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Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent

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Abstract

Available lithostratigraphic, tectonothermal, geochronological and paleomagnetic data from 2.1–1.8 Ga collisional orogens and related cratonic blocks around the world have established connections between South America and West Africa; Western Australia and South Africa; Laurentia and Baltica; Siberia and Laurentia; Laurentia and Central Australia; East Antarctica and Laurentia, and North China and India. These links are interpreted to indicate the presence of a supercontinent existing before Rodinia, referred to herein as Columbia, a name recently proposed by Rogers and Santosh [Gondwana Res. 5 (2002) 5] for a Paleo-Mesoproterozoic supercontinent. In this supercontinent, the Archean to Paleoproterozoic cratonic blocks were welded by the global 2.1–1.8 Ga collisional belts. The cratonic blocks in South America and West Africa were welded by the 2.1–2.0 Ga Transamazonian and Eburnean Orogens; the Kaapvaal and Zimbabwe Cratons in southern Africa were collided along the ~2.0 Ga Limpopo Belt; the cratonic blocks of Laurentia were sutured along the 1.9–1.8 Ga Trans-Hudson, Penokean, Taltson–Thelon, Wopmay, Ungava, Torngat and Nagssugtoqidian Orogens; the Kola, Karelia, Volgo–Uralia and Sarmatia (Ukrainian) Cratons in Baltica (Eastern Europe) were joined by the 1.9–1.8 Ga Kola–Karelia, Svecofennian, Volhyn–Central Russian and Pachelma Orogens; the Anabar and Aldan Cratons in Siberia were connected by the 1.9–1.8 Ga Akitkan and Central Aldan Orogens; the East Antarctica and an unknown continental block were joined by the Transantarctic Mountains Orogen; the South and North Indian Blocks were amalgamated along the Central Indian Tectonic Zone; and the Eastern and Western Blocks of the North China Craton were welded together by the ~1.85 Ga Trans-North China Orogen.The existence of Columbia is consistent with late Paleoproterozoic to Mesoproterozoic sedimentary and magmatic records. The ~2.0 Ga fluvio-deltaic deposits have been found in all cratonic blocks in South America and West Africa, and they are interpreted to have formed within foreland basins during the latest stage of the 2.1–2.0 Ga Transamazonian–Eburnean collisional event that resulted in the assembly of South America and West Africa. In Laurentia and Baltica, a 1.8–1.30 Ga subduction-related magmatic belt extends from Arizona through Colorado, Michigan, South Greenland, Sweden and Finland to western Russia. The occurrence of temporally and petrologically similar rocks across a distance of thousands of kilometers between these continents supports the existence of a Paleo-Mesoproterozoic supercontinent. Accretion, attenuation and final breakup of this supercontinent were associated with the emplacement of 1.6–1.2 Ga anorogenic anorthosite-mangerite-charnockite-

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rapakivi (AMCR) suites, 1.4–1.2 Ga mafic dyke swarms and the intrusion of kimberlite–lamproite–carbonatite suites throughout much of the supercontinent.

Keywords: collisional orogen; cratons; Paleo-Mesoproterozoic supercontinent; reconstruction

1. Introduction

The episodic character of orogenies since late Archean times has led to speculations that Phanerozoic-style plate tectonics can be applied to the Proterozoic, and that continental landmasses have periodically assembled and dispersed since the Paleoproterozoic as a result of plate convergence and separation (Hoffman, 1988, 1989a; Condie, 1989; Kröner and Layer, 1992; Van Kranendonk et al., 1993; Windley, 1993, 1995; Ledru et al., 1994). These speculations have provided a major stimulus to the reconstruction of ancient supercontinents, including Meso- to Neoproterozoic Rodinia, Neoproterozoic Pannotia/Gondwana and Paleozoic Pangea (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Li et al., 1995, 1996; Rogers, 1996; Unrug, 1996). These reconstructions have revealed that global-scale collisional orogenies (e.g. Mesoproterozoic Grenvillian and Phanerozoic Pan-African) resulted in the amalgamation of ancient continental fragments to form supercontinents. Therefore, the correlation of collisional orogens and the cratons they bound provides a means of establishing former linkages between separated blocks (Hoffman, 1991).

