arms are sinistral transpressional belts (Kaoko Belt: Dürr & Dingeldey 1996; Maloof 2000; Passchier *et al.* 2002; Goscombe *et al.* 2003*a*, *b* and Gariep Belt: Davies & Coward 1982; Frimmel 1995; Hälbich & Alchin 1995), whereas the Damara Belt is a divergent orogen that formed during high-angle convergence between the Congo and Kalahari cratons (Coward 1981; Miller 1983*a*; Porada *et al.* 1983). The junction between the southern Kaoko Belt and the Damara Belt (Fig. 3) is the distinctive Ugab Zone with complex fold interference (Coward 1983; Porada *et al.* 1983; Maloof 2000; Passchier *et al.* 2002; Goscombe *et al.* 2004).

The Kaoko Belt is dominated by two NNW-trending crustal-scale shear zones and interlinking shear zones that define orogen-scale shear lenses and similar-trending arcuate shear zones define the major boundaries in the Gariep Belt (Fig. 5). The Damara Belt consists of fault- and shear-bounded zones of varying structural style from north to south: a fold-thrust belt displaying complex fold interference, a granite-dominated inner-zone with elongate, WNW-trending basement cored domes and Damara Sequence basins, and in the south a transposed schist belt and another marginal fold-thrust zone with basement-cored fold nappes (Fig. 5).

Each belt of the Damara orogen is dominated by craton-vergent, imbricate thrust–shear zone systems (Fig. 4). Both the Kaoko and Gariep belts have crustal architectures with inferred west-dipping décollements (Fig. 4a, c). In the Kaoko Belt the steeply west-dipping mylonite zones and inclined E-vergent basement-cored fold-nappes are considered to be rooted in this décollement (Goscombe *et al.* 2005*a*). The Gariep Belt geometry (Fig. 4c) has a composite, obducted ophiolite thrust-nappe, overlying imbricate faults in the passive margin sequence (Frimmel 1995). In contrast, the Damara Belt is an asymmetric, doubly vergent orogen (Fig. 4b). The southern margin is defined by a wide zone of intense, north-dipping, shear-dominated transposed fabrics (Southern Zone) and basement-cored fold-nappes bordering the Kalahari Craton (Southern Margin Zone). The Northern Zone is a craton-vergent, fold-thrust belt without a strongly sheared transposed zone. The Northern and Southern Margin zones must have décollements dipping away from the respective cratons (Fig. 4b).

Metamorphism

The Damara orogen shows contrasting styles of metamorphism. The Kaoko Belt consists of high-grade amphibolite to granulite facies metamorphic rocks (Orogen Core of the Western Kaoko Zone) juxtaposed against intermediate-pressure amphibolite facies rocks (Escape Zone of the Central

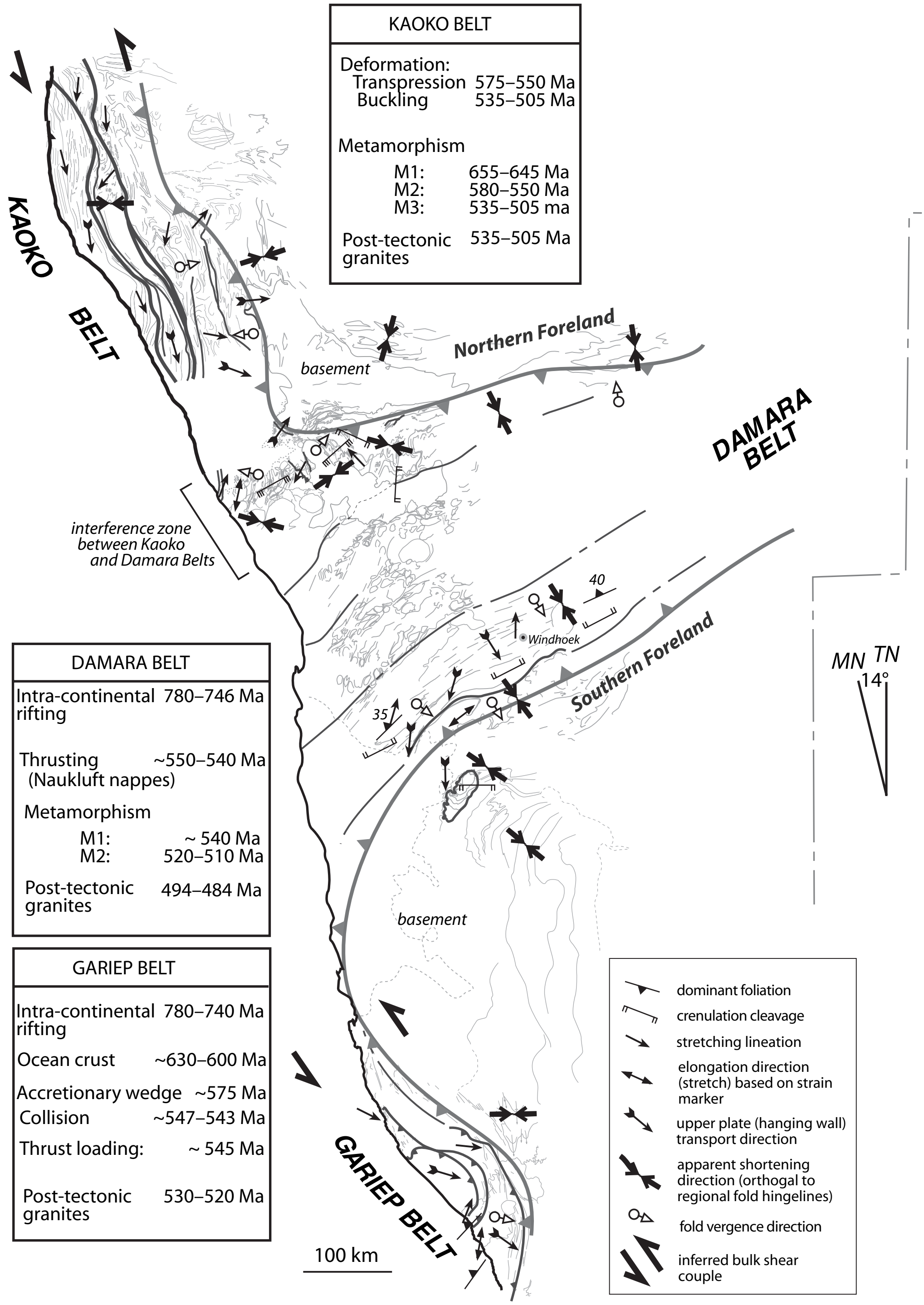

Fig. 5. Summary map of deformation kinematic data for the Damara orogen with insets providing a summary of the timing of key geological processes for each of the component fold belts. Kinematic data is based on the author's unpublished Namibian dataset. Note the fold vergence direction is drawn orthogonal to regional fold hinge lines.

Kaoko Zone) in the footwall of the Purros Mylonite Zone (PMZ, Fig. 3) and low-grade greenschist-facies rocks of the foreland or Eastern Kaoko Zone below the Sesfontein Thrust (ST, Fig. 3) (Goscombe *et al.* 2003*a*, 2005*a*; Will *et al.* 2004). The belt shows marked thermal partitioning into a heterogeneous though largely high-grade and high average thermal gradient Orogen Core bounded by major shear zones, and an inverted Barrovian-series margin of intermediate pressure with basement-cored fold-nappes thrust onto the Congo Craton. Peak metamorphic conditions for the high-grade parts of the Orogen Core were 800–840 °C and 6–8 kbar, and between 500 and 690 °C and 8–9 kbar in the Escape Zone. The Coastal Terrane of the western Kaoko Zone (CT, Fig. 3) experienced two metamorphic events: an early high-grade migmatitic event of *c.* 725 °C and 7 kbar and, during transpressional reworking, conditions of 550 °C and 4.5 kbar (Goscombe *et al.* 2005*a*).

