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Configuration of Columbia, a Mesoproterozoic Supercontinent

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Abstract

A supercontinent, here named Columbia, may have contained nearly all of the earth's continental blocks at some time between 1.9 Ga and 1.5 Ga. At that time, eastern India, Australia, and attached parts of Antarctica were apparently sutured to western North America, and the eastern margin of North America, southern margin of Baltica/North China, and western margin of the Amazon shield formed a continuous zone of continental outbuilding. Fragmentation began at ~1.6 Ga, when rifting occurred in North China. Rifting continued until about 1.4 Ga in most of Columbia, and a similar age of rifting north of the Zimbabwe craton of southern Africa suggests that an entire continental block stretching from Australia to South Africa separated from Columbia at this time. Further separation of North America from South America/Africa and rotation of the different blocks ultimately resulted in their reattachment during the Grenville orogeny to form the supercontinent Rodinia.

Key words: Supercontinent, Columbia, Rodinia, Ur, Pangea.

Introduction

Supercontinents containing most of the earth's continental crust are known to have existed at least twice in the past. The younger one, Pangea, formed at ~0.3 Ga by accretion of fragments produced by breakup of the older supercontinent Rodinia, which coalesced at ~1 Ga along Grenville-age sutures. The configuration of Pangea is well known because it can be reconstructed from patterns of ocean opening and the pre-drift fit of modern continents. It formed a slightly curved landmass about 15,000 km long (north–south) and 6,000 km wide (east–west), extending from the south pole, in present Antarctica, to Siberia, which was near the north pole (Lottes and Rowley, 1990).

Rodinia was apparently a globular landmass with a radius of several thousand km centered on present North America (Dalziel, 1997). Consolidation occurred along Grenville-age belts, which form a roughly circular pattern around an already coherent landmass consisting of North America, Siberia, Baltica, Greenland and most of East Antarctica. Because of its greater age, however, the configuration of Rodinia is somewhat less certain than that of Pangea (Moores, 1991; Li et al., 1995; Karlstrom et al., 1999; Burrett and Berry, 2000, 2002).

It now seems likely that Rodinia formed by accretion of fragments from an even older supercontinent with an age greater than ~1.5 Ga. We name this supercontinent Columbia because the key evidence for its existence is the relationship between eastern India and the Columbia region of North America, centered around the state of Washington. This paper proposes a configuration for Columbia based both on evidence of rifting and orogenic activity, compares Columbia with Pangea, briefly discusses models for the evolution of supercontinents, and then shows how the breakup of Columbia and rearrangement of the fragments formed Rodinia.

Columbia

Figure 1 shows the proposed configuration of the Mesoproterozoic supercontinent Columbia at ~1.5 Ga. The diagram is based on the locations of individual continental blocks, but it also groups them into the three long-lived continents outlined in Rogers (1996) and further discussed below. Three major continental blocks require special mention:

- North China became a coherent craton at ~1.8 Ga and was probably attached to Baltica at that time (Zhao

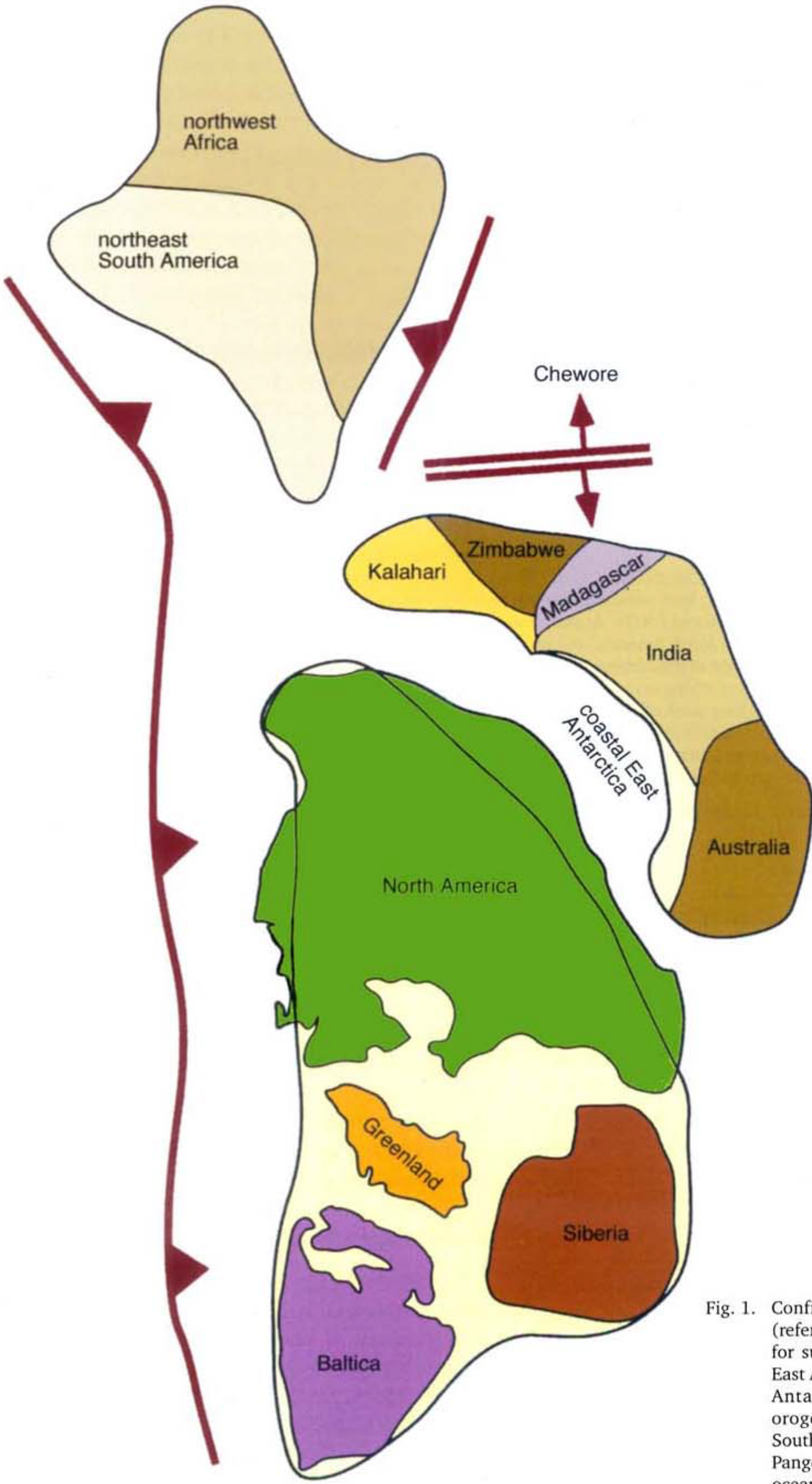

Fig. 1. Configuration of Columbia at ~1.5 Ga (references in text; conventional symbols for subduction zones and rifts). Coastal East Antarctica is the coastal zone of East Antarctica correlative with marginal orogenic belts in Australia, India and South Africa but separated during post-Pangea rifting. Chewore is the Chewore ocean basin discussed in the text.

et al., 2000; Jin, 2002; Lu et al., 2002; see Fig. 4 in Wilde et al., 2002). Rifting in North China from 1.7 Ga to 1.6 Ga indicates separation from Baltica at that time, presumably as accretion was occurring in most of Columbia, and for that reason we do not show North China in diagrams in this paper. After North China and Baltica separated, the further path of North China is unclear until it accreted to Pangea. North China does not appear in most diagrams of Rodinia (e.g., Dalziel, 1997), although other workers have proposed various positions (Wilde et al., 2002).

- South China became a coherent block during the Grenville orogeny (Li et al., 1995), and consequently it is not shown in figure 1 because it did not exist until after the breakup of Columbia.
- East Antarctica's ice cover prevents accurate determination of its ancient history. The margin along the Transantarctic Mountains was clearly somewhere against the western margin of North America in Rodinia, although the exact position is uncertain (see above). Also, the margin along the Indian Ocean shows Grenville activity overprinting older rocks, but we regard this margin as part of India and Australia (Harris, 1995), with the Grenville suture somewhere inland under the ice. Much of East Antarctica may consist of the 'Mawson continent' proposed by Fanning et al. (1996) and Peucat et al. (1999) to have formed at about 1.7 Ga, but Fitzsimons (2000) indicates that East Antarctica may not have been a coherent block before Grenville time. With these degrees of uncertainty, we omit East Antarctica from descriptions of Columbia.

The configuration of Columbia is based on evidence of rifting and orogenic activity, all of which is discussed below under four headings: rifting in western North America and India; general evidence of rifting and breakup of Columbia; orogeny between western North America and India–Australia–East Antarctica; continental-margin outgrowth along eastern North America/Baltica, southwestern North America, and the western margin of Amazonia.

