by Raphael Unrug

The assembly of Gondwanaland

Scientific results of IGCP Project 288: Gondwanaland sutures and mobile belts

Gondwanaland was assembled in the Neoproterozoic Pan African–Brasiliano orogeny following breakup of the preceding Rodinia supercontinent. The latter created and set in motion a new system of lithospheric plates that resulted in the formation of Neoproterozoic mobile belts suturing old cratons in Gondwanaland. East Gondwanaland was a fragment of Rodinia that survived the breakup and, during the Neoproterozoic, was affected only by intracontinental deformation. In West Gondwanaland, the opening of three oceans, from which Pan African–Brasiliano orogens were born, is traced to a period of crustal extension, rifting, transpression, magmatic arc activity, and a few documented terrane collisions (1000–720 Ma), bracketed by Rodinia assembly and breakup. All craton collisions involving closure of oceans (640–590 Ma), postdate the Rodinia breakup. The Pan African–Brasiliano orogeny (720–550 Ma) is redefined to include only the collision-related deformation, shearing and tectonic escape, and synorogenic magmatism postdating the Rodinia breakup. Two models have been proposed for postorogenic magmatism and uplift, widespread in Gondwanaland: lithospheric mantle delamination caused by continental collision in West Gondwanaland and underplating of basaltic magma in East Gondwanaland. Isotopic studies suggest large-scale addition of supergene water to hot crust in these post orogenic events. The assembly of Gondwanaland proceeded by docking of individual cratons and there is no evidence of one collision between West and East Gondwanaland. After the assembly of Gondwanaland, tectonic and magmatic activity shifted to the accretionary Pacific margin, and at the same time rifting and calving of terranes accelerated at the opposite margin of the supercontinent.

Introduction

Historically, Gondwanaland has been a fertile field of study. Emergence of the new paradigm of plate tectonics brought appreciation of the early syntheses of Suess (1985), Wegener (1915), and du Toit (1937), that were ahead of their time, and revived interest in Gondwanaland reconstruction based on marine geophysics. The Geological Map of Sectors of Gondwana (de Wit, 1988) focused on crustal extension preceding the Mesozoic breakup of Gondwanaland and initiation of sedimentary basins along the passive margins of present ex-Gondwanaland continents.

IGCP Project 288 *Gondwanaland sutures and fold belts* (1990–1995, extended in 1996) assembled a large and diverse number of participants. Detailed regional studies conducted in all ex-Gondwanaland southern continents were synthesised in the Geodynamic map of Gondwanaland Assembly produced jointly by IGCP Project 288 (database generation), the Council for Geoscience, Pretoria, South Africa (GIS and digital cartography), and the Bureau de Recherches Géologiques et Minières, Orléans, France (printing). In addition to the map, which is the major outcome of IGCP 288, the project achieved important results in refining the concept of Rodinia—the supercontinent precursor to Gondwana, dating the creation of the Pacific Ocean, and developing hypotheses on causes of the widespread decratonisation of old continental crust fragments and postorogenic magmatism in the Pan African–Brasiliano orogeny.

Progress towards solving the Gondwanaland assembly puzzle was rapid. Regional syntheses (Trompette, 1994; Stump, 1995) significantly advanced understanding the evolution of important parts of Gondwanaland. The reader is referred to the transcript of an open forum discussion held at the 8th International Gondwana Symposium in Hobart, Tasmania (Powell, 1993) and reviews (Unrug, 1992; Rogers, et al., 1995; Yoshida, 1995) for accounts of the evolving ideas. This paper presents the main points of current views on Gondwanaland assembly as of 1996. References are made to recent papers published during the life of IGCP Project 288.

From Rodinia to Gondwana to Pangea

Gondwanaland originated during the Neoproterozoic Pan African–Brasiliano orogenies (Figure 1) that resulted in ocean closure and rearrangement, collision, and suturing of older continental crust fragments produced by breakup of the precursor supercontinent Rodinia. The demise of Rodinia and formation of Gondwanaland is conveniently described in terms of the supercontinent cycle. A supercontinent is defined by its assembling global orogeny. The breakup pattern of the precursor supercontinent reshapes cratons for the next supercontinent cycle. In a cycle the breakup of an older supercontinent and accretion of a new supercontinent overlap in time but not in space.

Rodinia was assembled by late Mesoproterozoic (1300–1000 Ma) orogenies that produced the Sveco–Norwegian, Grenville, Sun-sas, Kibaran, Namaqua–Natal, Maudheim, Mozambique, Eastern Ghats, Albany, Fraser, Paterson–Musgrave, north-east Australia–Yangtze–Cathaysia and Kuanping mobile belts (Figure 2).