The Gariep Belt is mostly of low metamorphic grade (Frimmel 2000), with greenschist-to-transitional amphibolite facies conditions in the imbricated passive margin sequences of the Port Nolloth Zone (PNZ, Fig. 3) (Fig. 4c). Temperatures ranged from 400 °C to 500 °C and pressures from 2.5 to *c.* 3 kbar (Frimmel 2000). The Chameis Complex mélange of the Marmora Terrane (MT, Fig. 3) records sub-blueschist, subduction-related metamorphism and peak temperatures of 500 °C to 550 °C and pressures of *c.* 6 kbar (Frimmel 2000).

The Damara Belt consists of a central high-*T*/low-*P*, granite-dominated belt, flanked by the Northern, Southern, and Southern Margin zones (NZ, SZ and SMZ, Fig. 3), which have intermediate-*T*/intermediate-*P* metamorphism (Kasch 1983*a*). The granite-dominated Central Zone (CZ, Fig. 3) underwent peak temperatures of *c.* 750 °C and pressures of *c.* 5.0–6.0 kbar (Kasch 1983*a*; Jung *et al.* 2000). Post-kinematic granites are largely confined to the Central and Northern Zones of the Damara Belt (Fig. 3). These granitoids are typically composite bodies, some concentrically zoned, with at least three intrusive phases ranging from syenite to biotite granite and late-stage aplite dykes. The Southern Zone underwent peak temperatures of *c.* 600 °C and pressures of *c.* 10 kbar (Kasch 1983*a*). The Northern Zone of the Damara Belt shows along-strike variation in metamorphism during north-south convergence, with low-*P* contact metamorphism with anticlockwise *P–T* paths dominating in the west (Ugab, Fig. 3) and higher-*P* (Barrovian series) metamorphism with clockwise *P–T* paths in the east (Goscombe *et al.* 2005*a*). The eastern part of the Northern Zone has peak metamorphic conditions of 635 °C and 8.7 kbar and experienced deep burial, high-*P*/moderate-*T* Barrovian metamorphism (Goscombe *et al.* 2005*a*).

Orogen kinematics

Structurally the Gariep Belt shows bulk SE-directed transport (Fig. 5) partitioned into (a) strike-slip faulting (Davies & Coward 1982) and longitudinal or NW–SE stretching in the northern part and in major shear zones of the Marmora sheet (Davies & Coward 1982; Gresse 1994) and (b) very strong axial elongation or NE–SW stretching in the southern arc (Gresse 1994). In the outer Gariep Belt, particularly near the contact between the Holgat and Stinkfontein groups (Port Nolloth Zone), the development of sheath folds during transposition (Gresse 1994) reflects very high shear strains.

Folds in the Gariep Belt change character and vergence around the Gariep Arc (see Fig. 18 of Gresse 1994). In the NE outer arc, defined by the NE-trending Rosh Pinah thrust (RPT, Fig. 3), the folds are more open, east-vergent and associated with east-directed thrusting. Southwards, around the arc where the Eksteenfontein thrust (ET, Fig. 3) is north-trending, these folds become tighter and isoclinal, and have SE-vergence. Here, the early folds are overprinted by NE-vergent F_2 folds (Gresse 1994), associated with a north- to NW-trending crenulation cleavage suggestive of a late component of margin-orthogonal compression (cf. fig. 4 of Frimmel 2000).

In the Kaoko Belt a zone of craton-vergent, basement-cored, isoclinal fold-nappes in the Central Kaoko Zone (Fig. 3) or Escape Zone appear to extrude from the dominant, medial Purros Mylonite Zone (PMZ, Fig. 3) (Goscombe *et al.* 2005*a*, *b*). These fold-nappes coincide with a swing in the lineation pattern to higher angles (up to 70–80°) to the grain of the orogen, reflecting a component of high-angle escape towards the orogen margin (Dürr & Dingeldey 1996; Goscombe *et al.* 2003*a*, 2005*a*). The Orogen Core, or eastern part of the Western Kaoko Zone inboard of the Three Palms Mylonite Zone (TPMZ, Fig. 3), contains shear-zone bounded domains of sheared migmatites with steep foliations and sub-horizontal lineations, a single domain of lower-grade chevron-folded turbidites and reworked basement gneiss slivers (Goscombe *et al.* 2003*a*, *b*). Coastal Terrane migmatitic gneisses and orthogneisses were down-graded and heterogeneously reworked by steep mid-amphibolite facies foliations and discrete shear zones (Goscombe *et al.* 2005*a*).

The Damara Belt shows high-angle convergence (Fig. 5) and lacks evidence of oblique or transcurrent movements, despite arguments for sinistral movements and top-to-the-SW tectonic transport by Downing & Coward (1981) and Coward (1981, 1983). Shear bands, developed in Kuiseb Formation schist and units of the Southern Margin Zone indicate north-over-south movement in a north–south transport direction (Fig. 5). Variably noth-dipping, asymmetric crenulations and mesoscopic folds reflect a bulk south-directed shear strain (Fig. 5). High-strain at the basement/cover contact is shown by deformed conglomerates in the cover (Chuos Formation), down-dip stretching lineations and mylonitic basement. The frontal lobes of the Hakos fold-nappe (Fig. 3) display prolate strains with the stretch direction at high angles to the transport direction as shown by shear bands.

The Central Zone of the Damara Belt displays contrasting kinematic behaviour with orogen-parallel stretch and shortening at high angles to the orogen at different levels (Oliver 1994; Kisters *et al.* 2004). During high-grade metamorphism and migmatization, the deeper levels of the Central Zone underwent pure shear deformation, with lateral orogen-parallel stretch (Kisters *et al.* 2004). This is in marked contrast to interpretations of SW-directed orogen-parallel extrusion (e.g., Downing & Coward 1981; Oliver 1994), where the domes were interpreted as large, SW-facing sheath folds rooted in the northeast Central Zone and requiring top-to-the-SW transport in a crustal scale shear zone (Downing & Coward 1981; Coward 1981, 1983). At shallower crustal levels the Central Zone has undergone crustal thickening, orogen-normal shortening by folding and NE-directed thrusting (Kisters *et al.* 2004).

Within the Southern and Southern Margin zones major south-directed bulk shear strain deformation was responsible for crustal-scale underthrusting of the Kalahari Craton northwards (Fig. 4c), as well as continued thrusting and crustal thickening along the margins of the orogen. Crustal thickening and burial along this margin led to the Barrovian metamorphism. Significant magmatic underplating related to extension in the lower part of the overriding plate, led to marked magmatism and younger, high-T/low-P metamorphism in the Central Zone.

Temporal aspects of deformation, metamorphism and magmatism of the Damara Orogen: review

Geochronological studies in the Kaoko Belt (Goscombe *et al.* 2005*b*), in the Damara Belt (Jung & Mezger 2003) and in the Gariep Belt (Frimmel & Frank 1998), as well as a geochronological/thermochronological study across the Damara orogen (Gray *et al.* 2006) provide a more comprehensive picture of the tectonothermal evolution of the orogen (Fig. 6).

The Kaoko Belt preserves evidence for three distinct metamorphic episodes: M_1 (655–645 Ma, restricted to the westernmost Coastal Terrane), M_2 (580–570 Ma) and M_3 (530–505 Ma) (see Goscombe *et al.* 2005*a*). Collision and docking of the outboard Coastal Terrane with the rest of the Kaoko Belt occurred after 645 Ma, but prior to 580 Ma at the onset of transpressional orogenesis and M_2 metamorphism (Goscombe *et al.* 2005*b*). During transpression the Coastal Terrane rock sequences were reworked at lower strains and lower metamorphic grade compared to the rest of the Kaoko Belt (Goscombe *et al.* 2005*b*). Transpressional orogenesis in the Kaoko Belt and Ugab Zone had ceased by *c.* 535 Ma, with cratonization marked by intrusion of post-kinematic granite and pegmatite between 535 Ma and 505 Ma (Goscombe *et al.* 2005*b*).