Rifting in Western North America and India

Figure 2 diagrams the critical Mesoproterozoic rift and orogenic relationships between the western margin of North America and the eastern margin of India and attached Antarctica. The principal Indian rifts extend across the continental margin and one, Mahanadi, continues as the Lambert rift into Antarctica in a pre-drift configuration (Stagg, 1985; Mishra et al., 1999). Rifts in

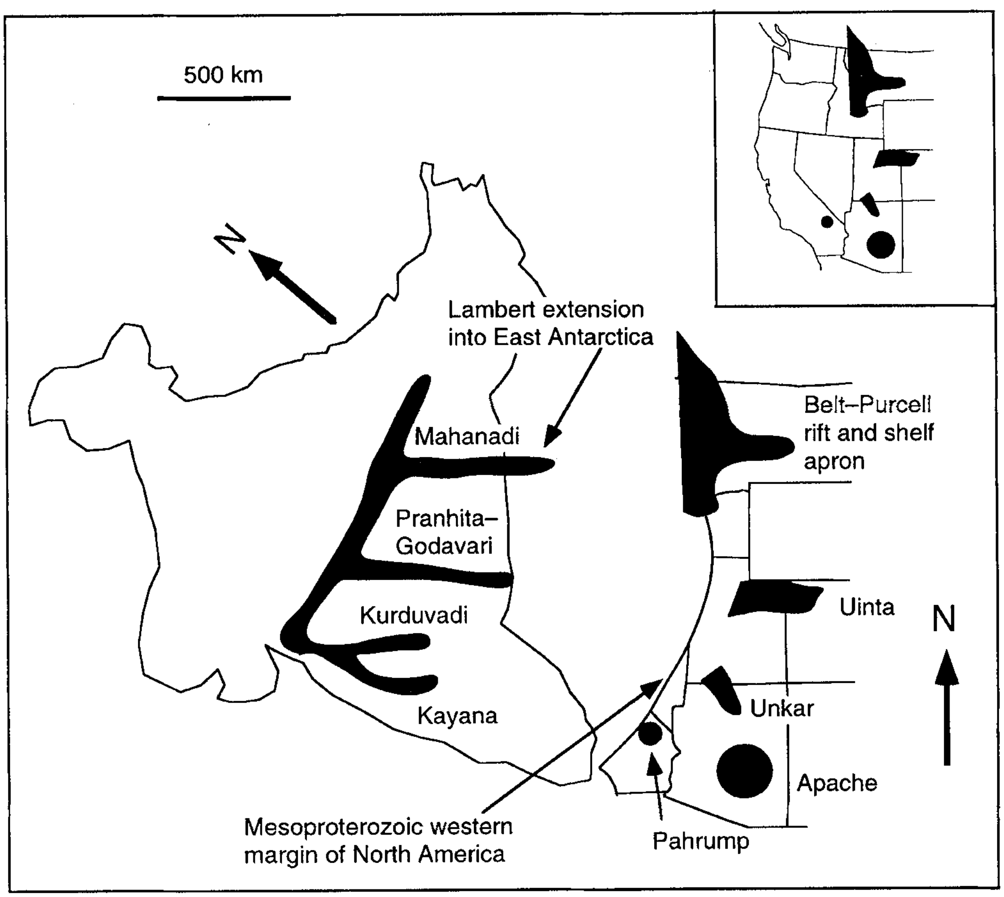

Fig. 2. Rifts in eastern India (left) and western North America (right). Arrows show present north for each area.

North America also appear to extend to the Mesoproterozoic continental margin, approximately in the position shown on figure 2. Phanerozoic accretion to this western margin and stretching in the basin and Range province, however, now put western terminations of these rifts up to 1500 kilometers east of the present continental margin.

Several rifts through the Precambrian crust of India have been episodically active from the Mesoproterozoic or earlier to the present (Naqvi et al., 1974; recent summaries by Chaudhuri et al., 2002, and Saha and Chaudhuri, 2002). Although they are mostly filled by 'Gondwana' (Permo-Triassic) sediments, the oldest sediments in these Indian basins are Mesoproterozoic or older. Good dates are not available for rocks within the Mahanadi suite, but they connect westward to sediments in the Son valley estimated to be approximately 1.3 billion years old (Seilacher et al., 1998). The Pakhal sediments of the Pranhita–Godavari rift also appear to have been deposited between ~1.5 Ga and ~1 Ga (Saha and Chaudhuri, 2002). Unfortunately, the Kurduvadi and Kayana rifts are known only from seismic data because they are completely buried by Deccan basalts, and whether they contain sediments older than the Gondwanas is unknown.

Mesoproterozoic rifting in eastern India created broad basins as well as the linear rifts discussed above (Fig. 2). Sediments in these basins thicken from the cratonic interior toward the east, apparently indicating an eastern continental margin formed by rifting at the time the basins were initiated (Saha and Chaudhuri, 2002). The exact position of this margin cannot be located, however, because of orogeny and uplift in eastern India and East Antarctica both at ~1.0 Ga and ~0.5 Ga (see below).

At least three rifts intersect the Precambrian western margin of North America (Fig. 2; summarized from Link et al., 1993). The Belt–Purcell trough started to rift before 1.47 Ga, when sediments near the base were intruded by mafic sills (Sears et al., 1998). The Uinta trough is atleast as old as Neoproterozoic, and its unexposed base could be Mesoproterozoic. The Unkar Group is a rift sequence intruded by 1.1 Ga mafic sills, but the age of initial sedimentation is controversial. Correlation with the apparently platformal Apache and Pahrump Groups indicate an Unkar age as old as 1.35 Ga, but Timmons et al. (2001) report an age no older than 1.2 Ga based on argon cooling ages of underlying rocks. Timmons et al. (2001) also propose that the Unkar and related suites were synchronous with the early stages of the Grenville orogeny. All three of the known rifts were also active in the Neoproterozoic at the time of rifting that broke up Rodinia, and it seems likely that the Neoproterozoic rifts followed the patterns established when Columbia fragmented.

The principal tie between the Indian and North American rifts is the fit of two rifts in India with two rifts in North America. The distance between the Mahanadi–Lambert rift of India and East Antarctica and the Godavari rift of India is approximately 500 km, the same as the distance between the Belt and Uinta rifts of North America. Because rifting clearly began at ~1.5 Ga in the Mahanadi, Godavari, and Belt rifts (and may have begun in the Uinta rift by this time), we suggest a correlation of the Mahanadi–Lambert rift with the Belt rift and the Godavari with the Uinta, with all of them initiated by the fragmentation of Columbia. Unfortunately, further correlation cannot be made at this time because any equivalent of the Unkar suite would presumably occur in the Kurduvadi and Kayana rifts.

Evidence for Mesoproterozoic rifting between India and North America is strengthened by mafic igneous suites. Dikes in the Albany belt of Australia and basalts in the Racklan orogen of western Canada both have ages of ~1.3 Ga (LeCheminant and Heaman, 1989; Myers, 1993), which are younger than 1.5 Ga but may be related to later stages of rifting. The Eastern Ghats Belt of India (see discussion of orogeny below) contains mafic granulites occurring mostly as small bodies, possibly dykes and sills, in the predominantly felsic terrane (Bhattacharya, 1996). They have ages of ~1.4 to ~1.5 Ga (Arima et al., 2000) and are apparently derived from igneous protoliths that show whole-rock Sm–Nd ages of ~1.4 Ga (Shaw et al., 1997). The Eastern Ghats also contain several anorthosites, and the only dated one has an age of ~1.3 Ga (Sarkar et al., 1981), consistent with anorogenic intrusion of anorthosite complexes elsewhere in the world (see below).

Placing eastern India and attached parts of East Antarctica against the western side of North America may explain why zircon and Sm–Nd data for Belt sediments show a source that was west (present orientation) of the Belt basin and was not part of North America (Ross et al., 1992). Provenance ages of these sediments are comparable with ages in potential source rocks in eastern India and the adjacent part of East Antarctica, suggesting that these areas could have supplied some of the Belt debris. This interpretation differs from the concept that Belt sediments were derived from Siberia (Sears and Price, 2000, 2002).