There is a broad agreement that the amalgamation of Meso- to Neoproterozoic Rodinia was completed by the global-scale Grenvillian Orogeny or its age-equivalent collisional events at ~ 1.0 Ga (Dalziel et al., 2000). However, in the current configuration of Rodinia (Fig. 1), most continental blocks welded by Grenville-aged orogens contain abundant evidence that these blocks are a collage of earlier tectonic events, for example, cratonic blocks within Laurentia, Siberia and Laurentia, East Antarctica and Laurentia, etc. Many of these blocks were amalgamated at 2.1–1.8 Ga, before the formation of Rodinia. Because the 2.1–1.8 Ga orogens have been recognized on nearly every continent, including the Transamazonian Orogen of South America, the Eburnean Orogen of West Africa, the Trans-Hudson Orogen and its age-equivalent orogens of North America, the Svecofennian and Kola–Karelia Orogens of northern Europe, the Akitan and Central Aldan Orogens of Siberia, the Capricorn Orogen of Western Australia, the Transantarctic Mountains Orogen of Antarctica, the Trans-North China Orogen in North China, etc. (Fig. 2), it may be that they represent the fragments of an older supercontinent that formed in response to global-scale collision at this time.

To test this hypothesis, we undertake the first major review of the 2.1–1.8 Ga orogens around the world, to examine whether these developed as a result of amalgamation of cratonic blocks. We then summarize connections established for these orogens based on the available lithostratigraphic, tectonothermal, geochronological and paleomagnetic data, to make a preliminary evaluation of whether there was a pre-Rodinia supercontinent.

2. Review of major 2.1–1.8 Ga orogens

2.1. The Transamazonian Orogen in South America

The Archean–Paleoproterozoic blocks in South America include the Guiana, Central Brazil, São Luis, São Francisco and Rio de la Plata Cratons (Fig. 3). The Transamazonian Orogen is mostly exposed in the northeastern part of the Guiana Craton and the eastern part of the São Francisco Craton or as inliers within the Pan-African/Brasiliano mobile belts (Fig. 3; Swapp and Onstott, 1989; Bertrand and Jardim de Sá, 1990; Ledru et al., 1994; Alkmim and Marshak, 1998). The orogen consists of reworked Archean basement and Paleoproterozoic fold belts. The Archean basement comprises 3.4–2.9 Ga TTG gneisses/migmatites complex and voluminous 2.8–2.6 Ga Late Archean plutons and greenstones (Barosa, 1989; Alkmim and Marshak, 1998). The Paleoproterozoic fold belts consist mostly of 2.5–2.0 Ga supracrustals, including basal shelf-type formations, thick turbidite–flysch deposits and volcanics, and 2.1–1.9 Ga syn-tectonic granites (Bertrand and Jardim de Sá, 1990). Both the Archean basement