The Damara and Gariep belts both show younger deformation and metamorphism than the Kaoko Belt (Fig. 6; Gray *et al.* 2006). Continued high-angle convergence through 530 Ma in the Damara Belt coincides with large-scale open east–west trending folds in the Kaoko Belt (Goscombe *et al.* 2003*a*, *b*).

The Gariep Belt underwent thrust-nappe emplacement onto the Kalahari Craton at *c.* 550–540 Ma (Frimmel & Frank 1998). Oceanic sequences in the Marmora Terrane preserve (1) an earlier seafloor metamorphism suggesting that Adamastor Ocean seafloor spreading was occurring at *c.* 630 Ma and (2) subduction-related metamorphism at *c.* 580–570 Ma, suggesting that the Adamastor Ocean was closing at this time (Frimmel & Frank 1998). The Gariep Belt was cratonized by 520 Ma, with erosion into the Nama foreland basin commencing at *c.* 540 Ma (Gresse & Germs 1993; Gresse 1994; Frimmel 2000). It was intruded by post-kinematic granites at *c.* 507 Ma (Frimmel 2000), although east-directed thrusting continued inboard within the Nama foreland basin through 496 Ma (Gresse *et al.* 1988).

The Damara Belt shows a more complex high-T metamorphic history from 540 to 510 Ma with metamorphism coincident with pulses of magmatism (Jung & Mezger 2003). Intrusion of post-kinematic A-type granites from 495 Ma to 486 Ma (McDermott *et al.* 2000) was followed by cooling and exhumation of the Damara Belt through 470 Ma (Gray *et al.* 2006).

Damara Orogen tectonic evolution: problems and issues

Problems pertaining to Damara orogen evolution relevant to Gondwana amalgamation relate to: (1) the positions of the respective cratons through time, (2) the sizes of the ocean basins between them and (3) the positions and directions of

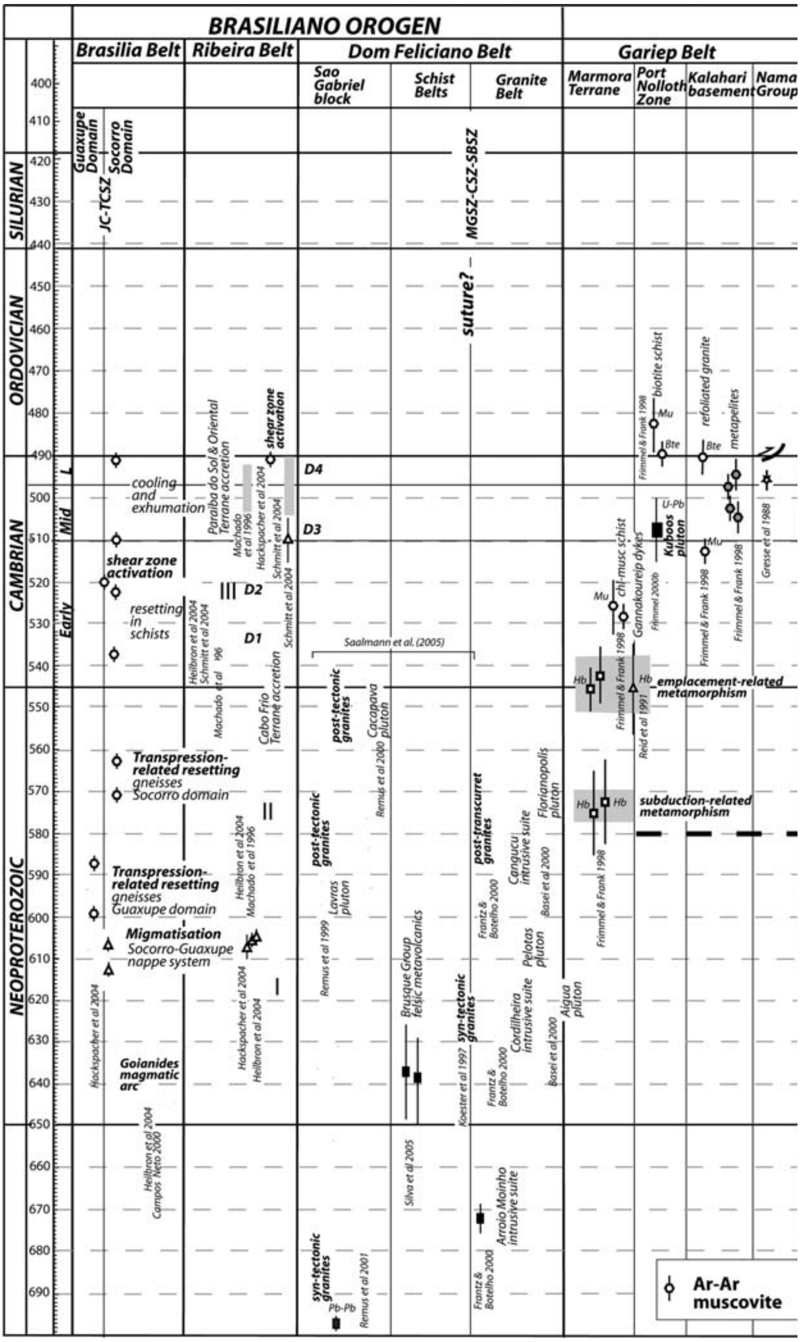

Fig. 6. Damara orogen and part of the Brasiliano time-space plot of recently published geochronological data including the $^{40}Ar/^{39}Ar$ data from Gray *et al.* (2006), and U–Pb data on zircon, monazite and titanite. Sources are listed in the figure. Unsourced data is from Gray *et al.* (2006). The diagram highlights the major periods of magmatism, metamorphism/deformation, thrusting and cooling and exhumation. Fault and shear zone abbreviations are as listed. WKZ, Western Kaoko Zone; CKZ, Central Kaoko Zone; EKZ, Eastern Kaoko Zone; TPMZ, Three Palms Mylonite Zone; VMZ, Village Mylonite Zone; PMZ, Purros Mylonite Zone; AMZ, Ahub Mylonite Zone; ST, Sesfontein Thrust; GMZ, Guantegab Mylonite Zone; OmL, Omaruru Lineament (Shear Zone); OkL, Okahandja Lineament (Shear Zone); JC-TCSZ, Jacutinga-Três Corações Shear Zones; MGSZ-CSZ-SBSZ, Major Gercino Shear Zone–Cordilhera Shear Zone–Sierra Ballena Shear Zone.