General Evidence of Rifting and Breakup of Columbia

Rifting occurred along both along the margins and interior of Columbia from about 1.6 Ga to 1.4 Ga. A rift along one margin is shown by the ~1.4 Ga Chewore ophiolite in the Zambezi orogenic belt between Zimbabwe and central Africa (Oliver et al., 1998; Johnson and Oliver,

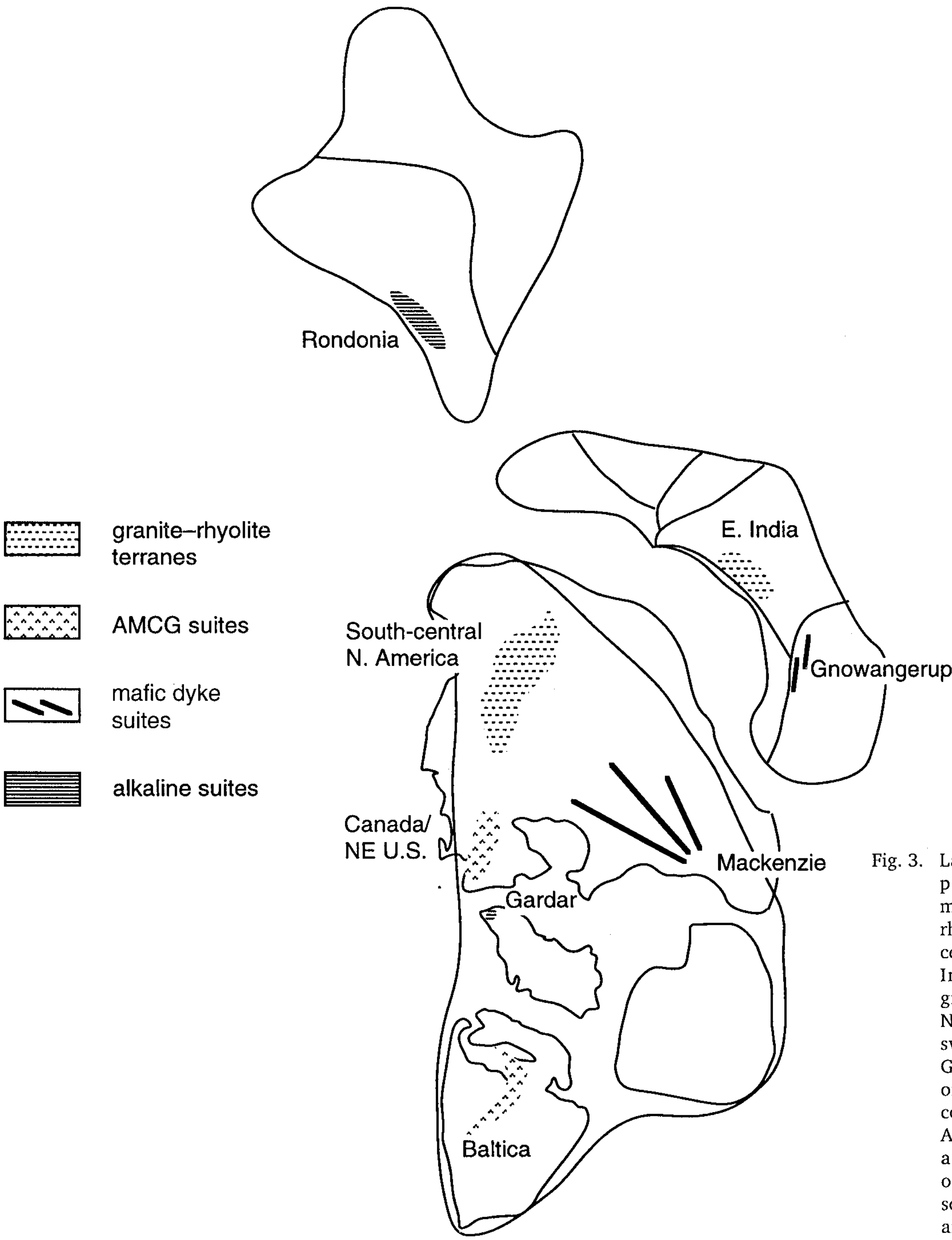

Fig. 3. Large areas of Mesoproterozoic post-orogenic and anorogenic magmatism in Columbia. Granite-rhyolite terranes occur in south-central North America and eastern India; ~1.4 Ga postorogenic granites occur in and around the North American terrane. Dyke swarms include Mackenzie and Gnowangerup. The AMCG suites of North America and Baltica were connected before opening of the Atlantic Ocean. Alkali granites and associated anorogenic activity occur in South America and southern Greenland. References and further descriptions in text.

2000). The ophiolite demonstrates the presence of a Chewore ocean basin (Fig. 1) that was probably formed by rifting along the northern margin (present orientation) of the Zimbabwe craton at ~1.5 Ga to ~1.4 Ga. It may indicate that the Tanzania craton rifted away from the Zimbabwe craton at this time and then moved across an intervening ocean basin to collide with the Congo craton during the Kibaran orogeny at ~1.3 Ga to ~1.2 Ga (Meert et al., 1994; Fernandez-Alonso and Theunissen, 1998).

In addition to the rifting that caused the breakup of Columbia, rifting at ~1.4 Ga was widespread in orogenic belts that formed the long margin of Columbia from Baltica to Amazonia (discussed below). In all of these areas, a period of stability and/or backarc rifting interrupted the subduction and outgrowth that appear to have begun about 1.8 Ga and extended to Grenville time. Some of these rifts could have been involved in the fragmentation of a Mesoproterozoic supercontinent if it had a different configuration from the one that we propose here.

Figure 3 shows that fragments formed from Columbia contain abundant evidence of post-orogenic and anorogenic magmatism in the approximate range of 1.6 Ga to 1.3 Ga. The principal suites include: the granite–rhyolite terrane and associated granites of North America; a dismembered granite–rhyolite terrane in the rifts and marginal basins of eastern India; AMCG plutons in northern North America and southern Baltica; the Rondonian 'tin' granites of Amazonia; the Mackenzie dyke swarm of North America the Gnowangerup dykes of western Australia; the Gardar alkaline suite of southern Greenland and the Dalma magmatic rocks of northeastern India.

The granite-rhyolite terrane is a widespread suite of ~1.4 Ga rhyolites and local granite that underlies much of midcontinent U.S. (Bickford and Anderson, 1993; Van Schmus et al., 1996). The ~1.4 Ga granites occur within the granite–rhyolite terrane and also are spread throughout most of the pre-1.5 Ga orogenic belts of the central and southwestern United States (Anderson and Morrison, 1992; Anderson and Cullers, 1999). They are a typical post-orogenic suite, consisting almost exclusively of granite without any associated mafic or intermediate rocks and no tendency toward high-alkali rocks.

A rhyolite province is now preserved only as fragments in the rifts and marginal basins of eastern India that began to form at approximately 1.5 Ga. Rocks consist partly of flows and ash flows but are predominantly air-fall tuffs containing crystal, vitric and lithic fragments (Patranabis Deb, 2002). Sedimentary structures show that much of the deposition occurred in water, and much of the ash is mixed into other sediments. Despite the absence of preserved granites, the suite is remarkably similar to the granite–rhyolite terrane of North America.

Several dozen plutonic assemblages in northern North America and southern Baltica contain a mixture of rock types broadly classified as AMCG (Emslie and Hunt, 1990; Haapala and Ramo, 1990; Puura and Floden, 1999; Ahall et al., 2000; Lu et al., 2002). They include massif-type anorthosites (A), mangerites (M), charnockites (C) that apparently were formed by igneous activity, and rapakivi granites (G). The proportions of the different rock types vary from one massif to another, and some rock types are completely absent from some of the bodies. Regardless of detailed petrology, almost all of the massifs have ages ranging from about 1.6 to 1.4 Ga, and all of them are clearly related to relaxation of horizontal stress shortly after orogenic crustal growth. Minor AMCG suites in North China have ages of ~1.6 Ga, similar to ages of older suites in Baltica and confirming this age of separation of the two cratons.

Rapakivi granites and related rocks form numerous plutonic suites in the Rondonian orogenic region of the southern Amazonian craton (Bettencourt et al., 1999). The massifs consist primarily of rapakivi granite with minor associated mafic rocks, and some alkaline intrusives are so metalliferous that the area is commonly referred to as the Rondonian tin province. Ages range from ~1.6 Ga to slightly greater than 1.3 Ga and center between 1.5 Ga and 1.4 Ga. They either follow, or are associated with, the last stages of the Rondonian orogeny (see below), presumably as a result of post-orogenic crustal extension.

The Mackenzie dyke swarm consists of mafic dykes that radiate from a small area of northwestern Canada and extend east and south across much of Canada. Widely spaced samples have ages closely centered at ~1.3 Ga (LeCheminant and Heaman, 1989), and the suite may include the Coppermine basalts of the Racklan orogen (see below). The continent-wide extent of these dykes indicates extension associated with asthenospheric uplift, possibly a broad mantle plume.

The Gnowangerup dykes are aligned along the southern margin of the Yilgarn block in the western Australian craton (Myers, 1993). Their intrusion at ~1.3 Ga is essentially synchronous with intrusion of the Mackenzie dyke swarm of North America and presumably indicates extension in this part of Australia/East Antarctica at this time.

Magmatic rocks in the Gardar province of southernmost Greenland are an approximately 1.3 Ga to 1.2 Ga assemblage of mafic dykes and highly alkaline plutonic suites. Many of them have compositions similar to those of the ultrapotassic and other alkaline rocks of the western branch of the East African rift zone (Macdonald and Upton, 1993), and this similarity presumably shows that the Gardar suite occupies a Mesoproterozoic rift.

