Rodinia to Gondwana:
The Geodynamic Map of Gondwana Supercontinent Assembly

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ABSTRACT

The new *Geodynamic Map of Gondwana Supercontinent Assembly* provides insight into the Neoproterozoic breakup of the Rodinia supercontinent that existed from 1000 to 725 Ma, and the subsequent amalgamation of Gondwanaland. Breakout of Laurentia from Rodinia at 725 Ma marks the reorganization of lithospheric plate motions that resulted in the Pan African–Brasiliano orogeny and assembly of Gondwanaland that lasted from 725 to 500 Ma.

INTRODUCTION

The Geodynamic Map of Gondwana Supercontinent Assembly[1] at a scale of 1:10 million was first presented at the 30th International Geological Congress, in Beijing, in August 1996. The map is a joint endeavor of International Geological Correlation Program Project 288 "Gondwanaland Sutures and Fold Belts" (database generation), the Council for Geoscience, Pretoria, South Africa (Geographic Information Systems [GIS] and digital cartography), and the Bureau de Recherches Géologiques et Minières, Orléans, France (printing). It contains original contributions by 67 coauthors from 11 countries. GIS and digital cartography were managed by L. G. Wolmarans (CGS). The Editorial Committee included: C. Castaing (BRGM), J. L. Feybesse (BRGM), P. G. Gresse (CGS), C. McA. Powell (UWA), G. R. Sadowski (USP), L. Tack (MRAC), and R. Unrug (WSU) (see p. 5).

Here I present the basis for constructing the geodynamic map from which the index and summary maps, Figures 1–3, were derived, and the synoptic insights gleaned from the cartographic visualiza-
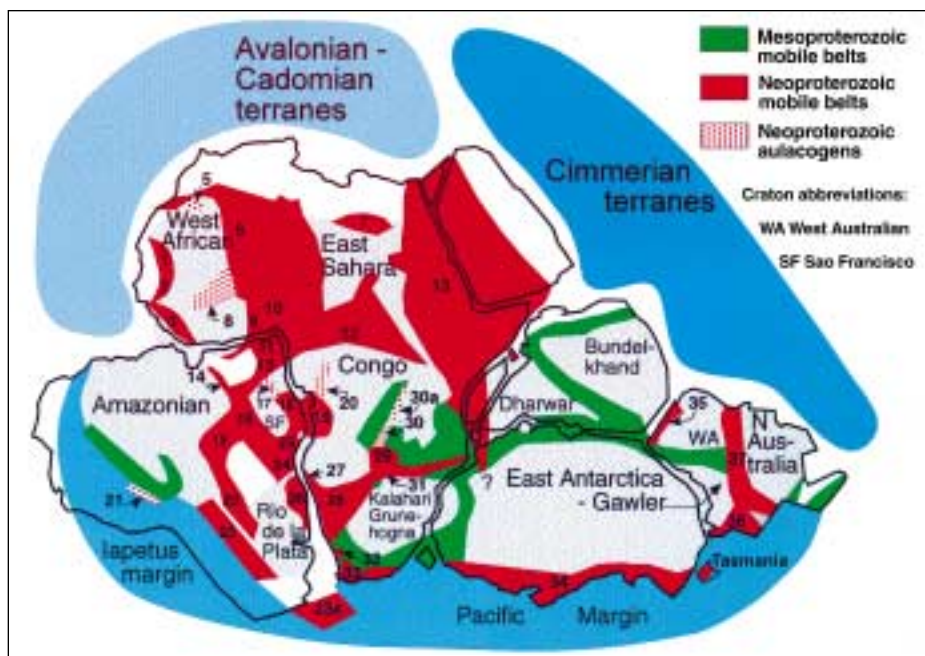
Figure 1. Reconstruction of Gondwanaland after 500 Ma and index map for Neoproterozoic mobile belts of Gondwanaland. Mobile belts include collisional and transpressional orogens and aulacogens. Aulacogens are aborted rifts, undeformed to mildly deformed, terminating inside cratons. Gray = Archean-Paleoproterozoic cratons (pre–1600 Ma); green = Mesoproterozoic (1600–100 Ma) mobile belts; Neoproterozoic (1000–440 Ma) orogens in red, and aulacogens in white with red stipple; geodynamic provinces peripheral to Gondwanaland in shades of blue. Mobile belt index: 1—Mauretanides, 2—Bassarides, 3—Rokelides, 4—Anti-Atlas, 5—Ougarta aulacogen, 6—Trans-Saharan, 7—Tibesti, 8—Gourma aulacogen, 9—Dahomeides, 10—Nigeria-Cameroon, 11—Borborema, 12—Sergipe-Oubanguide, 13—East African, 14—Araguaia, 15—Goias, 16—Brasilia, 17—Paramirim aulacogen, 18—Araçuai, 19—West Congo, 20—Sangha aulacogen, 21—Tucavaca aulacogen, 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—Paterson-Peterman Ranges.