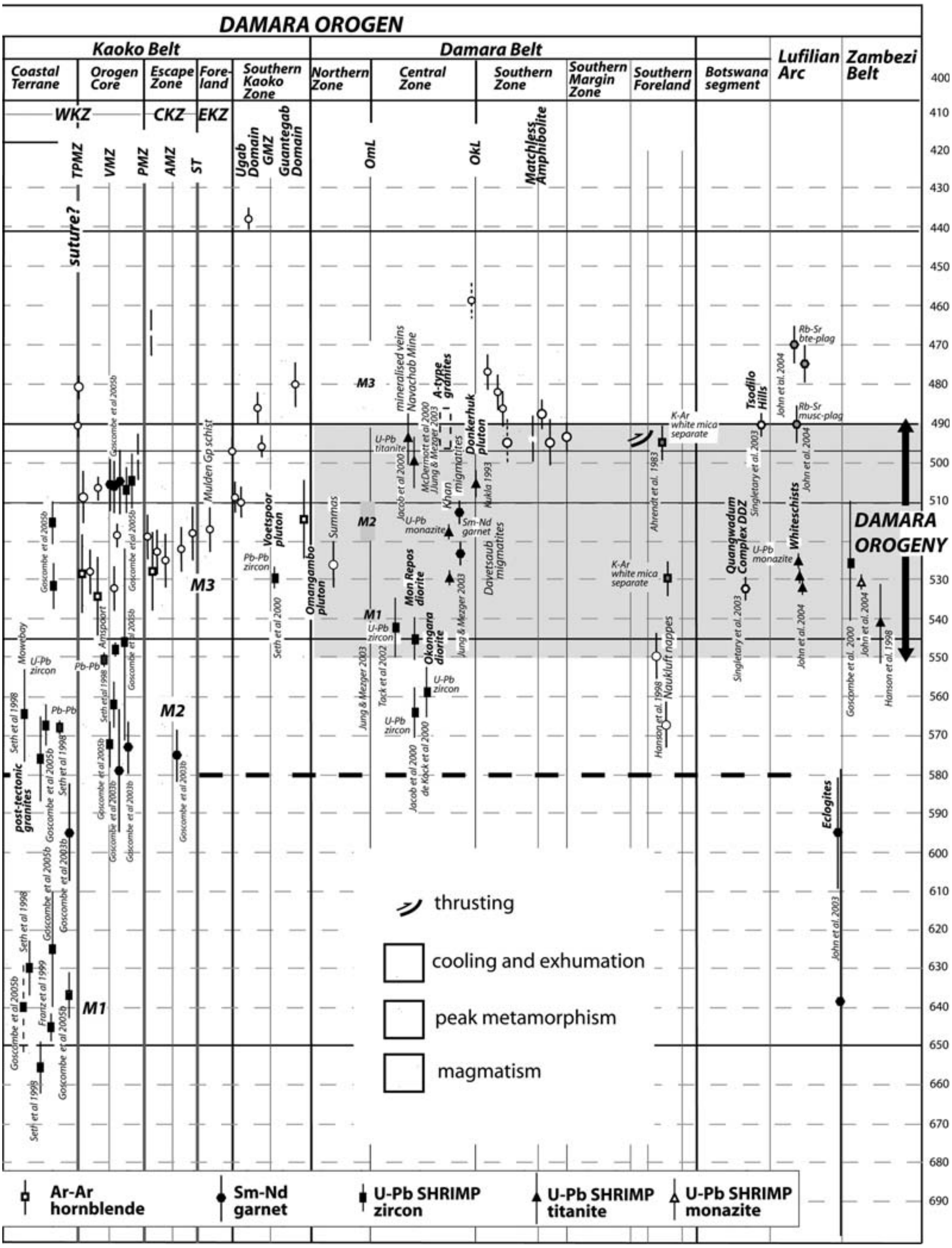

Fig. 6. (*Continued.*)

subduction zones that closed the ocean basins. Answers to problems (1) and (2) will require better definition of palaeomagnetic poles in the future, and particularly for that of the Kalahari Craton in the period 750–550 Ma. The presence and/or lack of subduction zones to close the intervening ocean basins will now be addressed.

Intracratonic orogeny with exclusive ensialic evolution has been applied to the Damara orogen, particularly for the Damara Belt (Kröner 1977; Martin & Porada 1977*a*, *b*; Porada 1979). In this model the strongly deformed and metamorphosed Matchless Amphibolite is questioned as an ophiolite remnant, despite MORB-type geochemistry (Barnes & Sawyer 1980) and a chert-Cu/Zn mineralization association (Killick 2000) typical of oceanic lithosphere. The lack of subduction-related metamorphism is also cited as evidence against ocean closure due to subduction, although the presence of eclogites in the Zambezi Belt (John *et al.* 2003) and white schists in the Lufilian Arc (John *et al.* 2004), part of the continuation of the Damara Belt into Zambia, provide alternative evidence.

In the Zambezi Belt, in contrast to Hanson *et al.* (1994) and Hanson (2003), John *et al.* (2003) argued for the presence of a large (>1000 km wide) ocean basin with MORB-type eclogites and meta-gabbros subducted to a depth of *c.* 90 km during basin closure. The timing of the eclogite facies metamorphism is 595 ± 10 Ma, suggesting that subduction was occurring at this time, some 60 Ma earlier than the *c.* 530 Ma peak of metamorphism in the central Damara Belt.

The long, apparently continuous, linear trace of the Matchless Amphibolite within intensely deformed Kuiseb Formation schist of the Southern Zone in the Damara Belt is unusual but may have similarities to the fault-bounded Dun Mountain ophiolite belt and Haast Schist of New Zealand (Gray *et al.* 2007). The transposed layering and pronounced schistosity in the Kuiseb Formation schist is almost identical to that of the central Otago part of the Haast Schist suggesting deformation under similar conditions in a scenario where the turbidite is on the down-going plate of an oceanic subduction system (see Coombs *et al.* 1976). In the Otago Schist an intermediate-*T*/intermediate-*P* (Barrovian-style) metamorphism linked to wedge thickening (Mortimer 2000) has almost totally eradicated the earlier subduction-related, intermediate-to high-*P* metamorphism (see Yardley 1982). The older metamorphism is only preserved as crossite relics in the cores of younger amphibole and albite porphyroblasts (see Fig. 2*c* of Yardley 1982). Widespread metamorphic overprinting at higher temperatures appears typical of Barrovian-style thickened and metamorphosed accretionary wedges, and is therefore likely to have obliterated any older intermediate-*P* to high-*P* metamorphism in the Kuiseb Formation schists of the Southern Zone.

The kinematics of the Southern Zone schists, by comparison with the Otago Schist Belt of New Zealand, combined with geochemistry of the more primitive diorites and syenites that are part of the Central Zone early magmatic history supports northward subduction of the Khomas Ocean lithosphere beneath the attenuated leading edge of the Congo Craton; as originally suggested by Barnes & Sawyer (1980) and Kasch (1983*b*).

For the Kaoko Belt, the lack of ophiolite sequences or high-*P* metamorphism has led to intracratonic fold belt interpretations (Dürr & Dingeldy 1996; Konopasek *et al.* 2005). More recently, the recognition of arc affinity for the Coastal Terrane has led to proposal of a subduction-related tectonic evolution, with subduction inferred to be both west-directed (Machado *et al.* 1996; Masberg *et al.* 2005) and further outboard east-directed subduction (Basei *et al.* 2000; Goscombe & Gray 2007).

If an ocean basin closed between the African and South American components of the Brasiliano/Pan-African orogenic system within the Kaoko Zone, the suture would have to be at the proto-Three Palms Mylonite Zone. Evidence for major crustal displacements with juxtaposition of distinctly different aged basement either side of the Purros Mylonite Zone (Goscombe *et al.* 2003*a*, *b*), combined with the lack of ophiolite slivers and high-*P* metamorphism, suggests that both shear zones are part of a broad, complex 'suturing' zone behind the former arc (i.e. in a back-arc position), between the arc and the African continental margin. This 'suturing' involved high-*T* metamorphism of turbidites deposited on the attenuated leading edge of the Congo Craton and included deformation and reworking of the cratonic basement (Goscombe & Gray 2007). This magmatic arc could well represent the continuation of the magmatic arc recognised in the Oriental Terrane of the Ribeira Belt (Heilbron *et al.* 2004) with similar ages and/or it could be part of the granite belt of the Dom Feliciano Belt.

Another issue for the Kaoko Belt is the inferred 750–600 Ma timing of foreland basin evolution for the Congo Craton (Prave 1996). This is problematical, in that the age of the Mulden Group is inconsistent with the 580–550 Ma and 530 Ma periods of deformation that established the tectonothermal character of the Kaoko Belt (Goscombe *et al.* 2005*a*, *b*). The Mulden Group was folded and metamorphosed prior to the late-stage thrusting event (Sesfontein Thrust), and a 750–600 Ma depositional age clearly predates the timing of peak (M_2) metamorphism. If the published Mulden Group age range is correct then the sedimentary facies and erosional hiatus of Prave (1996) must reflect instability associated with the initial collision of the Coastal Terrane, and therefore the Mulden Group sediments should contain a significant component of the 650 Ma detrital zircons.