The Dalma mafic/ultramafic rocks occur in an Archean craton north of the Mahanadi rift of northeastern India. They were derived from MORB-type sources at ~1.6 Ga and emplaced into a rift between two sialic blocks (Roy et al., 2002). The rocks were deformed by younger Proterozoic compression, showing that the rift lasted for only a brief period of time, perhaps because it was slightly older than the major Indian rift valleys discussed above.

The approximate age equivalence of all of these suites with the Mesoproterozoic rift valleys of India and North America discussed above suggests widespread relaxation of horizontal stress starting at about 1.6 Ga throughout much of the earth's continental crust. Presumably this relaxation was associated with the processes that caused the breakup of Columbia.

Orogeny Between Western North America and India–Australia–East Antarctica

Limited evidence for the correlation shown by rifts in figure 2 is provided by orogenic activity. Figure 4 shows areas where Mesoproterozoic orogeny occurs on the margins of cratonic areas stabilized by ~1.8 Ga or earlier. We discuss these areas in four segments.

The Racklan orogen is apparently a westward continuation of outgrowth of the Canadian shield, where both the Great Bear and Fort Simpson intrusive suites show eastward-directed subduction along its western margin from 1.9 Ga to 1.8 Ga (Ross, 1991). The Racklan orogen is exposed primarily as the Wernecke Group in Yukon and the Coppermine homocline to the northeast, and the term has also been used for events of roughly similar age that are known mostly in the subsurface of areas to the south (Cook, 1992). The Wernecke Group is a generally undated metasedimentary package that shows deformation both before and after intrusion of a breccia pipe at ~1.3 Ga. In the Coppermine homocline, sedimentation both preceded and followed eruption of the bimodal Narakay volcanic suite at ~1.7 Ga (Bowring and Ross, 1985). Petrology of the Narakay suite shows that it is subduction-related, and the first indication of extension in this area is extrusion of the Coppermine basalts at ~1.3 Ga. The entire Racklan suite is clearly the product of Mesoproterozoic subduction under the western margin of North America, perhaps with a period of extension during eruption of the Coppermine basalts (see Mackenzie dykes above).

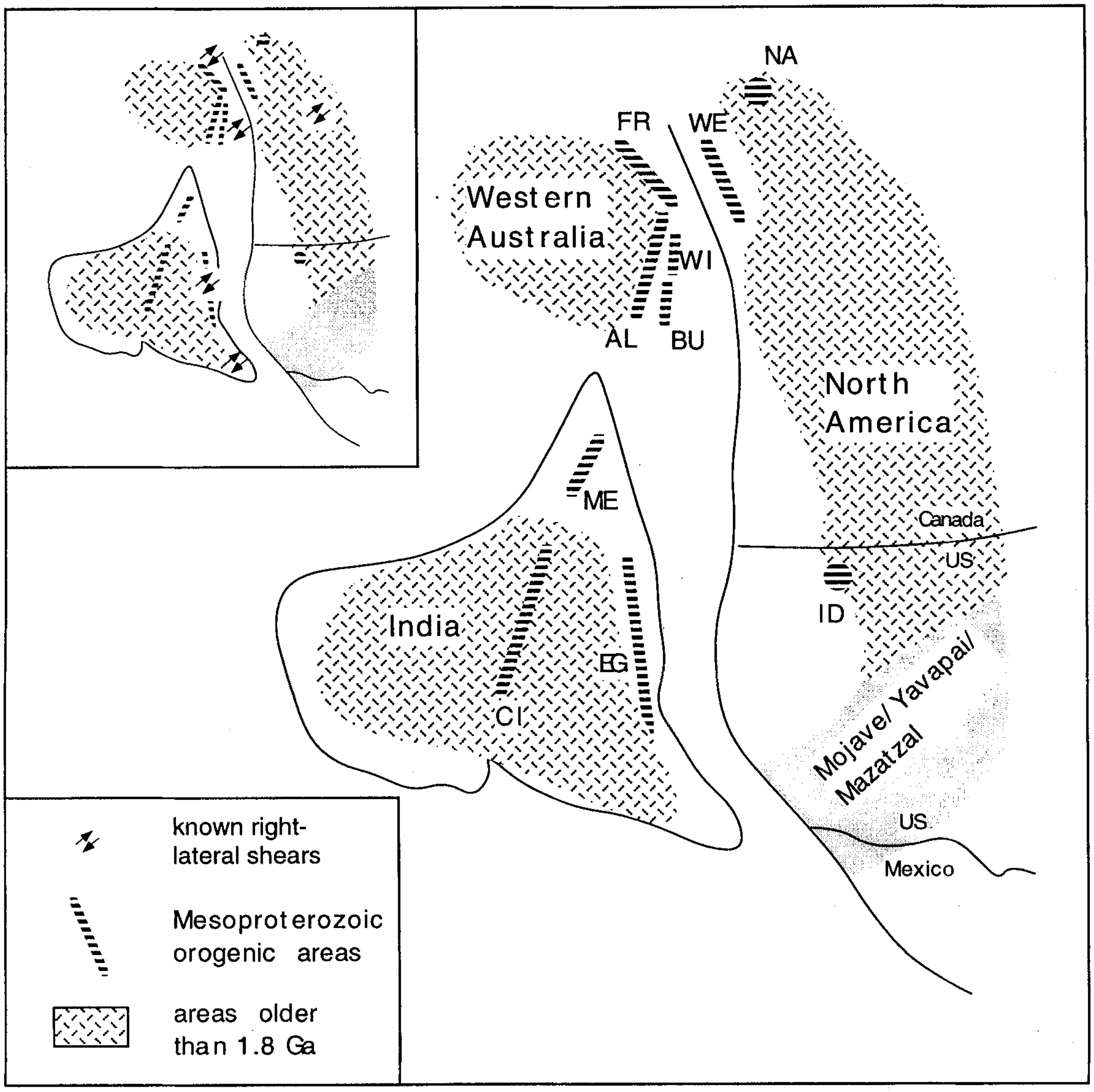

Fig. 4. Orogenic belts on the collisional margin along the western edge of North America. Abbreviations are: AL-Albany, BU-Bunger Hills, CI-Central Indian Tectonic Zone, EG-Eastern Ghats, FR-Fraser, ID-Mesoproterozoic isotopic inheritance in magmatic rocks of Idaho batholith, ME-Meghalaya, NA-Narakay volcanic suite in Racklan orogen, WE-Wernecke part of Racklan orogen, WI-Windmill Islands. References in text.

Mesoproterozoic activity along the western margin of North America is largely obscured between the Racklan orogen in the north and the Yavapai orogen to the south. The well-exposed Yavapai orogen caused southeastward outgrowth of cratonic North America from 1.8–1.6 Ga (see below), but it is almost wholly along the southeastern margin of the continent (Karlstrom and Humphreys, 1998; Karlstrom et al., 1999). Only the Mojave block in the southwesternmost tip of this orogen could have been in contact with India, Australia and Antarctica (Barth et al., 2000; Coleman et al., 2002). Between this tip and the Racklan orogen the evidence of Mesoproterozoic activity consists of isotopic information from younger rocks. Mueller et al. (1995) found an age of ~1.7 Ga for premagmatic zircons in a Mesozoic batholith and an identical T_{DM} age of ~1.7 Ga for the batholith.

The Albany and Fraser orogens of Australia extend into the Bunger Hills and Windmill Islands of coastal East Antarctica, which were attached in a pre-drift configuration (Harris, 1995). Together they form the southern and southeastern margins of the western Australian craton. Mesoproterozoic history is very difficult to determine because nearly all of these belts were affected by both the Grenville (~1 Ga) and Pan-African (~0.6 Ga) events, which overprinted older rocks.

The oldest well-known Mesoproterozoic activity in the Fraser belt consists of intrusion of subduction-related batholiths between approximately 1.7 and 1.6 Ga (Nelson et al., 1995), and the next well dated event was dextral transpression and intrusion of the Albany enderbite at ~1.3 Ga. This history is remarkably similar to that of the Windmill Islands and Bunger Hills of Antarctica (Harris, 1995). The Windmill Islands contain gneisses at least as old as 1.5 Ga, and orthogneisses in the Bunger Hills range from 1.7 Ga to 1.5 Ga. These Mesoproterozoic ages have not been found in the Albany belt, which shows the oldest orogenic activity at ~1.3 Ga, partly reworking Archean and Paleoproterozoic rocks in the southern margin of the Yilgarn shield part of the western Australian craton.

The Eastern Ghats granulite terrane of eastern India is mostly a suite of silicic metaigneous and metasedimentary rocks that show abundant isotopic evidence of Mesoproterozoic events prior to metamorphism during the Grenville (~1 Ga) and Pan-African (~0.5 Ga) events (Bhattacharya, 1996; Arima et al., 2000; Bhattacharya and Misra, 2002). Ultra-high temperature metamorphism of metapelites occurred at ~1.6 Ga (Dasgupta et al., 1999). Cooling ages of allanite and monazite from a pegmatite range from 1.7 Ga to 1.6 Ga (Mezger and Cosca, 1999). Shaw et al. (1997) report ages up to 1.5 Ga for a broad range of rock types and also show that both felsic and mafic rocks have Sm–Nd whole-rock ages of ~1.4 Ga, with some indication of older ages based mostly on U–Pb systems.