tion of the mobile belts that suture the cratons within Gondwanaland.

GEODYNAMIC MAP SETUP AND PHILOSOPHY

The objective of the *Geodynamic Map of Gondwana Supercontinent Assembly* is to present a synthesis of the accretion of Gondwanaland, which is composed of lithospheric plates that traveled large distances during the Neoproterozoic (1000 to 545 Ma). Latitudinal movements of the cratons that resided within Gondwana were determined from paleomagnetic data, and their relative movements were inferred from events registered in mobile belts in the reconstituted supercontinent. Intercontinental correlations of mobile

belts across modern oceans provided a means for reconstruction of supercontinent assembly by geodynamic interpretation of depositional, igneous, tectonic, and metamorphic events. Recognition of the role played by Laurentia in the assembly and breakup of Rodinia—the precursor supercontinent to Gondwanaland—and the application of lithotectonic terrane concepts to the better studied Neoproterozoic mobile belts added complexity to the geodynamic interpretation.

Chronostratigraphic limits for subdivision of the Proterozoic period into Mesoproterozoic (1600 to 1000 Ma) and Neoproterozoic (1000 Ma to the start of the

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Cambrian) periods follow the time scale approved by the International Union of Geological Sciences (IUGS). The beginning of the Cambrian Period is taken as ~545 Ma for correlation of chronometric and geologic time scales (Plumb, 1990; Brasier et al., 1994).

Archean to Paleoproterozoic (pre–1600 Ma) cratons that rode the moving lithospheric plates, but underwent no deformation during Mesoproterozoic, Neoproterozoic, and Paleozoic orogenies are considered passive elements of the Gondwanaland jigsaw puzzle. No structural details are shown in these cratons, except for Mesoproterozoic and Neoproterozoic cover units, intracratonic basins, and cratonic marginal foreland basins. Structural reactivation and rejuvenation of cratonic basement near younger mobile belts are indicated by special symbols. No geologic details are shown in post-Triassic cover postdating collisional and accretionary events related to Gondwanaland assembly.

The mobile belts are shown in as much detail as practicable at the map scale. Ages of rock units at supergroup, group, suite, and complex rank are shown in color and grouped in two-geon intervals (200 Ma) for the Mesoproterozoic and one-geon (100 Ma) intervals for the Neoproterozoic and Paleozoic. Locations of small igneous intrusions, ophiolitic sequences, eclogites, mafic to ultramafic metamorphic tectonites, glaciogenic sediments, and regions of thermal rejuvenation that are important for map interpretation but too small for cartographic presentation are shown by special symbols. Lithology of sedimentary rock units of supergroup and group rank and protoliths of metasedimentary rocks are shown with symbols indicating basin classification: rift, passive or active margin, oceanic, foreland, molasse, and aulacogen. Symbols for igneous rock units indicate rift-related, synorogenic, postorogenic, and anorogenic magmatic suites. Symbols for metamorphic rock units show foliation trends, nature of protoliths, and metamorphic facies. Structural symbols indicate plate margins, faults, structural trends of folds and foliation, and tectonic transport directions.

GONDWANALAND QUESTIONS

Neoproterozoic organization of continental crust into large supercontinents is the subject of ongoing debate, and various models are evolving as new data become available (Powell, 1993; Dalziel, 1991; Trompette, 1994; Stern, 1994; Rogers et al., 1995b; Unrug, 1995; Yoshida, 1995). The main questions are: Were there one or more Neoproterozoic supercontinents, and when did they (it) form and break up? How were the older cratons arranged within these supercontinents? Where are the sutures marking closure of oceans? Was there a collision between East and West Gondwanaland?