The breakup of Laurentia from East Antarctica and Australia to create the Pacific Ocean—the first major event in Rodinia disintegration—was dated on paleomagnetic data at 720 Ma (Powell et al., 1993, Powell, and Li, 1994b). Hoffman (1991) proposed that the breakup of Laurentia from Rodinia initiated the supercontinent reconfiguration that resulted in the formation of Gondwanaland. The breakup of Rodinia was preceded by the formation of rift and sag basins, intracontinental mobile belts, passive margins, and magmatic arcs that were later involved in the assembly of Gondwanaland. Thus, the breakup of Rodinia and assembly of Gondwanaland were partly coeval (Figure 3). Gondwanaland assembly was complete by earliest Paleozoic time. There could have been a geologically fleeting time when Laurentia was still joined with Siberia and Baltica

Figure 1
Gondwanaland
cratons and
Proterozoic mobile
belts.

Archean and Proterozoic cratons:

AMZ Amazonian
BDK Bundelkhand
CNG Congo
EAG East Antarctica-Gawler
ESN East Sahara-Nile
KG Kalahari-Grüneghna
MD Madagascar-Dharwar
NA North Australian
RLP Rio de la Plata
S Salvador
SF Sao Francisco
WA West Australian
WAF West African

Neoproterozoic mobile belts:

1 Mauretanides
2 Bassarides
3 Rockelides
4 Anti Atlas
5 Ougata aulacogen
6 Trans-Saharan
7 Tibesti
8 Gourma aulacogen
9 Dahomeides
10 Nigeria
11 Borborema
12 Sergipe-Oubanguide
13 ANEKT

14 Araguaia
15 Goiás
16 Brasília
17 Paramirim aulacogen
18 Aracuai
19 West Congo
20 Sangha aulacogen
21 Tucavaca
22 Paraguay-Cordoba
23 Pampean Ranges
23a Northern Patagonia
24 Ribeira
25 Rio Doce
26 Dom Feliciano

27 Kaoko
28 Damara
29 Lufilian
30 Kundelungu aulacogen
30a Bukoban aulacogen
31 Zambezi
32 Gariep
33 Saldania
34 Beardmore
35 Pinjarra
36 Adelaide
37 Patterson-Peterman Ranges

was in contact with the Amazonia and Rio de la Plata cratons and the rest of Gondwanaland, to form a latest Neoproterozoic supercontinent Pannotia (Powell, 1995). Whilst addition of Neoproterozoic juvenile continental crust was important in several regions of Gondwana, other regions were affected by intracontinental tectonic events. After the Neoproterozoic ocean closures in the Pan African and Brasiliano orogenies, Paleozoic formation of marginal Gondwanide accretionary orogens along the paleo-Pacific margin of Gondwanaland, brief collisions of Gondwanaland and Laurentia in the Ordovician and Devonian (Dalziel et al., 1993; 1994) and the late Paleozoic collision with Laurussia to form Pangea, did not change significantly the internal structure of Gondwanaland. Calving of terranes from the paleo-Tethys margin of Gondwanaland and Triassic deformation of the intracontinental Ventana-Cape fold belt and its extension as a foreland fold and thrust belt through Antarctica and eastern Australia, heralded the onset of Middle Triassic breakup of Pangea. This interpretation, the best available presently, is conditioned by incomplete knowledge of Mesoproterozoic and Neoproterozoic events, especially in Antarctica.

Geodynamic provinces of Gondwanaland

Paleomagnetic data, and age of suturing by mobile belts, permit the distinction between an East and a West Gondwanaland with contrasting Neoproterozoic histories. The former, which comprised the Kalahari-Grüneghna craton of Africa and East Antarctica, Madagascar, India, Antarctica, and Australia, was a surviving fragment of the preceding Mesoproterozoic Rodinia supercontinent that escaped breakup and remained coherent until the Mesozoic breakup of Gondwanaland (Unrug, 1992; 1994). It consisted of a number of Archean and Paleoproterozoic cratons sutured by Mesoproterozoic mobile belts. West Gondwanaland included a number of Archean-Paleoproterozoic cratons sutured by late Neoproterozoic mobile belts. In the Rodinia reconstruction the West Gondwana cratons: West African, Amazonian and Rio de la Plata were separated from the future East Gondwana craton assemblage by the Laurentian craton (Hoffman, 1991). Avalonian terranes (Nance and Murphy, 1994), and Cado-

Figure 2 The Rodinia supercontinent assembled at c. 1000 Ma.

mian terranes to the south-west of the Margin of Baltica—the Teisseyre–Tornquist line of Europe were part of the Avalonian–Cadomian province of Gondwanaland (Figure 1). Central and Eastern Asia terranes were part of the Cimmerian province of Gondwanaland (Katz, 1993; Metcalfe, 1993; 1994).