Events with ages of 1.9 Ga to 1.4 Ga are widespread throughout India. The Delhi orogen of northwestern India showed continued sedimentation and deformation from the Paleoproterozoic into the Mesoproterozoic, with ages of magmatic rocks from 1.9 Ga to 1.5 Ga (Chaudhary et al., 1984; Biju Sekhar et al., 2001). Gneisses in the Meghalaya area of northeastern India have an Rb–Sr age of ~1.7 Ga, and inclusions in a younger pluton have an Rb–Sr age of ~1.5 Ga (Ghosh et al., 1994). The Central Indian Tectonic Zone was a collisional orogen throughout much of the Proterozoic (Acharyya and Roy, 2000). Metasediments in the granulite terrane in southernmost India show 1.8 Ga ages by a variety of techniques, including single-zircon evaporation, zircon U–Pb, and garnet Sm–Nd (Bartlett et al., 1998). In the same area metapelites and charnockites have zircon U–Pb–Th ages of 2.2 Ga to 1.7 Ga (Santosh and Yokoyama, unpublished). It is not clear whether rocks in these belts were formed along a suture zone with North America, although Harris (1993) has correlated the Central Indian Tectonic Zone with the Albany belt of Australia.

Many of the areas along the proposed suture zone of figure 4 show right-lateral movement. They include the Eastern Ghats (Biswal et al., 2002), Albany and Fraser belts (Beeson et al., 1988), Southern Indian Granulite Terrane (Chetty and Bhaskar Rao, 1998), and the Snowbird zone within the North American craton (Kopf, 2002). Because of overprinting by younger deformational events, it is extremely difficult to know whether all of these areas underwent right-lateral translation in the range of 1.8 Ga to 1.5 Ga, but it is possible that the principal event along the suture zone was right-lateral transpression.

Much of the evidence along the proposed suture zone has been destroyed by some combination of tectonic overprinting, isotopic resetting, burial beneath younger sediments, and covering by thrust mountain ranges. Nevertheless, a general pattern can be discerned. From ~1.8 Ga to ~1.5 Ga compressional orogeny occurred along the western margin of North America and a margin consisting of eastern India, the southern part of western Australia, and adjoined parts of East Antarctica. Subuction was apparently downward under North America at the same time as granulite-facies metamorphism occurred along the India–Australia–Antarctica margin. This suggests that suturing (perhaps right-lateral) occurred between these two margins before rifting in the general age range of 1.5 Ga to 1.4 Ga.

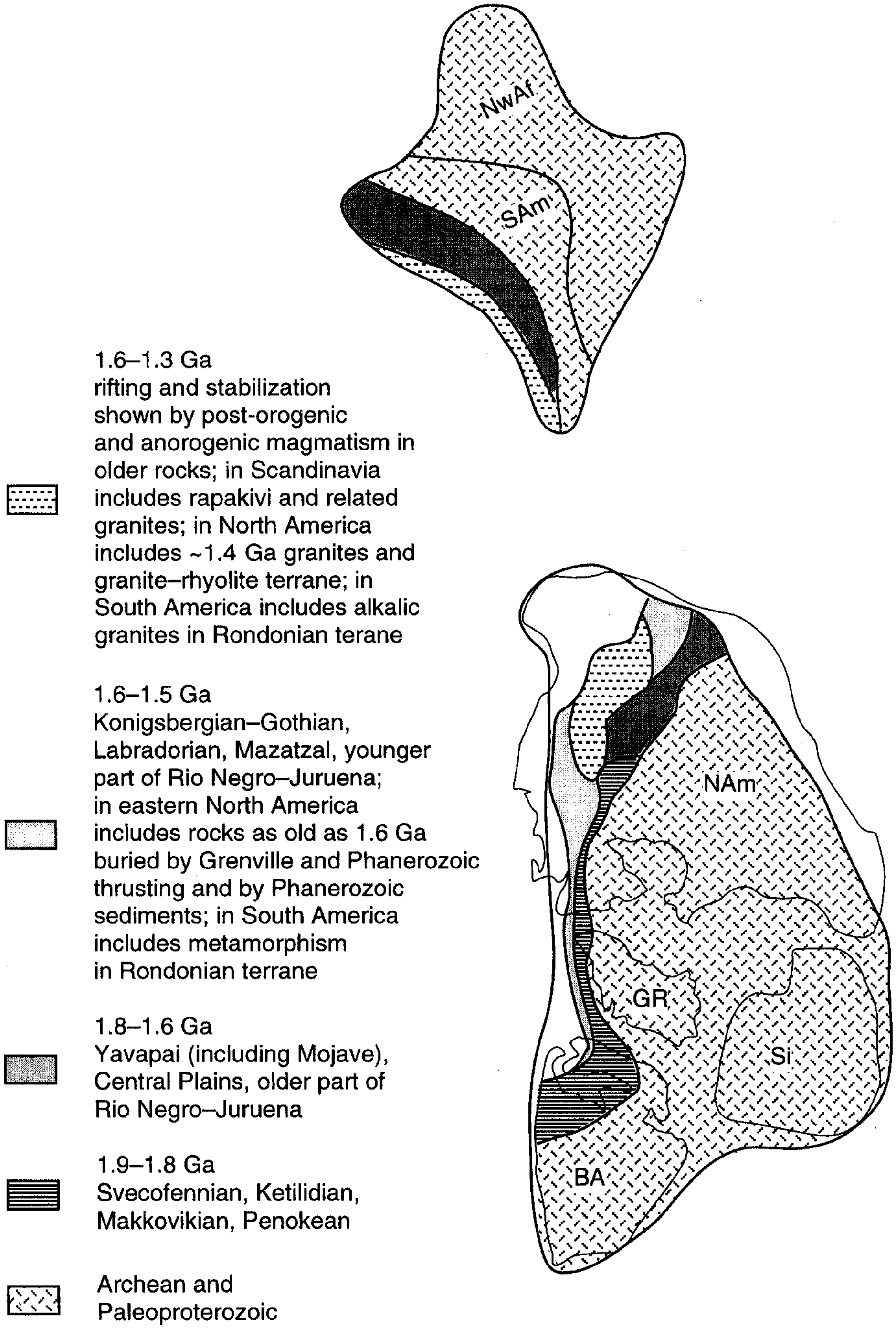

Fig. 5. Orogenic belts along the accretionary margin of Columbia. References and discussion in text. Si-Siberia, BA-Baltica, GR- Greenland, NAm-North America, SAm-South America, NwAf-Northwestern and central Africa.

Continental-Margin Outgrowth Along Eastern North America/Baltica, Southwestern North America and the Western Margin of Amazonia

The configuration of Columbia in figure 1 implies subduction-related outgrowth along nearly half of its continental margin. The principal suites are shown in figure 5, which omits assemblages formed after approximately 1.3 Ga. This age is commonly regarded as the early part of the Grenville orogeny and includes orogenic belts such as Sveconorwegian of Baltica, type Grenville and Elzivirian of North America, and Sunsas of Amazonia. All of these belts are involved in the development of Rodinia, which was later than the events discussed in this paper.

The Svecofennian orogen, Transscandinavian granite-porphyry belt, Western Gneiss region, Southwest Scandinavian Gneiss complex, and Konigsbergian–Gothian of Baltica are all parts of a long-continued outgrowth of the Baltic shield that began in the

Paleoproterozoic (Lindh and Persson, 1990). All belts are dominated by batholithic rocks intrusive into metasupracrustal assemblages. The Svecofennian orogen underwent a peak of metamorphism during the approximate period of 1.9 Ga to 1.8 Ga and the granite-porphyry belt from about 1.7 Ga to 1.65 Ga. The Western Gneiss region is a suite of migmatitic leucogneisses with ages of ~1.7 Ga to ~1.6 Ga (Tucker et al., 1990). The Southwest Scandinavian gneiss complex represents a broad suite of rocks with age ranges from 1.7 Ga to 0.8 Ga, which places younger parts within the Grenville–Sveconorwegian orogeny. The Konigsbergian–Gothian is a magmatic suite with ages of ~1.6 Ga to ~1.5 Ga (Ahall et al., 2000). A period centered around 1.4 Ga seems to have been a time of crustal stability and/or rifting when active compression did not occur throughout the region.

The Ketilidian province of Greenland and Makkovik province of Labrador consist of felsic gneisses among voluminous batholithic suites. Most of the intrusions formed between approximately 1.8 Ga and 1.7 Ga and post-date thrusting toward the continental interiors of Greenland and Canada (Kerr et al., 1996). In Labrador these suites are abruptly terminated southward by the Labradorian batholithic suite, with ages in the range of 1.7 Ga to 1.6 Ga.