The following discussion of the events that resulted in the agglomeration of Gondwanaland presents a balanced opinion, worked out during compilation of the *Geodynamic Map,* of the map Editorial Committee. The map was compiled from regional contributions by authors currently or recently active in research in the various parts of Gondwanaland. The availability of data along the individual mobile belts varies dramatically, with some African belts having been studied in the most detail. In poorly understood regions, relatively scarce reliable data have been combined with results several decades old. To simplify and focus descriptions on major super-regional relationships, diachronous rifting and collisional events along the margins of older cratons have been grouped. The synthesis presented here, founded on the database generated by the map's co-authors, is offered to invigorate debate on important questions of Neoproterozoic geodynamic evolution of continental crust.

RODINIA BREAKUP AND THE EARLY NEOPROTEROZOIC PAN-THALASSAN OCEAN

Gondwanaland originated during the Neoproterozoic Pan-African–Brasiliano orogeny that resulted in ocean closures and rearrangement, collision, and suturing of the older continental crustal fragments that constituted the Archean-Mesoproterozoic cratons (Fig. 1). The latter were produced by breakup of the precursor supercontinent Rodinia which has been reconstructed according to the SWEAT (Southwest United States–East Antarctic connection) hypothesis (Moores 1991; Dalziel, 1991; Hoffman, 1991). The assembly of Rodinia occurred by amalgamation of Archean-Paleoproterozoic cratons in collisions that produced late Mesoproterozoic (1300 to 1000 Ma) mobile belts (Fig. 2). These pericratonic orogenic belts formed a continuous system (Harris, 1995; Sadowski and Bettencourt, 1996). Truncations of these Mesoproterozoic orogens along younger continental margins form the "piercing points" used to pinpoint orogenic belt continuations and mark relative positions of older cratons in the Rodinia reconstruction (Dalziel, 1992). The North American craton, Laurentia, linked with Siberia (Condie and Rosen, 1994) forms the central keystone of Rodinia. Locations of the North China and South China cratonic blocks are from Li et al. (1995, 1996).

The reconstruction of Rodinia in Figure 2 accounts for all pre-Mesoproterozoic continental crust and Mesoproterozoic orogens except for the small Archean crustal blocks of Tarim, Lut, and central Iran. These blocks were presumably part of Rodinia, but their relative positions are unknown. Thus, Rodinia was a Pangean-size supercontinent, and the rest of Earth's surface was covered by a Panthalassan-size ocean.

EARLY NEOPROTEROZOIC EVENTS AND THE BREAKUP OF RODINIA

Events between 1000 and 720 Ma that postdated the assembly and predated the breakup of Rodinia included widespread shearing and tectonic escape, post-tectonic magmatism, extension, rifting, and intracontinental mobile belt formation. The evolution of most western Gondwanaland Neoproterozoic sedimentary basins can be traced to crustal extension and rifting predating the breakup of Rodinia. The breakaway of Laurentia from East Antarctica and Australia which began the disintegration of Rodinia by cutting the supercontinent in half (see Fig. 2) and creating the Pacific Ocean, is dated at 725 Ma by paleomagnetic data (Powell et al., 1994). Some of the important events preceding this breakup are summarized below and their results shown in Figure 2.

In Australia, formation of rift and sag basins in the Adelaide "geosyncline" had begun by 830 Ma. Correlative sediments were deposited in central Australian basins whose margins were later deformed in an intracontinental mobile belt at 600 to 550 Ma (Myers et al., 1994; Powell et al., 1994). In the Ross orogen of East Antarctica, rifting starting at about 750 Ma (Stump, 1995) led to deposition of a passive margin sequence.

Rifting is also documented in the deformed corridor between the Kalahari and Congo cratons of Africa. In this region, transtensional and transpressive events occurred successively as a series of younging-to-the-east rift basins formed between 1100 and 950 Ma (Unrug, 1995). In the Lurio shear zone in the Mozambique orogen, post-tectonic magmatism lasted until 850 Ma (Pinna et al., 1993). This shear zone extends into the Zambezi belt rift basin, which opened at 880 Ma and was deformed at 820 Ma (Barton et al., 1993; Wilson et al., 1993).