West Gondwanaland included the Archean–Paleoproterozoic East Sahara–Nile, West African, Amazonian, and Rio de la Plata cratons, and possibly a separate cratonic block now in the basement of the Parana basin of South America. These cratons are sutured by mobile belts formed during the Neoproterozoic Pan African–Brasiliano orogenies. Some mobile belts contain oceanic sequences and sutures marked by ophiolites and gravity anomalies.

Rodinia configuration and breakup

The reconstruction of Rodinia at the end of Mesoproterozoic (Figure 2) is based upon the SWEAT hypothesis (Moores, 1991; Dalziel, 1991). Sadowski and Bettencourt, (1996) have described details of the suture of the Laurentian and Amazonia cratons lying in the Grenville–Sunsas orogen. In Australia Archean–Paleoproterozoic cratons were first amalgamated into a configuration similar to the present one in the interval 1300–1000 Ma (Myers et al., 1994; Shaw et al., 1994). The Albany–Fraser orogen contains the major Australia–Antarctica suture, and the associated continental-scale shear zone extends into the Bunge Hills of Antarctica, and into Meghalaya in India (Harris, 1994; 1995). The suture linking Antarctica to India lies in the Eastern Ghats–circum East Antarctic mobile belt (Yoshida, 1995). The Indian and Australian mobile belts have extensive foreland basins preserved (e. g. Myers, 1990; Wetherley, et al., 1994). Li et al. (1994) defined the position of North China and South China cratons in Rodinia.

The Namaqua–Natal–Maudheim mobile belt borders the Kalahari–Grünhegna craton of south Africa and eastern Antarctica (Groenewald et al., 1991; Groenewald, 1993) and from Dronning Maud Land joins the circum-East Antarctica belt. A suture zone is interpreted from geophysical data in the Namaqua–Natal belt at 1100–1000 Ma (Gresse, in Powell, 1993). The Mozambique belt in Mozambique and southern Tanzania is a late orogen in the Rodinia assembly in which continental collision dated at 950 Ma (Pinna et al., 1993) was preceded by early metamorphic events beginning at about 1200 Ma (Groenewald, et al., 1991; Groenewald, 1993). The entirely Neoproterozoic belt farther north in East Africa, for which the acronym ANEKT (Arabia–Nubia–Ethiopia–Kenya–Tanzania)

Archean and Paleoproterozoic cratons:

AMZ Amazonian
BDK Bundelkhand
CNG Congo
D Dharwar
EA East Antarctica
GA Gawler
ESN East Sahara–Nile
KG Kalahari–Grünhegna
LAU Laurentia
MD Madagascar–Dharwar
NA North Australian
NC North China
R Rockall
RLP Rio de la Plata
S Salvador
SC South China
SF Sao Francisco
SIB Siberia
WA West Australian
WAF West African

Mesoproterozoic mobile belts:

1 Espinhaco–Praminim
1a Mayombe
1b Araxa
1c Sao Roca
1d Tijucas
2 Kibaran–Irumide
3 Mozambique
4 Namaqua–Natal–Falklands/Malvinas
5 E Ghats–Central India–Maghalaya
6 Aravalli
7 Albany–Fraser
8 Paterson–Musgrove
9 NE Australia
10 Yangtze–Cathaysia
11 Grenville
12 Sunsas
13 Aguapei
14 Sveco–Norwegian–Greenland–Svalbard
15 Kuanping

was coined (Unrug, 1992), is younger and belongs entirely to the Gondwanaland cycle. The Mozambique belt was probably prolonging into the circum-East Antarctica mobile belt, and Sri Lanka was located at the juncture of the two (Yoshida, 1994; 1995).

The intracontinental Kibaran–Irumide belts of eastern equatorial Africa originated during an extensional event between 1350 and 1180 Ma and were deformed in a compressional event ending at 1100 Ma (Klerkx, 1992). They are linked by transcontinental shear zones to the collisional mobile belts surrounding the Kalahari craton, and are regarded as impactogens created by continental collisions in the Namaqua and Mozambique belts.

A system of basins filled with sedimentary and volcanic rocks of Mesoproterozoic age (review in Trompette, 1994), deformed in the Neoproterozoic, is present on both sides of the southern Atlantic. The Ribeira mobile belt, and part of the Dom Feliciano mobile belt of Brazil and Uruguay, and the Mayombe unit of the West Congo belt of Equatorial Africa contain the metamorphosed sedimentary fill of these basins and reactivated basement inliers. These basins are interpreted as Mesoproterozoic aulacogens deformed in the Neoproterozoic. Their original position in Rodinia is uncertain, but they appear to be linked to the Congo craton.