Gower et al. (1990) and Rivers (1997) described the pre-Grenville history of eastern Canada as a period of continental-margin outgrowth beginning at ~1.8 Ga followed by backarc rifting and stability from approximately 1.5 Ga to 1.3 Ga. This stability was terminated when the early stages of the Grenville orogeny began shortly after 1.3 Ga.

Farther south in eastern North America, rocks older than Grenville crop out only in a few isolated patches where they have been uncovered by erosion of Paleozoic thrust complexes in the Blue Ridge province. They are all granulites and exhibit poorly defined ages in the range of 1.8 Ga to 1.6 Ga.

Midcontinent North America is almost entirely covered by undeformed sediments that began to accumulate when the underlying basement was stabilized. In much of the area, the oldest rocks found in sparse outcrops or by drilling are parts of the granite-rhyolite terrane (see above), with the underlying basement unknown. The oldest rocks in this area belong to the Central Plains Orogen and consist of metaigneous and metasedimentary rocks of amphibolite grade or lower (Van Schmus et al., 1993). Ages commonly range from 1.8 Ga to 1.6 Ga, consistent with those of the Yavapai and Mazatzal orogens to the southwest.

The Yavapai and Mazatzal orogens are exposed throughout much of the arid southwestern U.S. (Karlstrom and Humphreys, 1998). They both contain a series of accreted arcs and continental-margin supracrustal rocks intruded by batholithic suites. The Yavapai province apparently completed its accretion in the period from 1.8 Ga to 1.7 Ga, and the isotopically distinct Mojave area has the same history as the rest of the Yavapai province (Barth et al., 2000; Coleman et al., 2002). The Mazatzal province followed from about 1.7 Ga to 1.5 Ga and continued the process of outgrowth of the North American craton. Mesoproterozoic growth was followed by the early stages of the Grenville collisional orogeny (1.3 Ga to 1.2 Ga), which consolidated this portion of Rodinia (Condie, 1992; Van Schmus et al., 1996).

The western part of the Amazon craton also underwent marginal growth at about the same time as eastern North America until it was incorporated into Rodinia during the Grenville collision (Sadowski and Bettencourt, 1996; Brito Neves, 2002). Growth took place on the margin of a large 2.1–to 2.0 Ga continent (referred to as Atlantica) that included much of cratonic South America and part of northwestern Africa (Ledru et al., 1994; Hartmann, 2002). The two major belts are Rio Negro–Juruena and Rondonian, both of which consist of supracrustal and intrusive rocks formed during subduction under the western margin of Amazonia. The Rio Negro–Juruena suite developed approximately during the period 1.8 Ga to 1.5 Ga and lies on a basement consisting of the 2.0 Ga and older rocks of the Amazonian craton. Rondonian growth and metamorphism west of the Rio Negro–Juruena suite apparently continued until ~1.3 Ga, when it was accompanied by crustal relaxation associated with emplacement of the Rondonian intrusive complex (see above).

Worldwide Orogenic Events Starting at ~1.9 Ga

Condie (2000, 2002) proposed that ~1.9 Ga was the beginning of a period of rapid crustal growth and mantle reorganization, and numerous orogenic belts described above began activity at about this time. In addition, important orogenic events were initiated elsewhere. Much of eastern Australia began to accrete to the Archean shields in the west at ~1.8 Ga (Burrett and Berry, 2000). The Trans-Hudson orogen of North America showed a peak of activity, which has been variously interpreted as accretion of two widely separated parts of the Canadian shield or as an area of limited development of juvenile crust in an orogen largely undergoing resetting of older rocks (Bickford et al., 1994; Orrell et al., 1999).

Whether these other belts and areas of crustal growth were involved in the formation of Columbia is unknown. If they were, then the Mesoproterozoic supercontinent may have had a somewhat different configuration than the one shown in figure 1.

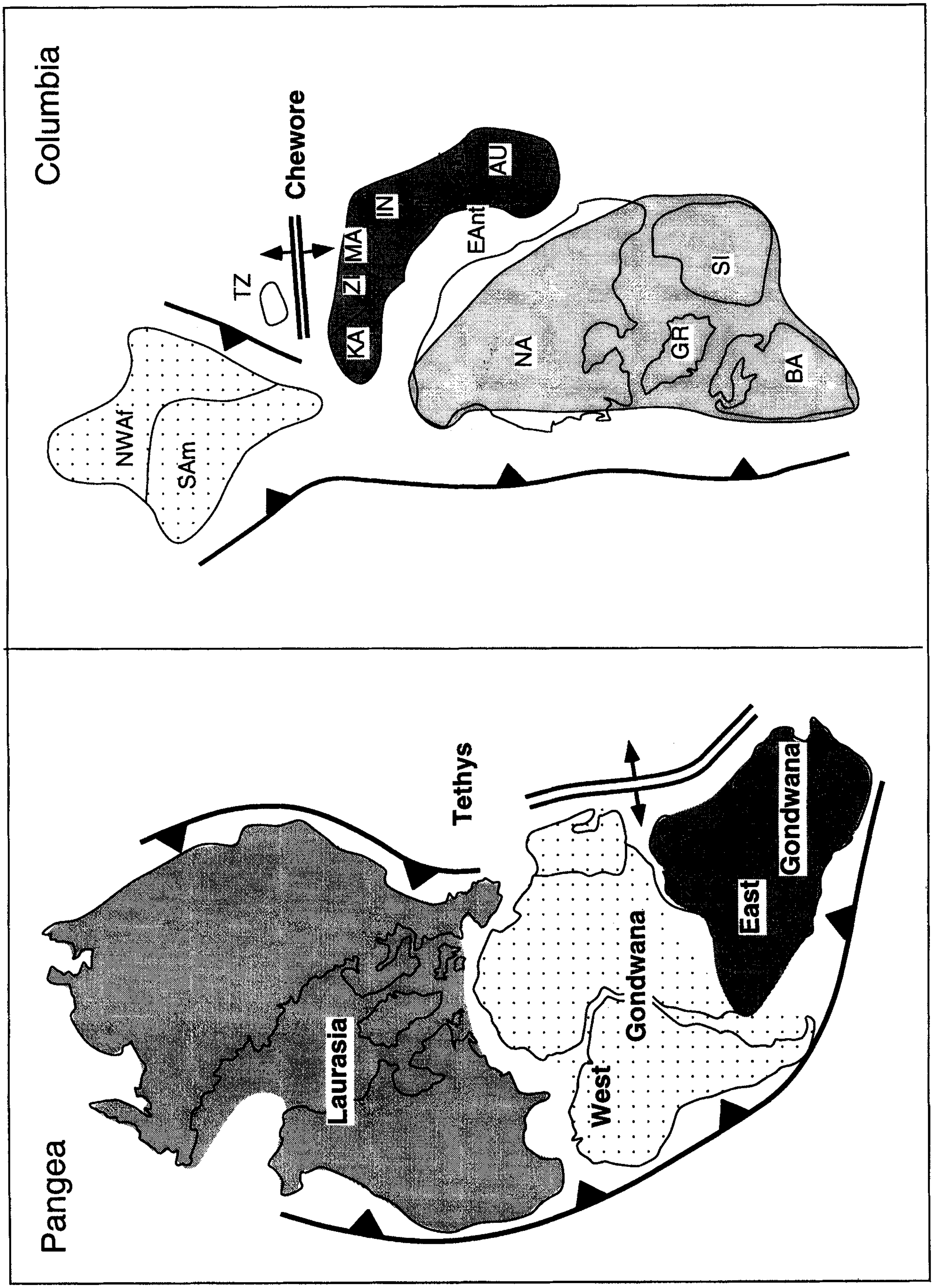

Fig. 6. Comparison of Columbia and Pangea. Discussion in text. SI-Siberia; BA-Baltica; GR-Greenland; EAnt-coastal zone of East Antarctica correlative with marginal orogenic belts in Australia, India and South Africa but separated during post-Pangea rifting; AU-Australia; NA-North America; IN-India; MA-Madagascar; ZI-Zimbabwe; KA-Kalahari; SAm-South America; NWAf-Northwestern and central Africa; TZ-Tanzania. Chewore is the Chewore ocean basin discussed in the text.