Latest Mesoproterozoic–early Neoproterozoic events are also recognized in the southern segment of the East African orogen. Separation of the Congo and the contiguous East Sahara cratons from Rodinia started at about 1200 Ma, as did the evolution of the sedimentary basin in Kenya. By 820 Ma, a passive margin was developing east of the Tanganyika shield of the Congo craton, and migmatization, early collision, ophiolite emplacement, and metamorphism were occurring in the Kenyan segment of the East African orogen (Shackleton, 1986; Mosley, 1993). In the northern East African orogen, bimodal rift-related magmatism has been dated at 870 to 840 Ma in the Nubian shield and at 880 Ma in the Arabian shield (review in Stern, 1994).

In the Borborema tectonic province of northeastern South America, widespread rifting at about 1000 Ma (Van Schmus et al., 1995) affected a large region of crust. The affected crust contains some Archean inliers, but was principally formed during the Paleoproterozoic Amazonian and Eburnean orogenies. The continuity of South American Neoproterozoic mobile belts across the Atlantic and the rifting ages of 800 Ma in the northern Cameroon region (Toteu et al., 1987) suggest that this general rifting was a long-lasting event. Some of the far-traveled terranes of the West African Tuareg shield, whose positions in Rodinia are unclear, have Archean or Eburnean basement ages and early Neoproterozoic passive margin sequences (Black and Liégois,. 1993) consistent with their having rifted from Rodinia during this event.

Late Mesoproterozoic to early Neoproterozoic rifting events reconfigured the global oceanic realm. The large Arabian-Nubian and Pharusian oceans opened (in modern coordinates) east and west, respectively, of the Congo–East Sahara–Nile craton cluster (Fig. 2). Passive margins developed at about 1000 Ma along the eastern margins of the West African, Amazonian, and Rio de la Plata cratons (Trompette, 1994). The Adamastor ocean opened between the Kalahari, Congo, Saõ Francisco, and Rio de la Plata cratons, and a side branch extended between the Kalahari and Congo cratons. Rifting that is dated at 900 to 800 Ma occurred along the western margin of the Kalahari craton (P. G. Gresse in Powell, 1993).

Subduction also occurred during this period. Juvenile crust formed in early Neoproterozoic magmatic arcs has been recognized in the East African orogenic belt in the Arabian-Nubian shield, in the Trans-Saharan belt, and at the margins of the South American Amazonian and Rio de la Plata cratons. A long history of Neoproterozoic magmatic-arc collisions and large-scale additions of juvenile crust is recorded in the northern East African orogenic belt (Stern, 1994). The Trans-Saharan belt contains Neoproterozoic calc-alkaline magmatic arcs with ages of 870 to 840 Ma (pre–Pan-African; see below), 750 to 665 Ma, and 650 to 570 Ma that are related to east-dipping subduction zones (Black et al., 1994). At the eastern margin of the South American Rio de la Plata craton, polyphase magmatic activity in the Pelotas composite batholith started with arc magmatism at 850 to 830 Ma (review in Trompette, 1994). In the Dom Feliciano orogen on the eastern side of the Rio de la Plata craton, the Villa Nova belt contains early Neoproterozoic juvenile crust (Babinski et al., 1996). In the South American Goias massif, southeast of the Amazonian craton, protoliths of orthogneisses have crystallization ages of 899 Ma and metavolcanic rocks have ages of 929 to 877 Ma and 764 Ma (Pimentel and Fuck, 1992).

PAN-AFRICAN–BRASILIANO OROGENY AND GONDWANALAND ASSEMBLY

The Pan-African–Brasiliano orogenic belts (red belts in Fig. 1; Fig. 3) mark the collisional zones between the continental pieces that reassembled to form the Gondwanaland supercontinent after the breakup of Rodinia. In the first stage of this breakup, Laurentia separated from the eastern Australia–East Antarctica rifted margin of the part of Rodinia that later became East Gondwanaland. As Laurentia drifted away, it pushed the cluster of Amazonian–West African–Rio de la Plata cratons (Fig. 2) away from East Gondwanaland. These cratons later collided, creating the Pan-African–Brasiliano orogenic belts of West Gondwanaland (Fig. 3).