Early events in the Gondwanaland cycle

Neoproterozoic events predating the breakup of Rodinia (Figure 3) are considered early events in the Gondwanaland cycle. Widespread early Neoproterozoic extension, rifting and intracontinental and oceanic basin formation overlapped in time with post-tectonic magmatism dated at 850 Ma (Groenewald, 1993; Pinna, et al., 1993) shearing and tectonic escape events following Rodinia assembly.

In Australia the formation of a rift and sag basin in the Adelaide ‘geosyncline’ started at 830 Ma or earlier (Powell et al., 1994; Myers et al., 1994). Correlative sediments are present in the Savory–Officer and Amadeus–Ngalia basins (Powell et al., 1995). Early events are widespread in the ANEKT orogen: bimodal magmatism dated at 880 Ma in the Arabian shield and 870–840 Ma in the Nubian shield is interpreted as a rifting event, and ophiolite emplacement is dated at 880–690 Ma (Stern, 1994). Farther south in Kenya, the sedimentary phase of the mobile belt evolution is placed at 1200–820 Ma and migmatitisation, start of collision, and ophiolite emplacement at 830 Ma (Mosley, 1993).

Several early rifting events are known in the deformed corridor between the Kalahari and the Congo cratons of southern Africa. Sed-

Figure 3 Early Neoproterozoic events (1000–700 Ma) events in Rodinia.

imentary basins of the Ghanzi rift, and the Rufunsa and Fingoe basins formed at c. 1100 Ma, younging to the north-west (Unrug, 1995). The Rufunsa metasedimentary succession is intruded by granite and rhyolite dated at 944 Ma. In the next rifting event, bimodal volcanism marked the opening of the sedimentary basin of the intracontinental Zambezi belt at 880 Ma. The Zambezi belt was transpressionally deformed at 820 Ma (Barton et al., 1983; Wilson et al., 1993). The Lurio belt in the Mozambique orogen is believed to be a prolongation of the Zambezi belt (Pinna et al., 1993). Transpression in the north-eastern part of the mobile belt between the Kalahari and Congo cratons had a rotational kinematic component, as at the same time the Tsumis rift opened farther to the south-west in the future Damara belt. This rifting event was abortive, and the evolution of the Damara basin did not start until the Nosib rift formed at 770 Ma (Unrug, 1995). In southern Africa, a rifting event opened the basin of the Saldania belt at c. 900–800 Ma (Gresse, in Powell, 1993).

The basin of the Katangan Supergroup in the Lufilian fold belt opened probably in the latest Mesoproterozoic. The clastic and shallow marine carbonates of the lower part of the succession are overlain by conglomerates and basalt lava flows and intruded by basic stocks and sills of the Lower Kundelungu group (Unrug, 1994). The Lower Kundelungu marks a second rifting episode, widespread in central Africa from southern Kasai to the Tanzania shield. Basalts are dated at several locations at 950–800 Ma. This rifting event formed the Kundelungu and Bukoban aulacogens and a number of smaller basins.

In South America, widespread rifting at c. 1000 Ma has been recognised in the Borborema tectonic province of north-eastern

Brazil (Van Schmus, et al., 1991; Brito Neves et al., 1994). Continuity of structures across the Atlantic and data from Nigeria and northern Cameroon where rifting is dated at 800 Ma suggest this rifting event was extensive and long lasting.

Juvenile crust accretion in early events of the Gondwanaland cycle has been recognised in South America. Early Neoproterozoic age was determined for the western part of the crystalline Goiás massif, previously regarded as Archean. Protoliths of orthogneisses crystallised at 899 Ma and metavolcanic rocks yielded ages of 929–877 Ma and 764 Ma (Pimentel and Fuck, 1992). At the eastern margin of the Rio de la Plata craton the polyphase magmatic activity in the Pelotas composite batholith started with a magmatic arc at 850–830 Ma (Trompette, 1994). In the Rossorogen of East Antarctica rifting started at c. 750 Ma (Stump, 1995). The rift evolved into a passive margin sequence, in which shallow marine carbonates and deeper-water turbidites were deposited.

Pan African–Brasiliano events

The Pan African–Brasiliano orogeny that shaped the Gondwanaland supercontinent accretion is redefined here: it began at 750–730 Ma with the reorganisation of crustal plate motions following the breakup of Rodinia. The better known Pan African–Brasiliano mobile belts of western Gondwanaland contain magmatic arcs and lithotectonic terranes that originated during early Neoproterozoic events. However, the large cratons were individualised after Rodinia breakup, and, with the exception of an early collisional event in the ANEKT belt, all craton collisions postdate the breakup of Rodinia (Figure 4).

Figure 4
The Pan African–Brasiliano orogeny and the assembly of Gondwanaland, 720–550 Ma.