An ensimatic, subduction-related origin has been accepted for the Gariep Belt, largely due to the Chameis Complex mélange of the Marmora Terrane with its mafic and ultramafic blocks, some of which contain Na-rich amphibole (Frimmel & Hartnady 1992). Although not strictly blueschist metamorphism, intermediate pressure (*c.* 6 kbar) and low temperature metamorphic conditions combined with the facies association of mélange (Chameis Complex), turbidites (Oranjemund Formation) and metavolcanic rocks (Grootderm Formation) support this contention (see descriptions and discussions in Frimmel 2000).

The direction of subduction has been discussed (see Frimmel *et al.* 1996), and recent provenance work on detrital zircon populations (Basei *et al.* 2005, this volume) supports west-directed subduction beneath the Río de la Plata Craton. This establishes continuity of a linked west- or north-directed subduction system that closed the former Adamastor Ocean and subsequently the Khomas Ocean to form the Gariep Belt and then the Damara Belt.

Damara Orogen tectonic evolution in a global context

West Gondwana amalgamation is shown in a series of global reconstructions for different time periods (modified from Collins & Pisarevsky 2005) incorporating temporal and tectonothermal constraints from the Damara orogen. In these tectonic reconstructions fragments of ophiolite and calc- alkaline volcanic rocks have been used as indicators of ocean closure, the ages of metamorphism and deformation indicate periods of accretion and crustal thickening, and the age of post-kinematic magmatism indicates the timing of cratonization.

780 Ma to 740 Ma (Fig. 7)

In our 750 Ma reconstruction the cratonic nuclei that eventually come together to form West Gondwana are separated by some 30° latitude with an ocean of unknown dimensions inferred between the Congo and Kalahari cratonic fragments. Such a reconstruction either contradicts or conflicts with previous interpretations of intracratonic rifting between these cratons, as represented by the Nosib rhyolites of the Congo margin and the Rosh Pinah volcanic rocks of the Kalahari margin (see fig. 7 of Frimmel & Frank 1998).

This is, however, a difficult time for which to fully constrain the palaeogeography. There are no reliable late Neoproterozoic poles from the Kalahari Craton. Collins & Pisarevsky (2005) argued for a Kalahari–West Australia connection based partly on the presence of overlapping Grenvillian-age

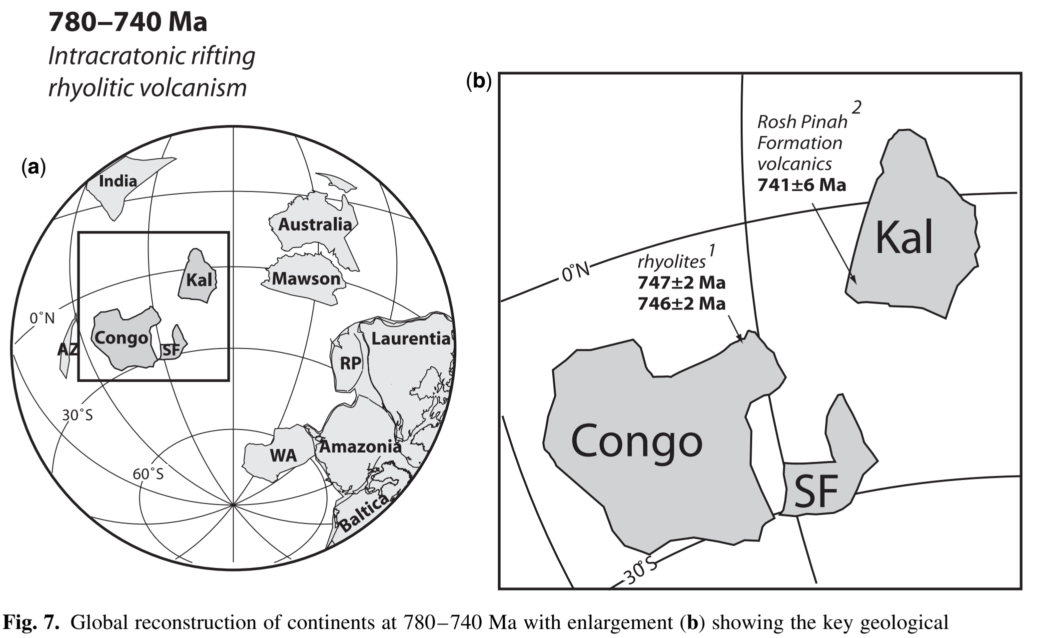

Fig. 7. Global reconstruction of continents at 780–740 Ma with enlargement (**b**) showing the key geological constraints during this time period from the Congo, Kalahari and São Francisco cratons prior to the development of the Pan-African/Brasiliano orogenic system. Continental fragments are AZ, Azania; SF, São Francisco; RP, Río de la Plata; WA, West Africa; Kal, Kalahari. Data references: 1, Hoffman *et al.* (1996); 2, Frimmel *et al.* (1996).

events in the Northampton Block (Australia) and the Namaqua–Natal belts (Kalahari Craton). Both the Kalahari Craton and Australia have reliable palaeomagnetic poles of Grenvillian age (1050–1100 Ma; see Meert & Torsvik 2003; Pesonen *et al.* 2003). These Grenvillian poles show a latitudinal offset between the Northampton Block and Kalahari of more than 30 degrees. Thus, in our reconstruction, we show the Kalahari Craton in proximity to the Congo–São Francisco craton, but detached from it. The position of the Congo–São Francisco cratons is based on the 755 Ma Mbozi Complex pole (Meert *et al.* 1995).

655 Ma to 600 Ma (Fig. 8)

Subduction-related closure begins in the northern Adamastor Ocean as evidenced by calc-alkaline magmatism in the Araçuaí and Ribeira belts between 625 Ma and 585 Ma, in the Dom Feliciano Belt from 620 Ma to *c.* 580 Ma (Basei *et al.* 2000), and from 655 Ma to 625 Ma in the Coastal Terrane of the Kaoko Belt (Masberg *et al.* 2005; Goscombe *et al.* 2005*b*). Collisional orogenesis was taking place in the Brasilano orogen at *c.* 640 Ma with nappe emplacements over the São Francisco Craton between 640 Ma and 630 Ma (Valeriano *et al.* 2004, 2008), due to collision with the Paranapanema block, now hidden under the Paraná Basin.

At *c.* 630 Ma seafloor spreading was underway in the southern Adamastor Ocean as recorded by seafloor metamorphism in Marmora Terrane of the Gariep Belt (Frimmel & Frank 1998).

580 Ma to 550 Ma (Fig. 9)

Arc–continent collision occurred in the Ribeira Belt (Río Negro arc: 595–560 Ma; Heilbron *et al.* 2004) and in the Kaoko Belt (Coastal Terrane: pre-580 Ma; Goscombe *et al.* 2005*b*). Peak metamorphism in the Kaoko Belt occurred at *c.* 580–570 Ma with transpressional reworking from 570–550 Ma (Goscombe *et al.* 2005*b*).

At this time (580–570 Ma) subduction-related metamorphism was taking place in the southern Adamastor Ocean (Marmora Terrane, Gariep Belt; Frimmel & Frank 1998) with subduction-related ocean closure in the Khomas Ocean (560–550 Ma) suggested by mafic magmatism (diorites).