Comparison of Columbia and Pangea

A supercontinent Columbia with the configuration shown in figure 1 bears striking similarity to Pangea (Fig. 6). The western margin of Pangea was a site of continual continental-margin orogeny without collision of major continental fragments, and one margin (western?) of Columbia underwent similar outgrowth

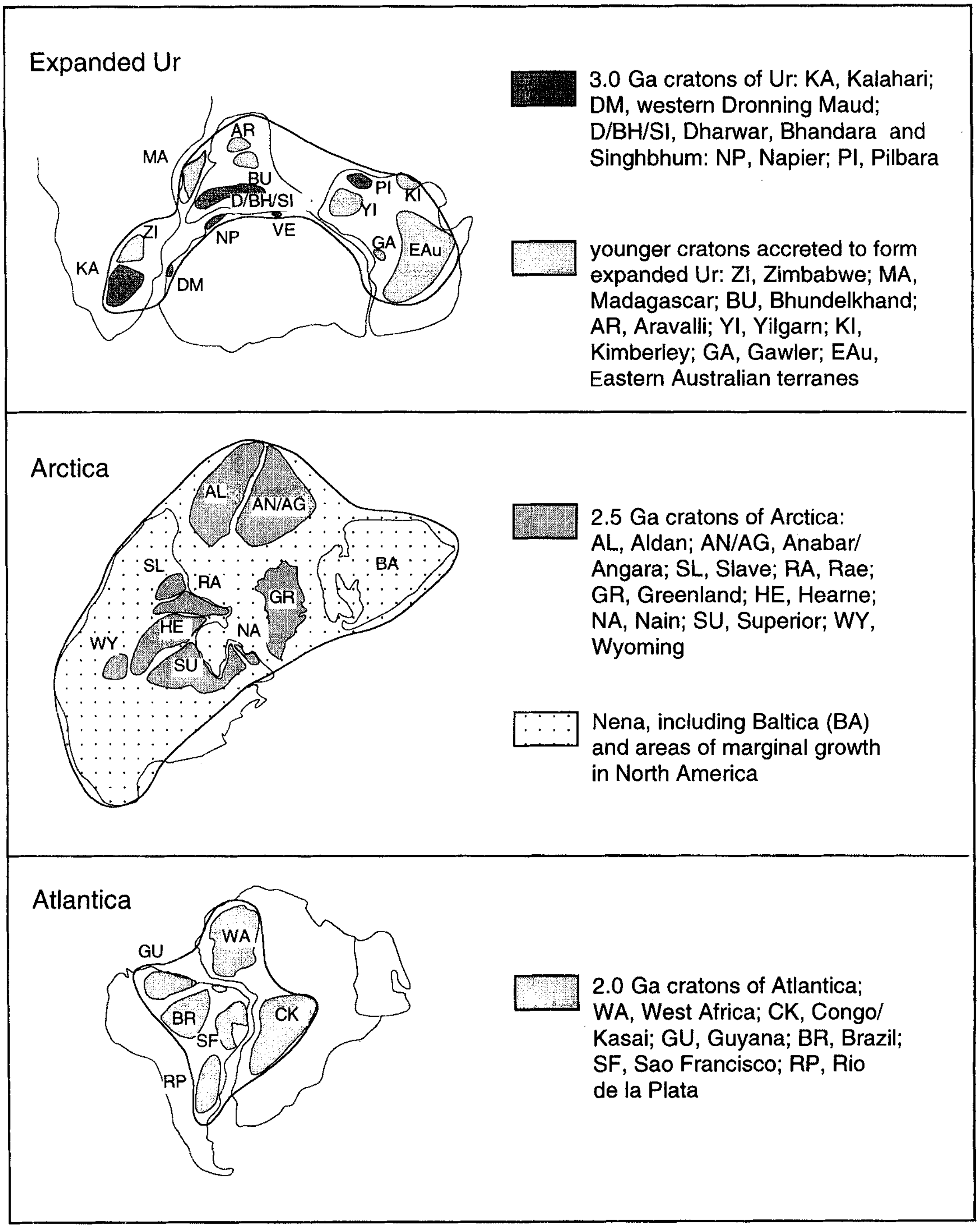

Fig. 7. Three old continents (Rogers, 1996) Ur and expanded Ur: Cratons in Ur (black) are: KA-Kalahari; DM-western Dronning Maud Land; D/BH/SI-a block containing the Dharwar, Bhandara, and Singhbhum cratons; NP-Napier; VE-Vestfold; PI-Pilbara. Additional cratons of expanded UR (gray) at 1.5 GA are: ZI–Zimbabwe; MA–Madagascar; BU–Bundelkhand; AR–Aravalli; YI–Yilgarn; KI-Kimberley; GA-Gawler; EAu-eastern Australian terranes. Arctica and Nena: Cratons of Arctica (black) are: AL–Aldan; AN/AG–Anabar/Angara; SL–Slave; RA–Rae; GR– Greenland; HE-Hearne; NA-Nain; SU-Superior; WY-Wyoming. Nena includes Arctica, Baltica (BA), areas of marginal growth around Arctica, plus attachment of East Antarctica at some time before 1.0 Ga. Atlantica: cratons of Atlantica (black) are: WA-West Africa; WN–West Nile; CK-Congo/Kasai; GU-Guyana; BR-Brazil; SF-Sao Francisco; RP-Rio de la Plata.

during the Middle Proterozoic. On the eastern margin of Pangea, rifting of blocks from the southern part and accretion on the north opened and closed successive ocean basins generally referred to as Tethyan. Similarly, the southern part of one margin (eastern?) of Columbia was a zone of rifting, separating the Tanzanian craton, and probably other blocks, that moved northward and collided with the northern part of the margin in central and northwestern Africa.

Models for Formation of Supercontinents

Formation of supercontinents is commonly explained by the coalescence of numerous continental fragments (cratons) along sutures formed by the closure of small ocean basins between them (Unrug, 1992). An alternative explanation is the continual reorganization of a few large continental masses with ages greater than 1.5 Ga (Fig. 7; Rogers, 1996). These continents are:

- the ~3 Ga Ur, which included much of India, the Kalahari craton of southern Africa, the Pilbara craton of western Australia, the coastal region of East Antarctica, and extended an unknown distance beneath the Antarctic ice cap. Ur grew to the expanded Ur shown in figure 7 before 1.5 Ga by progressively incorporating other Indian cratons, the Zimbabwe craton of southern Africa and eastern Australia.
- the ~2.5 Ga Arctica, which consisted of much of cratonic North America, Siberia and Greenland. The principal question about this reconstruction is the position of Siberia (Condie and Rosen, 1994; Sears and Price, 2000, 2002). Arctica grew to the continent Nena earlier than 1.5 Ga by fusion with the ~2 Ga Baltica (Fig. 7; Gower et al., 1990) and by marginal growth on all sides of North America.
- the ~2 Ga Atlantica, which consisted of much of northeastern South America and much of West Africa (Fig. 7; Ledru et al., 1994).

Figure 8 shows Columbia and Pangea consisting of these three old continents plus younger accreted continental blocks. The presence of these three recognizable landmasses in both supercontinents shows that they