Terranes in the Tuareg and Arabian–Nubian shields:

- 1 Egere–Aleksod
- 2 Iskel
- 3 In Teidini
- 4 Aouzegueur–Barghot
- 5 Assode–Issalane
- 6 Serouenout
- 7 In Ouazzal
- 8 Kidal
- 9 Tilemsi
- 11 Midyan
- 12 Hijaz–Gebeit
- 13 Bayuda
- 14 Haya
- 15 Asir
- 16 Afif
- 17 Ar Rayn

SB Senegal block
NB Nigeria–Borborema
PR Parana block

The ANEKT belt

In the ANEKT belt, the early Gondwanaland events pass into the main structural and metamorphic evolution in the 730–630 Ma interval (Mosley, 1993). Granulite facies metamorphism is dated at 715–630 Ma in Tanzania and 740–710 Ma in Sudan. Final suturing of the composite superterrane of the Arabian–Nubian shield was completed at 680–640 Ma. A number of ophiolite belts outline terrane boundaries in the ANEKT belt. The oldest ophiolites emplaced prior to Rodinia breakup are known in the Arabian shield. Development of large shear zones lasted from 660 Ma to 530 Ma, indicating a long period of convergence of East Gondwanaland and the Congo craton. The Tanganyika shield of the Congo craton acted as a rigid indenter causing tectonic escape directed mainly to the north (Stern, 1994). Younger granulites in the ANEKT belt, dated at 545 Ma, are similar in age to granulites of Madagascar and southern India.

The trans-Saharan belt

The trans-Saharan mobile belt exposed in the Tuareg shield of western Africa is interpreted as a collage of lithotectonic terranes with a complex polyphase deformation history. Basement blocks, some with passive margin sedimentary sequences, magmatic arcs, and accretionary wedge terranes, some with possible ophiolite remnants, are distinguished (Black et al., 1994). Early collision of terranes with the western margin of the East Sahara craton, deformation and west-dipping subduction-related magmatism recorded in the Air and eastern Hoggar at 750–660 Ma was followed by deposition of the early Pan African Proche Ténéré molasse (Liégeois et al., 1994). Terrane collisions in western Hoggar and Adrar des Iforas were associated with late Pan African magmatism related to east-dipping subduction

zones and continental collision with the West African craton are dated at 640–580 Ma (Black et al., 1994). In the Anti Atlas in the north-eastern corner of the West African craton the emplacement of the Bou Azzer is somewhat older: the ophiolite dated at c. 790 Ma and the metamorphism related to the obduction was dated at 685 Ma. A younger deformation phase is placed at 620–615 Ma (Villeneuve et al., 1993).

Two shearing events are distinguished: the older one at 645–580 Ma produced the dextral Raghane (8°30') shear zone; the younger produced sinistral shear zones cutting all previous terranes. The age of the latter event is estimated at 525 Ma (Liégeois et al., 1994).

The Dahomeide belt

The southern prolongation of the trans-Saharan belt—the Dahomeide belt—is thrust over the foreland Volta basin that sits on the eastern margin of the West African craton. The basin fill includes a passive margin sequence developed during the 700–600 Ma interval, facing an ocean to the east. Various interpretations of the Dahomeide belt have been proposed. Classically regarded as marking the western margin of the West African zone of microcontinent aggregation (Attoh et al., 1991) and a suture (Attoh and Dallmeyer, 1992), it was attributed recently to intracontinental rifting (Castaing et al., 1994).

The Mauretanides and Bassarides belts

On the western side of the West African craton the Mauretanide and Bassaride belts are interpreted as having evolved from a narrow oceanic basin of Red Sea type which opened at c. 700 Ma and deformed at c. 650 Ma (Villeneuve et al., 1993).

The Borborema tectonic province

In South America, the prolongation of the 4°50' shear zone of the Tuareg shield is placed in the Sobral shear zone (Caby, 1990). In the Borborema tectonic province of Brazil, east of the trans-Saharan-Medio Coreau belt (Trompette, 1994) a network of Pan-African shear zones and mobile belts separate small units of Archean and Paleoproterozoic basement and basins filled with Mesoproterozoic metasediments. Neoproterozoic magmatism is widespread. Rift-related volcano-sedimentary sequences in the mobile belts are dated at c. 1000 Ma (Van Schmus, et al., 1991; Brito Neves et al., 1994). This region is regarded as an agglomeration of terranes including older basement blocks, magmatic arcs, oceanic sequences and passive margin basins in the north-east Brazil-Nigeria-Cameroon province of the Pan African-Brasiliano orogen. The geochronology remains insufficiently known, and the interpretation of older Rb-Sr dates is difficult. The shear zone contained between the Patos and Pernambuco lineament of north-east Brazil can be traced into Cameroon (Trompette, 1994).