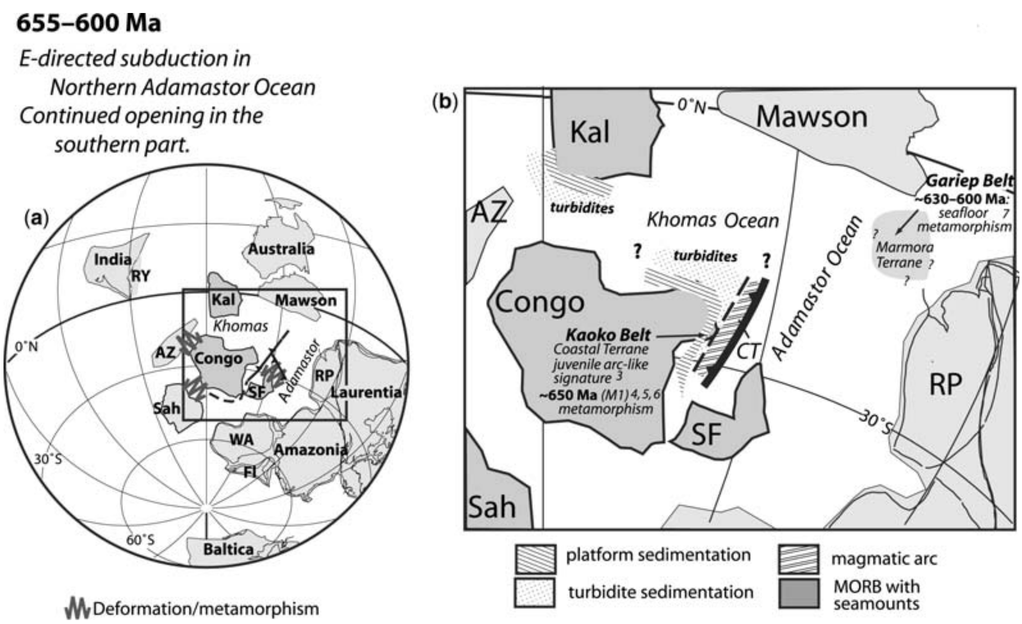

Fig. 8. Global reconstruction of continents at 655–600 Ma with enlargement (**b**) showing palaeogeographic lithofacies distributions and the key geological constraints during this time period from the Congo, Kalahari and São Francisco cratons prior to the development of the Pan-African/Brasiliano orogenic system. Traces of subduction zones are shown by heavy lines with barbs, where the barbs are drawn on the upper plate side and designate the subduction zone dip. CT, Coastal Terrane of the Kaoko Belt (shown as magmatic arc); Sah, Saharan Craton; MT, Marmora Terrane of the Gariep Belt (shown as oceanic lithosphere). Other abbreviations as in Figure 7. Data references: 3, Masberg *et al.* (2005); 4, Franz *et al.* (1999); 5, Seth *et al.* (1998); 6, Goscombe *et al.* (2005*b*); 7, Frimmel & Frank (1998).

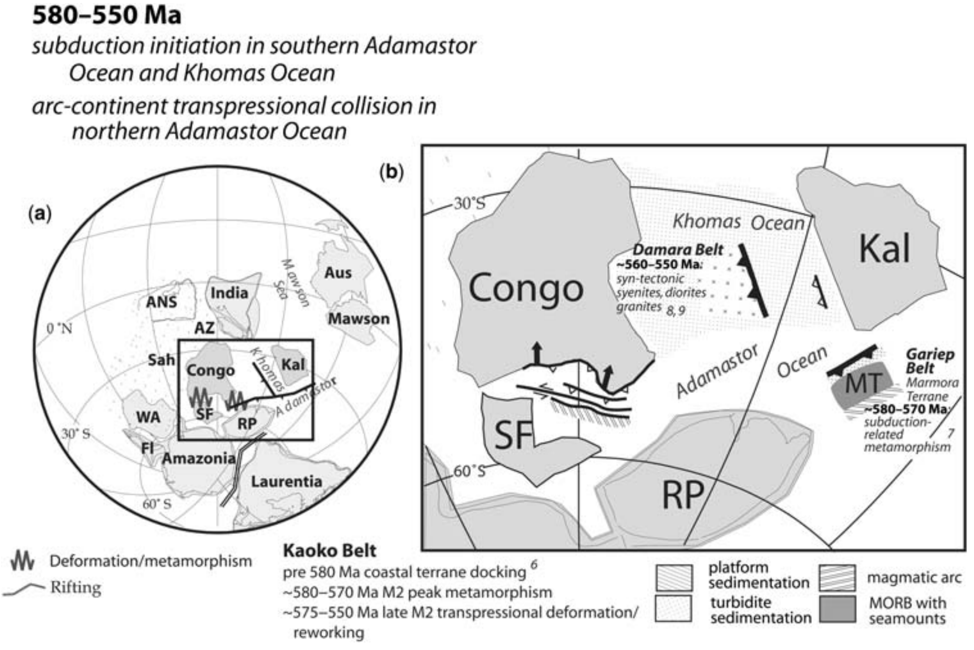

Fig. 9. Global reconstruction of continents at 580–550 Ma with enlargement (**b**) showing palaeogeographic lithofacies distributions and the key geological constraints during this time period from the Congo, Kalahari and São Francisco cratons prior to the development of the Pan-African/Brasiliano orogenic system. Traces of subduction zones are shown by heavy lines with barbs, where the barbs are drawn on the upper plate side and designate the subduction zone dip. An, Antarctica. Other abbreviations as in Figures 7 and 8. Data references: 6, Goscombe *et al.* (2005*b*); 7, Frimmel & Frank (1998); 8, Jacob *et al.* (2000); 9, de Kock *et al.* (2000).

550 Ma to 500 Ma (Fig. 10)

Closure of the southern Adamastor Ocean occurred from *c.* 550 to 540 Ma (Frimmel & Frank 1998) with oblique transpressional obduction of the Marmora Terrane oceanic suite over the imbricated passive margin sequence (Port Nolloth Zone, Gariep Belt) and initiation of Nama sequence foreland basin sedimentation (Gresse & Germs 1994).

Peak deformation/metamorphism took place in the Damara Belt through the Lufilian Arc into the Zambezi Belt at *c.* 530–520 Ma (Goscombe *et al.* 2000; Jung & Mezger 2003; Singletary *et al.* 2003; John *et al.* 2003, 2004). The Damara Belt shows marked magmatism and high-T/low-P metamorphism at this time (Kasch 1983*a*). At the margins of the orogen, over-thrusting and related crustal thickening caused intermediate-T/intermediate-P (Barrovian style) metamorphism (Northern Zone: Goscombe *et al.* 2004; Southern Zone: Kasch 1983*a*, *b*; Kukla 1993) with thrusting of the passive margin sequences back over the cratonic nuclei (Naukluft Nappes: *c.* 500 Ma; Ahrendt *et al.* 1977). Effects of the Damara Belt collisional deformation are seen as broad warpings and a younger thermal and magmatic event (M_3: 530–505 Ma) in the Kaoko Belt (Goscombe *et al.* 2005*b*).

In the Cabo Frio domain of the Ribeira Belt relatively high pressure and high temperature metamorphism at 530–510 Ma is interpreted as related to collision (Schmitt *et al.* 2004).

505 Ma to 480 Ma (Fig. 11)

Inboard transmission of stress from the outboard, Gondwana margin (Ross–Delamerian) subduction system caused continued thrusting (Naukluft Nappes: 500–495 Ma; Ahrendt *et al.* 1983) and syn-tectonic sedimentation in the Nama foreland basin (Ahrendt *et al.* 1983; Gresse *et al.* 1988; Gresse & Germs 1993) and in the Camaquã and Itajaí basins of Brazil (Gresse *et al.* 1996). It also led to shear zone reactivation in the Kaoko Belt (490–467 Ma; Gray *et al.* 2006) and Gariep Belt (506–495 Ma; Frimmel & Frank 1998).