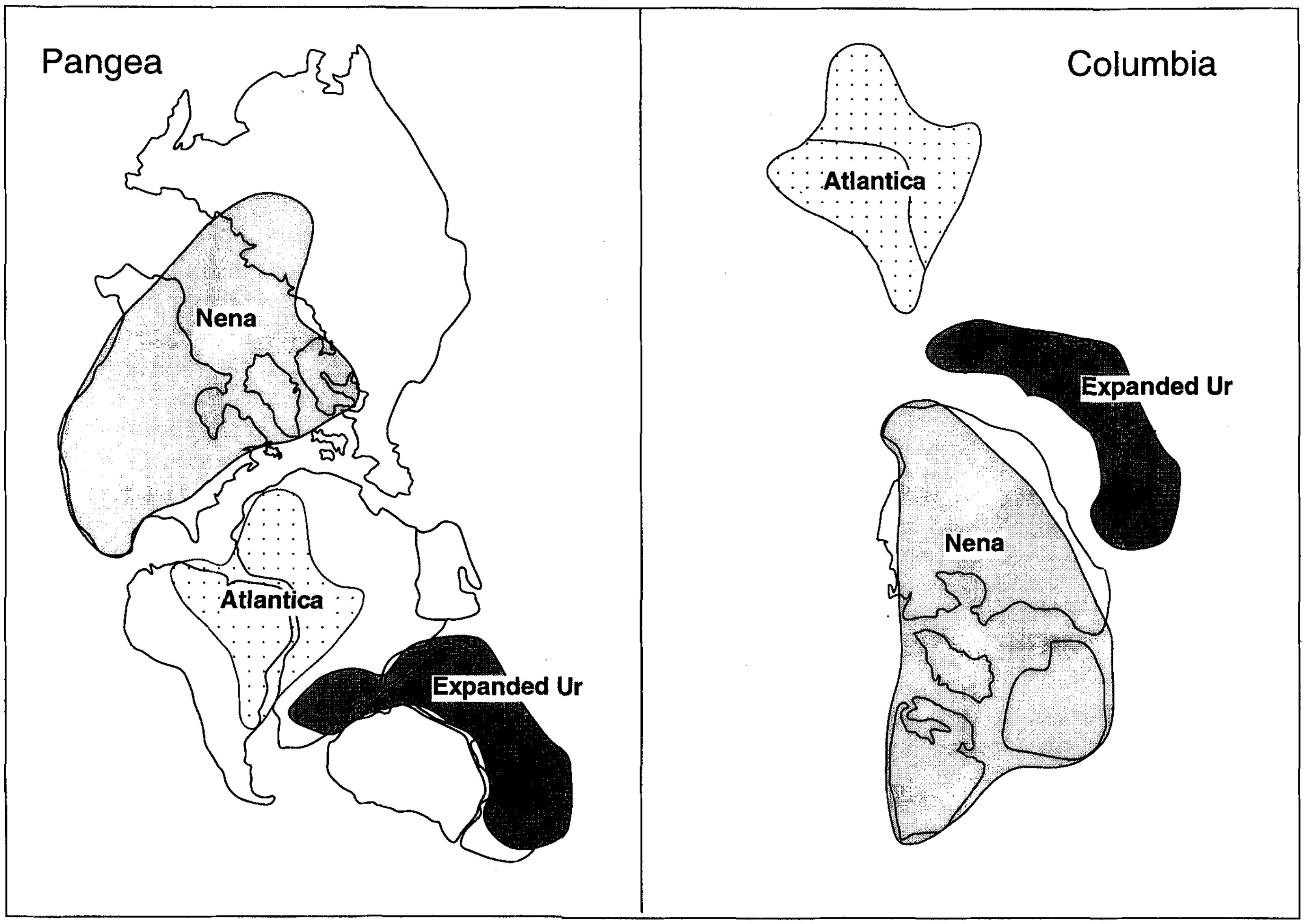

Fig. 8. Columbia and Pangea consisting of the three major continents of figure 7 plus smaller accreted blocks.

remained intact from their separate ages of formation until they broke up during the fragmentation of Pangea. Presumably these continents were also coherent parts of Rodinia, and the following discussion of the accretion of Columbia and its breakup to form Rodinia uses this model.

Accretion and Dispersal of Columbia

Columbia must have formed along at least two major zones of accretion somewhat earlier than 1.5 Ga, perhaps beginning about 1.9 Ga in some areas. Using present orientations, one was between western North America (part of Nena), and eastern India, western Australia, and attached East Antarctica (part of expanded Ur). A definable suture is not preserved, but it seems likely that it contained the Racklan orogen and areas farther south in North America, the Albany–Fraser belts, and the Eastern Ghats. The other collision placed southern North America (part of Nena) against northern South America (part of Atlantica). We have been unable to find direct evidence for this collision and infer it from the similarity in histories of continental-margin outbuilding during the Mesoproterozoic and the similarity between a Columbia with this configuration and Pangea. Accretion to form Columbia may have occurred at the same time as the

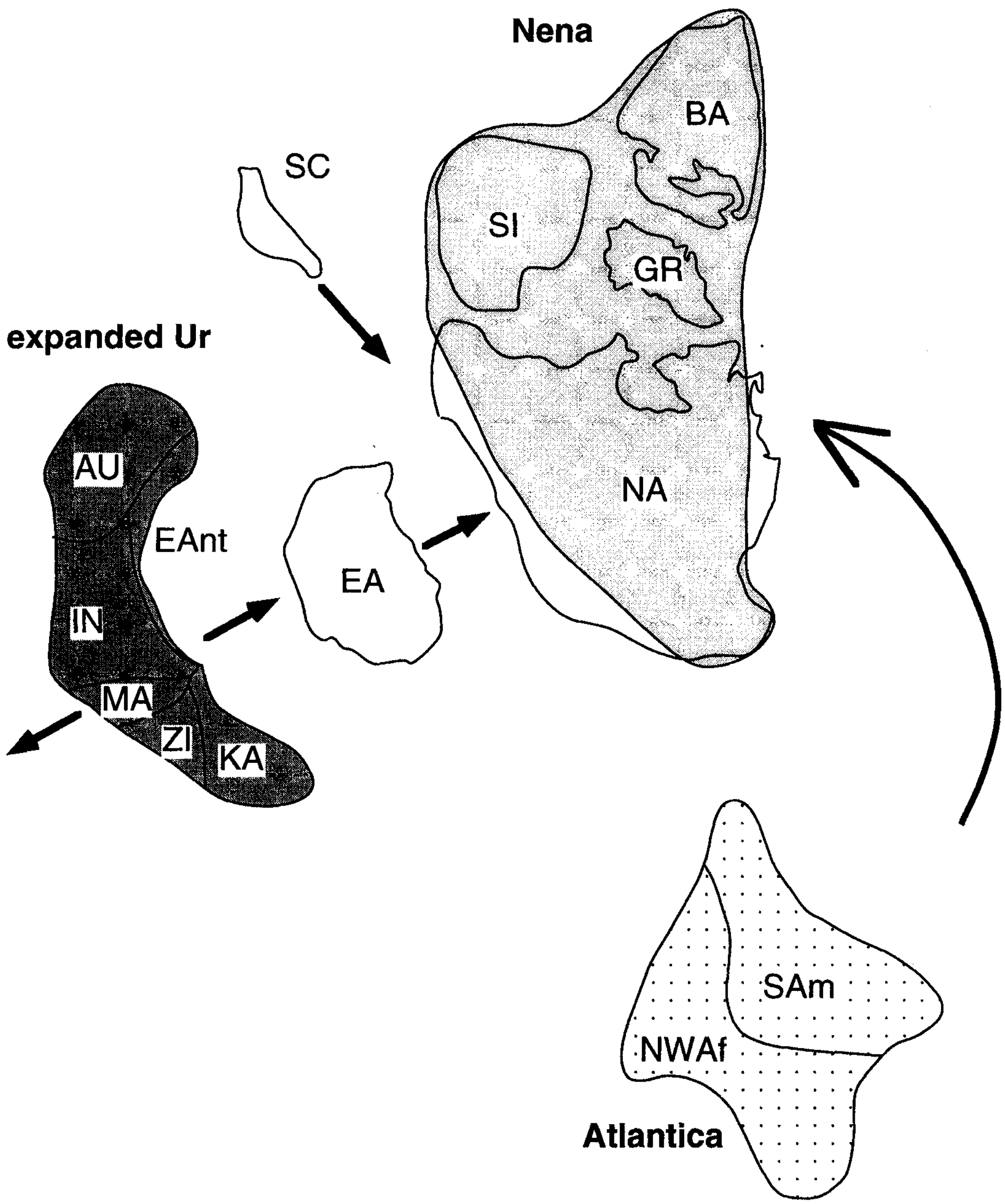

Fig. 9. Reorganization from Columbia to Rodinia. Symbols as in figure 6 plus: SC–South China; EA–part of East Antarctica inland from the coast.

assembly of eastern Australia against western Australia (Burrett and Berry, 2000, 2002).

Evidence of rifting around the margins of expanded Ur suggests that fragmentation of Columbia occurred from about 1.6 Ga to 1.4 Ga. Further breakup separated Atlantica (South America and Africa) from Nena in an uncertain time range that probably includes 1.5 Ga, although direct evidence for this event has not been found.

Overlap between the ages of compressional orogeny and ages of fragmentation show that the history of Columbia was more complex than accretion of the entire supercontinent followed by its rifting apart. Many studies of Rodinia and Pangea show similar overlap (e.g., Unrug, 1992), and it seems clear that the history of supercontinents follows three stages: (1) an initial period of accretion, (2) an intermediate period in which accretion continues in some areas while rifting begins in others and (3) a final period in which complete fragmentation is achieved. Presumably a 'maximum packing' of continental blocks is achieved at some time during the intermediate period, and for Columbia we estimate that it occurred at about 1.5 Ga.

The assembly of Rodinia at ~1 Ga (Grenville time) involved fragments from Columbia plus one or two additional continental blocks (Fig. 9). The existing parts of South America and Africa (Atlantica) rotated from their position in Columbia and collided with eastern North America (Nena). Australia, India, and southern Africa (expanded Ur) moved away from their suture against North America, and the North China Craton was detached from the Baltic part of Nena. The newly stabilized South China block may have been sutured between the Canadian part of North America and eastern Australia (Li et al., 1995). According to the SWEAT connection (Moores, 1991), one margin of East Antarctica (Trans-Antarctic Mountains) was attached to western North America. The size of this Antarctic block (possibly 'Mawson continent') is unclear, but it could not have extended to most of coastal East Antarctica, which had been attached to India and Australia during the entire Proterozoic. Once East Antarctica, and possibly South China, were in place against the western North American part of Nena, Grenville-age suturing with expanded Ur completed the formation of Rodinia.

Summary

The supercontinent Columbia apparently accreted between approximately 1.9 Ga and 1.5 Ga. One suture was between western North America and an orogenic belt along the margins of eastern India, western Australia and attached parts of coastal East Antarctica. Columbia resembled Pangea, with one half of its margin undergoing continental outbuilding along southern Baltica, eastern and southern North America, and the western edge of the Amazon shield, and the other half of the margin divided between a zone of rifting and a zone of accretion of the rifted blocks. Separation beginning at ~1.6 Ga formed correlative rift valleys in India and North America and ultimately led to the fragmentation of Columbia and its reorganization to Rodinia.

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