The Sergipe-Oubanguide belt

The south-vergent, east-west-trending Oubanguide-Sergipano mobile belt correlated from South America to Africa is thrust over the northern margin of the Congo-Salvador craton. In Brazil, in the Sergipano belt, a south-to-north transition from passive margin carbonates to greywacke-dominated sedimentary protoliths is recognised. Higher-grade metasediments in the central part of the belt contain a mafic-ultramafic complex. The age of metamorphism and syntectonic granitoids is estimated as 660 Ma. In Africa, the Oubanguide belt evolved from several rift basins formed during an early-Neoproterozoic extensional event through a passive margin in the south to a turbidite dominated sequence in the central part of the belt. The metamorphic grade increases to the north, away from the margin of the Congo craton. A granulite-grade metamorphic event dated at c. 650–640 Ma was followed by the main deformation phase and emplacement of a regionally extensive basic to intermediate plutonic suite at c. 630 Ma. The plutonic suite has calc-alkaline affinity and is believed to represent Neoproterozoic juvenile crust (Toteu et al.,

1990). A structurally higher unit is composed of syntectonic migmatites and gneissic granites intruded by syntectonic foliated granites. Eclogite-grade mafic metavolcanic rocks may represent a narrow slice of oceanic crust, and associated gravimetric anomalies are interpreted as marking a suture at the south-eastern front of the migmatite and gneiss unit. The structure of the mobile belt is dominated by sub-meridional trends, attributed to east-west compression in a wide zone along the northern margin of the Congo craton (Cornaccia et al., 1990 NANCY).

Farther to the north-east in Tchad, migmatite gneisses with granite intrusions are tentatively assigned a Neoproterozoic age (Kusnir, 1993). The NNE trend of foliation in the migmatites is similar to the main structural trends of the Oubanguide belt. Current interpretations consider the Nigeria-Oubanguides as a collisional orogen involving several lithotectonic terranes and the closure of a narrow ocean. The Tchad region may belong here as well.

The Brasilia belt

In the Brasilia belt, the early Neoproterozoic magmatic arc produced juvenile crust in the Goiás massif. Oceanic metasedimentary sequences were deposited before c. 640 Ma, and metamorphism and deformation peaked in the 640–600 Ma interval marking collision of the Amazonian and São Francisco cratons. Formation of east-vergent thrust sheets and intrusion of rare syntectonic granites is dated at c. 600 Ma.

The west Congo-Araçuaí belts and the Mantiqueira province

The West Congo and Araçuaí mobile belts, the Paramirim aulacogen, and the Mantiqueira tectonic province of Brazil mobile belt form a vast region straddling the southern Atlantic, in which pre-Mesoproterozoic basement terranes, Mesoproterozoic aulacogens and Neoproterozoic intracontinental basins were deformed in the Pan African-Brasiliano orogeny. Lithological correlations are provided by glaciogenic sediments. The Mesoproterozoic metasediments and associated mafic or bimodal igneous rocks include the Mayombe group of the West Congo belt, the Espinhaço group of the

Figure 5 Cambrian-Ordovician events in Gondwanaland, 560–440 Ma.

Sao Francisco craton and the Araçuaí belt, and the various units of the Mantiqueira province. Other than the cratonic cover units, e.g. the West Congo group basin and the Sangha aulacogen on the African side and the Bambuí Group in South America, the only Neoproterozoic basin of the mobile belt is Macaúbas group basin in the Araçuaí belt in Brazil. It is filled with high-grade metasediments interpreted to be originally some 15 km thick (Trompette, 1994). The West Congo and Araçuaí belts have a divergent fan structure, the west Congo belt having been thrust eastward over the Congocraton and the Araçuaí belt westward over the Sao Francisco craton. Metamorphism and igneous activity are dated in the West Congo–Araçuaí belt at 630–600 Ma. In current interpretations, the east–west crustal shortening in the West Congo and Araçuaí belts terminating against continuous cratonic basement to the north, is accommodated by Neoproterozoic deformation in the Paramirim aulacogen that separates the Sao Francisco craton *sensu stricto* from the Congo–Salvador craton (Uhlein, et al., 1990; Chemale et al., 1993).

The Mantiqueira tectonic province contains the Cubatã–Alem Paraíba megashear zone in which vertical transcurrent faults pass, to the north–west, into flat thrust sheets. The transcurrent faults, mostly dextral, separate basement horsts and Mesoproterozoic basins. With the exception of small molasse basins there are no Neoproterozoic rocks in the Mantiqueira province. The deformation is Brasiliano, with two phases at 750–660 Ma and 550 Ma (Sadowski et al., 1994). At its southern end, the Ribeira belt passes west of the Louis Alves cratonic basement block that links presumably with the Rio de la Plata craton. Abundant granitoid intrusions along the Atlantic coastal zone of the Ribeira and Dom Feliciano belts, accompanied by gneisses and charnokites constitute the Rio Doce magmatic arc dated at 550–500 Ma.