Most of the Pan-African–Brasiliano orogenic belts were formed between 725 Ma and 500 Ma by collisional events resulting from the convergence of lithospheric microplates created by the breakup

of Rodinia (Fig. 3). One of the principal belts, the East African orogen (13 in Fig. 1; see Fig. 3), contains the Arabian shield onto which several ensimatic and continental terranes were accreted between 715 and 630 Ma (Stoeser and Camp, 1985). Accretion ages of terranes in Yemen (Windley et al., 1996) are probably similar. Farther south in Tanzania, granulite metamorphism associated with crustal thickening related to collision is dated at 715 to 652 Ma (review in Stern, 1994). In the Aïr region of the Trans-Saharan orogenic belt (6 in Fig. 1), collision related to a west-dipping subduction zone is indicated by magmatic rocks with ages of 730 to 700 Ma (Liégeois et al., 1994). A collision of the West African craton with the terrane agglomeration of the Trans-Saharan belt (6 in Fig. 1) at 600 Ma has been recognized by Black et al. (1994). In the Bassarides and Mauretanides mobile belts (1 and 2 in Fig. 1) at the western margin of the West African craton, collision is dated at 660 to 650 Ma. A younger collisional event in the Anti-Atlas (4 in Fig. 1) is dated at 620 to 600 Ma (Villeneuve et al., 1993). Mobile belts of South America and equatorial and southern Africa show diachronous collisions: 700 Ma in the Dom Feliciano belt (26 in Fig. 1; Fernandes et al., 1992), 630 to 620 Ma in the Ribeira and Oubanguides belt (12 and 24 in Fig. 1; Tassinari and Campos Neto, 1988; Penaye et al., 1993), 560 to 530 Ma in the Rio Doce belt (25 in Fig. 1; Campos Neto and Figueredo, 1995), and 590 Ma in the Damara belt (28 in Fig. 1; K. H. Hoffmann, 1992, personal commun.).

Trompette (1994) drew attention to a second generation of West Gondwanaland mobile belts that originated as post-Rodinian break-up rifts after 650 Ma and underwent compressional or transpressional deformation at about 550 Ma. These belts include the Western Africa Rokelide belt (3 in Fig. 1), which formed by dextral shearing between the Amazonian and West African cratons, and the South American Araguaia(?)-Paraguay-Cordoba belts (14 and 22 in Fig. 1) where authors of the *Geodynamic Map* recognize oceanic crustal and metasedimentary sequences. The Paraguay-Cordoba belt contains a polyphase-deformed, cratonic marginal basin that was intruded by late-tectonic granites at 550 to 500 Ma.

The concept of a single collision between East and West Gondwanaland in the Neoproterozoic appears to be an oversimplification. During the assembly of West Gondwanaland, several lithospheric plates carrying large cratons and a number of smaller lithotectonic terranes were telescoped (Fig. 3). This resulted in closures of intervening oceanic basins, and sequential docking of the terranes onto an evolving Neoproterozoic tectonic collage on the
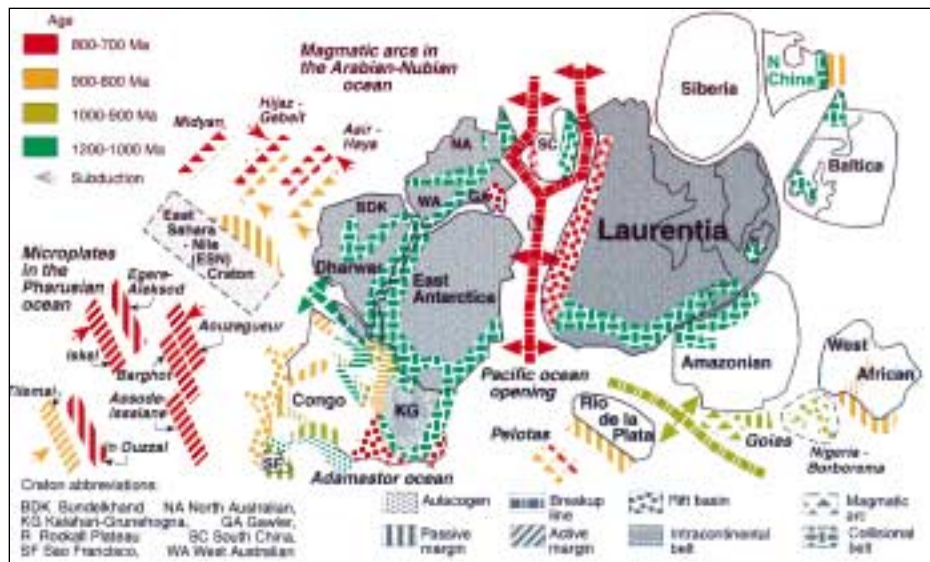