Emplacement of post-tectonic A-type granites occurred in the Central Zone (McDermott *et al.*

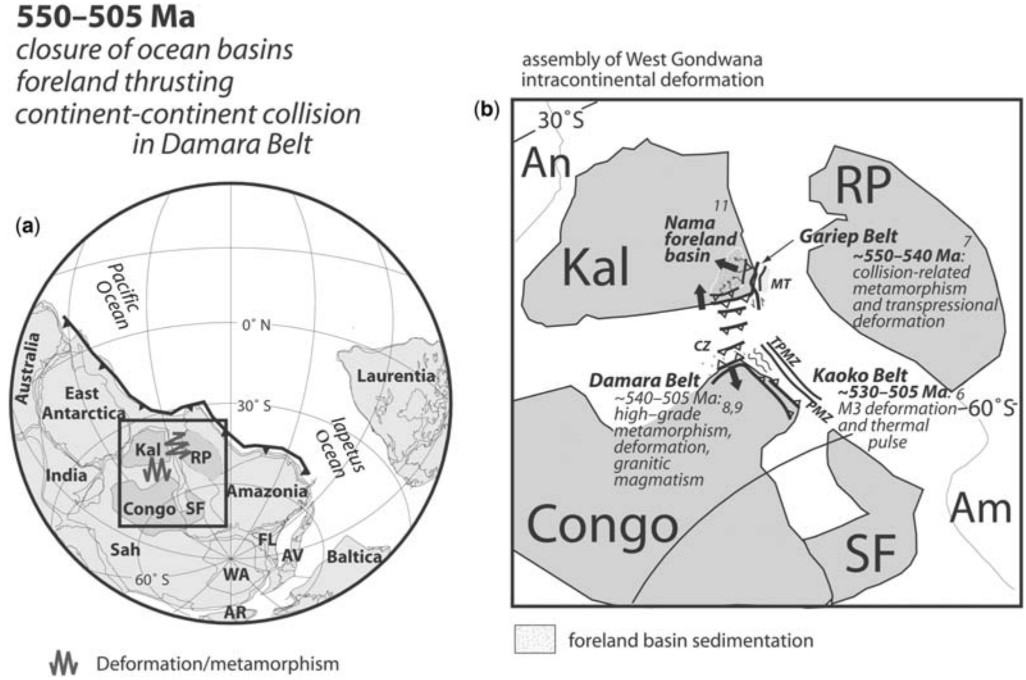

Fig. 10. Global reconstruction of continents at 550–505 Ma with enlargement (**b**) showing palaeogeographical lithofacies distributions and the key geological constraints during this time period from the Congo, Kalahari and São Francisco cratons during the development of the Pan-African/Brasiliano orogenic system. Traces of subduction zones are shown by heavy lines with barbs, where the barbs are drawn on the upper plate side and designate the subduction zone dip. The thinner heavy lines in (b) are fault traces. PMZ, Purros Mylonite Zone; TPMZ, Three Palms Mylonite Zone of the Kaoko Belt; AR, Armorica; AV, Avalonia; Fl, Florida. Other abbreviations as in Figures 7–9. Data references: 6, Goscombe *et al.* (2005); 7, Frimmel & Frank (1998); 8, Jacob *et al.* (2000); 9, de Kock *et al.* (2000); 10, Jung & Mezger (2003); 11, Gresse & Germs (1993).

2000) with continued cooling and exhumation in the Damara Belt through 480 Ma (Gray *et al.* 2006).

Significance for Gondwana assembly

From a western African perspective, the assembly of Gondwana shows complex suturing that does not reflect a simple final amalgamation of East and West Gondwana (Fig. 12). It is perhaps better described as an amalgamation of North (São Francisco–Congo–India) and South (Kalahari–Antarctica) Gondwana during the Kuunga orogeny (550–530 Ma), as proposed by Meert (2003) and Boger & Miller (2004) for the assembly of eastern Gondwana. Geochronological data from South America and southwestern Africa (Fig. 6) suggest closure of a Khomas–Mozambique ocean from 530 to 500 Ma, as part of a combined Damara–Kuunga orogeny. The composite Kuunga–Damara orogen incorporates the Damara orogen of Namibia, the Lufilian Arc and Zambezi Belt of Zambia, and joins the Lurio Belt of Mozambique and a belt made up of the Napier Complex of Antarctica, and the Eastern Ghats of India. It has dimensions comparable to the younger Ross–Delamerian orogen (Fig. 12).

Global reconstructions based on palaeomagnetic data suggest larger separations, and therefore significant ocean basins between the Río de la Plata, Congo and Kalahari cratonic nuclei that eventually define West Gondwana. This has a requirement of ensimatic subduction-related ocean closures, rather than ensialic, intracratonic evolutions that were originally proposed to explain many of the Brasiliano/Pan-African orogens. The position of the Kalahari Craton however, remains controversial. In the Collins & Pisarevsky (2005) reconstructions the Kalahari Craton abuts against the West Australian side of the Australian craton (Fig. 6), whereas according to Meert (2003, Fig. 1) it is situated outboard of a conjoined East Antarctica–Laurentia surrounded by Congo–São Francisco and Río de la Plata. From an African perspective

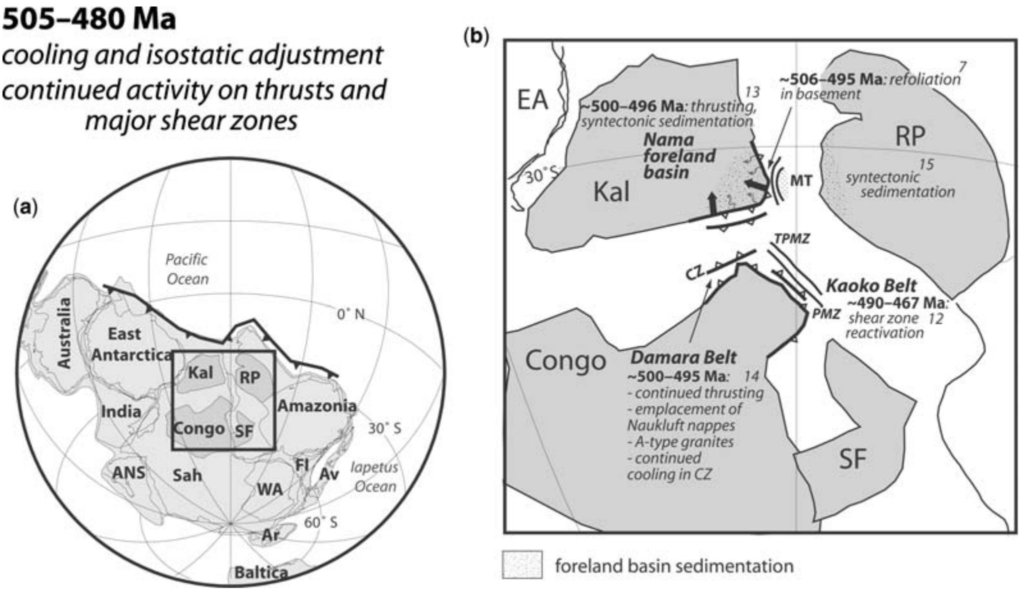

Fig. 11. Global reconstruction of continents at 505–480 Ma with enlargement (**b**) showing palaeogeographical lithofacies distributions and the key geological constraints during this time period from the Congo, Kalahari and São Francisco cratons during the development of the Pan-African/Brasiliano orogenic system. Reconstruction (**a**) is based on Figure 6 of Grunow *et al.* (1996). Traces of subduction zones are shown by heavy lines with barbs, where the barbs are drawn on the upper plate side and designate the subduction zone dip. The thinner heavy lines in (**b**) are fault traces. ANS, Arabian/Nubian Shield; Av, Avalonia; Ar, Armorica; EA, East Antarctica; Fl, Florida; CZ, Central Zone (Damara Belt). Other abbreviations as in Figs 7–10. Data references: 6, Goscombe *et al.* (2005*b*); 11, Gresse & Germs (1993); 12, Gray *et al.* (2006); 13, Gresse *et al.* (1988); 14, Ahrendt *et al.* (1977); 15, Gresse *et al.* (1996).

this provides a better fit for Gondwana assembly, as shown in Figures 7–11.