The Dom Feliciano belt extends as far as the eastern side of the Rio de la Plata craton. The westernmost unit, emerging from under the cover of the Parana basin, is the Villa Nova belt. It includes a rift to passive margin sequence—the Vacacai (also called Llavaleja) supergroup, and the Cambai complex consisting of gneissic granite and mafic to ultramafic rocks (Fernandez et al., 1992). The latter contains juvenile crust formed at 750–700 Ma in a magmatic arc, (Babinski et al., 1996). Farther east, Mesoproterozoic metasediments of the Tijucas belt, separate the Villa Nova belt from the Pelotas batholith formed in an early Neoproterozoic polyphase magmatic arc in which subduction-related magmatic activity began at 850–830 Ma, followed by anatectic granitoids at 750 Ma. Younger granitoids intruded at 550–500 Ma are assigned to the Rio Doce magmatic arc. A Late Neoproterozoic molasse basin deformed at 550–500 Ma sits on top of the Villa Nova belt.

The Damara, Gariep, and Saldania mobile belts

The evolution of the Damara mobile belts started with the formation of the Nosib volcano-sedimentary sequence deposited in a rift basin dated at 770 Ma. The post-rift massive margin of the Congo craton developed in the 710–660 Ma interval and was followed by the formation of a continental margin magmatic arc with calc-alkaline intrusives, amphibolite grade metamorphism and polyphase deformation in the 660–590 Ma interval ended by continental collision. Farther to the south-east is an accretionary wedge complex with high-pressure metamorphism. Sedimentation on the passive margin of the Kalahari craton lasted till c. 570 Ma. Remnants of a foreland thrust and fold belt, emplaced over the Nama foreland basin in the Kalahari craton, form the southernmost part of the Damara belt. Post-continental collision shear zones divided the mobile belt into a number of terranes (Gresse et al., 1994). Current interpretations based on sedimentological studies (Henry et al., 1990; Stanistreet et al., 1991; Kukla and Stanistreet, 1991) view the Damara belt as evolving from an oceanic basin, possibly of limited width. In this context it is possible that the Angola shield was independent of the rest of the Congo craton, and the West Congo belt links with the Lufilian belt under the younger cover of the Berets basin. Peak metamorphism in the central part of the Lufilian belt is dated at 700 Ma (Cosi et al.,

1992), and deformation in the north of the Lufilian belt is interpreted as falling in the 670–600 Ma interval.

The Gariep belt of coastal south-western Africa contains a rift sequence and a composite terrane of oceanic rocks both thrust on the Kalahari craton. The Saldania mobile belt along the western and southern margin of the Kalahari craton contains a volcano-sedimentary sequence deformed at 650 Ma. It contains mafic volcanic rock-stentatively interpreted as possible ophiolitic remnants. Syn- to late-tectonic granitoids intruded the belt in the 610–520 Ma interval (Hälbich, 1992; Gresse, 1990).

The younger generation of mobile belts in West Gondwanaland

The beginning of evolution of all mobile belts of western Gondwanaland described above can be traced to the early Neoproterozoic period of crustal extension predating the breakup of Rodinia. Trompette (1994) drew attention to a second generation of mobile belts in West Gondwanaland, originating from rifts younger than 650 Ma and deformed at about 550 Ma. These belts include the Rokelide belt of Western Africa and the Araguaia–Paraguay–Cordoba belts of South America. The nature of the belts is however different: the Rokelide belt is attributed to dextral shearing between the Amazonia and the West African craton (Villeneuve et al., 1993). The nature of the Araguaia belt is unclear but current interpretation leans towards a Brasiliano belt involving oceanic crust and metasedimentary sequences. The Paraguay–Cordoba belt includes a craton margin basin with polyphase deformation, intruded by 550–500-Ma-old late tectonic granites (Trompette, 1994).

The above generalised description of West Gondwanaland mobile belts contradicts the concept of ‘collision’ of West Gondwanaland with East Gondwanaland. A number of terranes and intervening ocean basins telescoped between the major cratons during the assembly of West Gondwanaland but this process was continuous and involved a number of collisional events during a long period of convergence, rather than one major collision between East and West Gondwanaland.