Figure 2. Reconstruction of Rodinia showing early Neoproterozoic events (1000 to 700 Ma). The magmatic arcs and microplates in the Arabian-Nubian and Pharusian oceans are schematic. Medium gray is East Gondwanaland. Green is Mesoproterozoic mobile belts suturing older cratons in Rodinia. Other colors indicate ages of early Neoproterozoic mobile belts and basins. Abbreviations of cratonic names: BDK—Bundelkhand, G—Grunehogna, GA—Gawler, NA—North Australia, R—Rockall Plateau, SC—South China, SF—Saõ Francisco, WA—West Australia.

western side of East Gondwanaland. East Gondwanaland, comprising Australia, East Antarctica, India, and part of Madagascar (compare Figs. 1 and 3), formed a stable Gondwanaland nucleus, which was subjected only to intracratonic deformation.

The authors of the map suggest that the term "Pan-African–Brasiliano orogeny" be applied only to the collisional events that led to the suturing of West Gondwanaland. The term should not be for ear-

lier, extension-dominated Neoproterozoic events related to the breakup of Rodinia.

The assembly of Gondwanaland was complete by earliest Paleozoic time. There could have been a short time in the latest Neoproterozoic when Laurentia, still joined with Siberia and Baltica, was in contact with the Amazonian and Rio de la Plata cratons, which were already part of West Gondwanaland. This combination would form the short-lived supercontinent
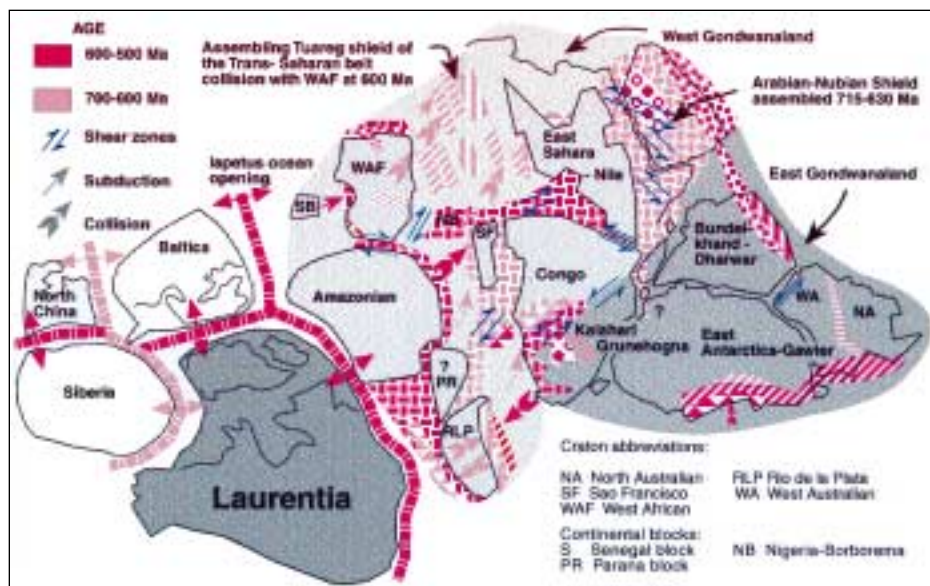
Figure 3. Map showing East Gonwanaland (medium gray), assembly of West Gondwanaland (light gray) from 700 to 500 Ma, and possible Pannotian supercontinent. Pan-African–Brasiliano mobile belts within and on the margins of assembling West Gondwanaland. The Pannotia supercontinent could have existed briefly after the agglomeration of West Gondwanaland and the assembly of Gondwanaland, and before Laurentia separated from the Baltica, Amazonia, and Rio de la Plata cratons. Symbols for geodynamic classification of belts and craton abbreviations as in Figure 2.

called Pannotia (see Powell, 1955). Pannotia would have to have been destroyed by about 540 Ma, when the Iapetus ocean formed as Laurentia separated from the Baltica, Amazonian, and Rio de la Plata cratons (Fig. 3).