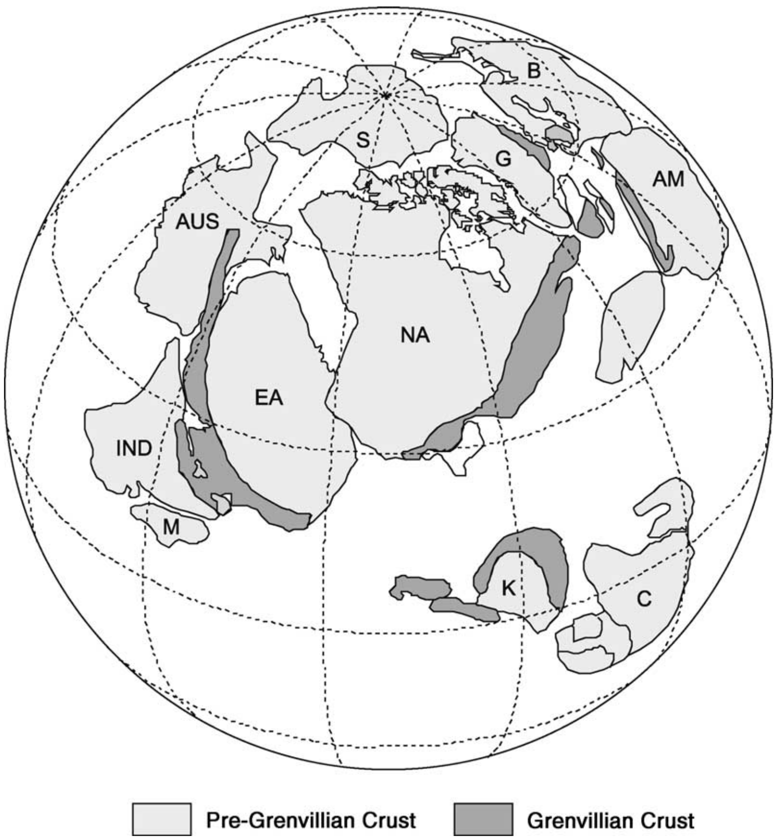


Fig. 1. Reconstruction of the hypothetical Rodinia Supercontinent of ~1000–750 Ma, as in Dalziel et al. (2000). Abbreviations: AM—Amazonia; Aus—Australia; B—Baltica (including Eastern Europe); C—Congo Craton; EA—East Antarctica; G—Greenland; IND—India; K—Kalahari Block; M—Madagascar; NA—North America; RP—Rio de la Plata; S—Siberia.

rocks and the Paleoproterozoic supracrustals have been reworked to different degrees during the Transamazonian Orogeny. The Archean basement rocks were strongly remobilized and underwent granulite facies metamorphism between 2.15 and 2.08 Ga (Ledru et al., 1994). The Paleoproterozoic supracrustal rocks in the eastern part of the São Francisco Craton underwent greenschist to granulite facies metamorphism associated with large-scale northwest-directed thrusting (Ledru et al., 1994). Alkmim and Marshak (1998) recognized two sets of Transamazonian structures in the southern São Francisco Craton. The first set, represented by northwest-verging thrusts and approximately north–south-trending sinistral strike-slip faults affecting supracrustal sequences, developed as a fold-thrust belt setting shortly after 2.1 Ga, during the closure of a passive-margin basin that had been initiated along the margins of the São Francisco Craton. The second set is represented by dome-and-keel structures that reflect the consequence of orogenic collapse during uplift and exhumation. The Paleoproterozoic units along the northern part of the Guiana Craton were involved in collision tectonics marked essentially by the northward thrusting of high-grade rocks in the southern part of French Guiana and the development of a ubiquitous first foliation (Ledru et al., 1994). Later, these Paleoproterozoic units were involved in transcurrent tectonics that caused major E–W to NW–SE sinistral strike-slip ductile faults and the development of a second foliation in the vicinity of the ductile shear zone (Ledru et al., 1994). Swapp and Onstott (1989) identified three metamorphic stages from the Transamazonian granulites of the Imataca Complex: prograde, peak and decompression metamorphism. The