Neoproterozoic oceans

Three major Neoproterozoic oceans closed during the assembly of Gondwanaland. Firstly, rocks formed by amalgamation of juvenile magmatic arcs and other terranes (Stoeser et al., 1991) in the ANEKT Ocean are exposed in the Arabian–Nubian shield. In the east this ocean was bordered by the East Gondwana continent. In the west a remnant of a passive margin to the East Sahara–Nile craton is preserved (Stern et al., 1993), but the Nile craton appears to be distinctly fragmented (Schandelmeyer, 1993). The Pharusian ocean named after the accretionary wedge east of the West African craton, the second large ocean of West Gondwanaland, was situated along the eastern margins of the West African cratons. Its closure resulted in the formation of the Trans-Saharan mobile belts of West Africa and the Medio Coreau (Trompette, 1994) mobile belts of South America. The Pharusian ocean could extend farther south into the ocean from which the Brasilia belt was formed between the eastern margin of the Amazonian craton and the western margin of the Sao Francisco craton but the possible junction area is concealed by the Phanerozoic Parnaíba. A difference of opinion persists over the question of the intervening Nigeria–Borboroma province, where continental rifting and shear zone development is believed by some authors to have played a dominant role in the reactivation of older structures (Jardim de Sa et al., 1990; Brito Neves 1994; Castaing et al., 1994), while others regard ocean closure and amalgamation terranes as principal geodynamic events (Liegeois et al., 1994). The Oubangide belt is possibly the southern part of Pharusian ocean. The third—the Adamastor Ocean—lay between the western part of the Congo craton, the Kalahari craton of East Gondwana and the Rio de la Plata craton of south America. The Damara and Gariep mobile belts, and the Dom Feliciano mobile belt of Brasilia and Uruguay (Fernandez et al., 1992; Babinski et al., 1996) contain ophiolites and magmatic arcs formed in this ocean.

Shear zones

All internal mobile belts suturing West Gondwanaland contain large shear zones formed during late stages of craton convergence. Improved intercontinental correlation of the shear zones (e.g. Srinivasan, 1994) indicate the importance of tectonic escape processes and adjustment of young hot crust between the colder rigid cratons (Black and Liégeois, 1993). It is noteworthy that the Congo craton is surrounded by shear zones produced by a generalised east–west compression, and appears to form the keystone of the West Gondwanaland assembly.

Late- to postorogenic events in Gondwanaland

Widespread late- and postorogenic magmatism, shearing and major uplift leading to deep exhumation of the mobile belts are salient features of Gondwanaland assembly, generally attributed to a major thermal event lasting into the Cambrian–Ordovician. Two models have been proposed to account for this event: In the Antarctic shield, which apparently was stable from the Mesoproterozoic consolidation of Rodinia, underplating by basaltic magma derived from the asthenosphere, and resulting heat advection, has been postulated (Stüve and Sandiford, 1993). In northern Africa, where Neoproterozoic mobile belts reach great width in the Tuareg and Arabian–Nubian shields and the intervening East Saharan–Nile craton was partly dismembered during the Pan African orogeny, the late- to postorogenic effects are attributed to lithospheric mantle delamination and thinning or elimination of the lithospheric mechanical boundary layer following collision of lithospheric plates, and direct contact of crust with upwelling asthenosphere. The rapid change of synorogenic calc-alkaline magmatism to postorogenic alkaline would be explained by change from a subduction-related magma source to a less depleted asthenospheric source (Black and Liégeois, 1993). Isotopic studies indicate large-scale addition of supergene water as an important factor in Pan African radiometric rejuvenation of basement rocks of Gondwanaland (Longinelli et al., 1994).

Young radiometric ages, formation of granulites, and mylonitisation (550–450 Ma) extending from the East African ANEKT belt into Madagascar, Southern India, Sri Lanka and East Antarctica were interpreted as indicating a possible suture zone between East and West Gondwanaland extending from East Africa into the Sor Tondane Mountains of east Antarctica (Rogers et al., 1994). This matter is unresolved, but other authors have stressed that the structural influence of Neoproterozoic to earliest Paleozoic events in Dronning Maud Land is minimal (Moyes, et al. 1993, Yoshida and Vitanage (1993). Charnokitisation in southern India has been attributed to a distensional regime at 500 Ma (Santosh, et al., 1994).

The Pacific margin of Gondwanaland

In Paleozoic time, the locus of geodynamic activity shifted to the margins of Gondwanaland (Figure 5). Whilst accretionary processes dominated at the Pacific and Iapetus margin, rifting and calving of terranes proceeded in the Avalonian–Cadomian and Cimmerian provinces of Gondwanaland. The Ross–Delamerian magmatic arc was active along eastern Australia and East Antarctica, and the Lachlan Thomson active margin was situated offshore. West of the Rio de la Plata craton there was a complex exchange of terranes between the Amazonian craton and Laurentia that resulted in the formation of the Famatinian collisional orogen and transfer of the Precordillera terrane from Laurentia to Gondwana (Dalziel, 1992 Dalziel et al., 1993; Dalla Salda et al., 1993a, b). The Pampean exotic terrane and the Arequipa terrane were possibly detached from the western margin of the Amazonian craton, following the Late-Neoproterozoic break up of Laurentia from Amazonia (G R Sadowski, personal communication, 1995).

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