The West Gondwana suture between Africa and South America reflects the closure of the Adamastor Ocean, and provides the most detailed evolution sequences for SW Gondwana assembly (Fig. 12b). The Brasiliano orogens of South America show more complicated tectonic evolution with multiple tectonothermal events (see also Fig. 6), although the Dom Feliciano and Ribeira belts flanking the Río de la Plata Craton experienced collisional orogenesis with a transpressional component at the same time as the main phase deformation in the Kaoko Belt (Frantz & Botelho 2000; Heilbron & Machado 2003; Heilbron *et al.* 2004; Goscombe *et al.* 2005*b*). The collisional stage in the Ribeira orogen was at 590–560 Ma and is characterised by terranes juxtaposed by relatively steeply dipping, dextral transcurrent shear zones (Heilbron *et al.* 2004). In the Kaoko Belt collision immediately pre-dates main phase orogenesis in the period from 580–550 Ma (Goscombe *et al.* 2005*b*).

The linkage between the Brasiliano and Damara orogens is a *c.* 680–580 Ma magmatic arc component along the 2800 km long composite orogenic system (Fig. 2). In the former Adamastor Ocean, records of arc magmatism suggest a more complex tectonic evolution than perhaps a simple southwards migration of ocean closure, although this appears to be the case in the Ribeira–Dom Feliciano/Kaoko–Gariep part of the orogenic system.

Arc magmatism varies from 680–670 Ma in the Brasiliano belts along the west side of the São Francisco Craton (Heilbron *et al.* 2004), to 650–640 Ma in the Coastal Terrane of the Namibian Kaoko Belt (Seth *et al.* 1998; Franz *et al.* 1999), and from 620–580 Ma in the granite belt of the Dom Feliciano Belt (Basei *et al.* 2000). Southward migration of arc magmatism is further suggested by southward younging of the granite batholiths within the ‘granite belt’ of the Dom Feliciano Belt; the northernmost Florianopolis Batholith has an age of *c.* 620 Ma, the centrally located Pelotas Batholith an age of *c.* 610 Ma, and the southernmost Aguia Batholith an age of*c.* 580 Ma (Basei *et al.* 2000).

A 630–585 calc-alkaline magmatic arc in the Araçuaí Belt suggests that the main arc system may have followed the Brasiliano trend around the São Francisco Craton, rather than through the Araçuaí orogen, which shows a younger subduction-related closure of a Red Sea-type rift

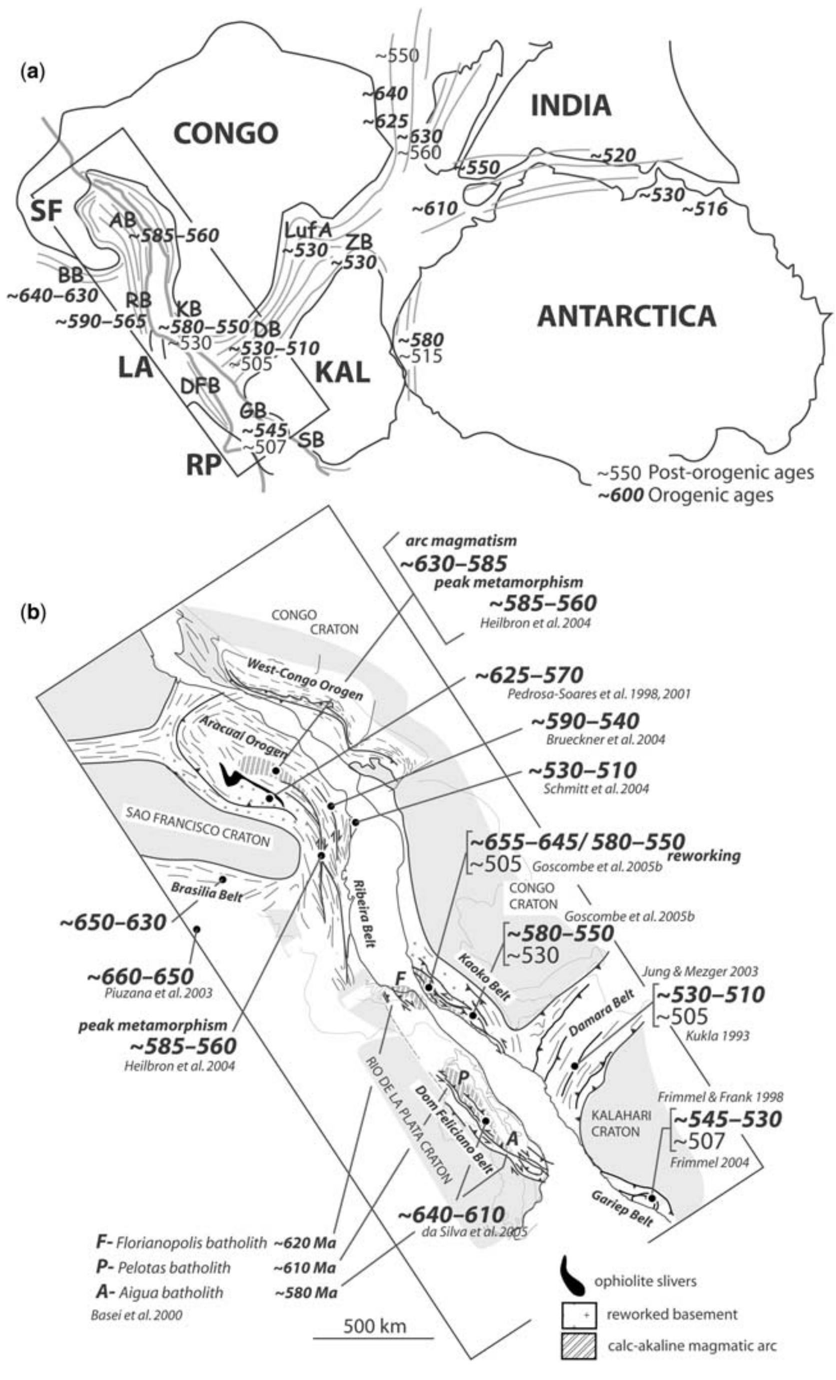

Fig. 12. Ages of orogenic suturing across Gondwana (modified from fig. 10 of Meert, 2003). The Gondwana reconstruction shows the various component orogens, the orogenic ages (bold italic) reflecting the timing of peak metamorphism/deformation, and post-orogenic ages (normal font) reflecting post-tectonic magmatism and therefore the timing of cratonisation, for each of the component belts. The inset (**b**) is an enlargement of the West Gondwana suture resulting from the closure of the Adamastor Ocean. The cratons include SF (São Francisco), LA (Luis Alves), RP (Río de la Plata), Kal (Kalahari), Congo, India and Antarctica. Component belts are BB, Brasília Belt; AB, Araçuaí Belt; RB, Ribeira Belt; KB, Kaoko Belt; DFB, Dom Feliciano Belt; GB, Gariep Belt; SB, Saldania Belt; DB, Damara Belt; LufA, Lufilian Arc; ZB, Zambezi Belt. Data sources are shown on the figure.

arm of the Adamastor Ocean (cf. Alkmin *et al.* 2006).

In summary, the closing of the Adamastor and Khomas oceans between three continental or cratonic blocks, the Río de la Plata, Congo and Kalahari cratons, resulted in a three-fold orogenic system or collisional triple junction during the welding of the Gondwana supercontinent. The differences in timing between deformation, metamorphism, and magmatism of the component belts of the Damara orogen provide a history of Gondwana suturing that is more refined than the palaeomagnetic data indicating that these cratonic nuclei were together by 550 Ma.

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