LATE- TO POSTOROGENIC EVENTS

Widespread late- to postorogenic magmatism, shearing and lateral tectonic escape and major uplift resulting in deep exhumation of mobile belts are salient features in all of Gondwanaland including the Himalayan basement of greater India. These features are generally attributed to a major thermal event that lasted into the Cambrian-Ordovician and led to widespread resetting of isotopic ages. In the Antarctic shield, which apparently had been stable since the Mesoproterozoic consolidation of Rodinia, Stüwe and Sandiford (1993) have attributed this thermal event to underplating by asthenospheric-derived basaltic magmas and related heat advection. In northern Africa, where wide Neoproterozoic mobile belts developed in the Tuareg and Arabian-Nubian shields and partial dismemberment of the intervening East Saharan–Nile craton occurred during the Pan-African orogeny (Schandelmeier et al., 1994), late- to postorogenic effects are attributed to lithospheric mantle delamination following collision of lithospheric plates. This delamination is suggested to result in thinning or elimination of the lithospheric mechanical boundary layer, recycling of upper-mantle material in the asthenosphere, and direct contact of crust with upwelling asthenosphere (Black and Liégeois, 1993).

A late Precambrian–early Paleozoic suture between East and West Gondwanaland that extended from East Africa into the Sør Rondane Mountains of East Antarctica has been suggested by Rogers et al. (1995a). This suggestion is based on radiometric ages of 550 to 450 Ma for granulite formation and for mylonites that occur in a belt extending from the East African orogen into Madagascar, southern India, Sri Lanka, and East Antarctica. This suture is controversial; others argue that Neoproterozoic to earliest Paleozoic structural events in Dronning Maud Land in Antarctica are minor (Moyes et al., 1993), and that metamorphism in the Sør Rondane Mountains and formation of anhydrous, high-temperature charnockites in southern India at about 500 Ma are better attributed to a distensional or transcurrent tectonic regime and lithospheric mantle delamination (Yoshida, 1995; Bartlett et al., 1995).

PACIFIC MARGIN OF GONDWANALAND

By Paleozoic time, the locus of geodynamic activity had shifted to the margins of Gondwanaland. Accretionary processes were dominant on the Pacific and Iapetus

margin, whereas rifting was occurring in the Avalonian-Cadomian and Cimmerian provinces (Nance and Murphy, 1994; Metcalfe, 1993). The Ross-Delamerian magmatic arc was active along eastern Australia and East Antarctica, and the Lachlan-Thomson accretionary-magmatic arc assemblage was forming offshore Australia. West of the South American Rio de la Plata craton, a complex exchange of terranes between the Amazonian craton and Laurentia resulted in the formation of the Famatinian collisional orogen and the transfer of the Precordillera terrane from Laurentia to Gondwana (Dalla Salda et al., 1993). The Pampean exotic terrane and the Arequipa terrane were possibly detached from the western margin of the Amazonian craton (Ramos, 1996), following the late Neoproterozoic breakup of Laurentia and Amazonia.

ACKNOWLEDGMENTS

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Alternates Receive 1996 Student Research Grants

Each year when the Committee on Research Grants selects student grant recipients, they also select an alternate group of recipients in the event that some of the grantees return part or all of their funds because they have received funding elsewhere or have changed their research plans. As the returned funds become available, they are re-awarded by the Research Grants Administrator to the alternates named by the committee.

In 1996 ten alternates received funding following the initial awarding of grants. They are: Daniel A. Cenderelli, Colorado State University; Ziqiang Chen, Florida State University; Tina M. Dochat, University of Wisconsin—Madison; Ruifang He, University of Quebec—Chicoutimi; Emmanuelle Javaux, Dalhousie University; Rynn M. Lamb, Western Washington University; Richard Allyn Meyers, University of Calgary; James R. Ostdick, California State University—Bakersfield; Andrew John Willis, University of Toronto; and Adam D. Woods, University of Southern California.

Why the Journals Are Late

Changes in the editorial-and-production processing of the *GSA Bulletin* have resulted in delayed publication time for the journal. The *Bulletin* and *Geology* are grouped for mailing, to take advantage of significant savings on packaging, processing, and postage rates; thus, both journals were mailed late for November, December, and January. We are working to get the *Bulletin* back on schedule, and we hope to mail it, as well as *Geology,* on their regular dates (typically, within the first ten days of the month) in March.