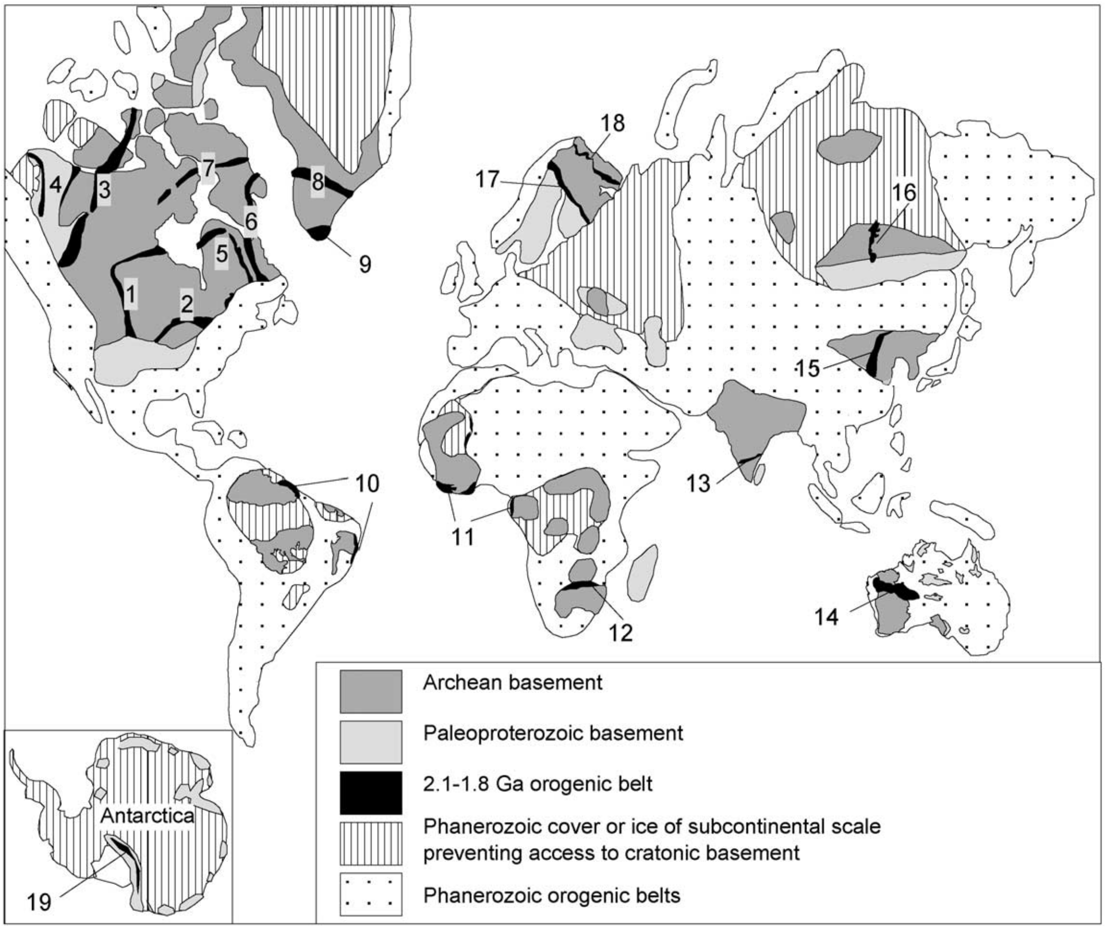


Fig. 2. Spatial distribution of 2.1–1.8 Ga orogens and associated Archean cratons. 1—Trans-Hudson Orogen; 2—Penokean Orogen; 3—Taltson–Thelon Orogen; 4—Wopmay Orogen; 5—Cape Smith–New Quebec Orogen; 6—Torngat Orogen; 7—Foxe Orogen; 8—Nagssugtoqidian Orogen; 9—Makkovikian—Ketilidian Orogen; 10—Transamazonian Orogen; 11—Eburnian Orogen; 12—Limpopo Belt; 13—Moyar Belt; 14—Capricorn Orogen; 15—Trans-North China Orogen; 16—Central Aldan Belt; 17—Svecofennian Orogen; 18—Kola–Karelian Orogen; 19—Transantarctic Orogen.

quantitative $P–T$ estimates for the peak and decompression stages define a nearly isothermal decompression $P–T$ path (Swapp and Onstott, 1989). Barosa (1989) also established a similar clockwise, nearly isothermal decompression, $P–T–t$ path for the Transamazonian granulites in the São Francisco Craton, which was considered to result from collisional tectonics (Barosa, 1989).

2.2. The Eburnean Orogen in West Africa

The Archean–Paleoproterozoic basement in West Africa consists of two major cratonic blocks, called the West African and Congo Cratons. The Eburnean orogen is extensively exposed in the southwestern and southern parts of the Western African Craton, represented by the Birimian Formation, and in the western part of Congo Craton, represented by the Ogooué Formation (Fig. 4).

The geometry and deformation of the Birimian Formation are controlled by both the early tangential tectonics and the later transcurrent tectonics (Ledru et al., 1994). The former is mainly characterized by major thrusts and nearly north–south-trending sinistral strike-slip faults along the southwestern and southern margins of the West African Craton (Fig. 4;

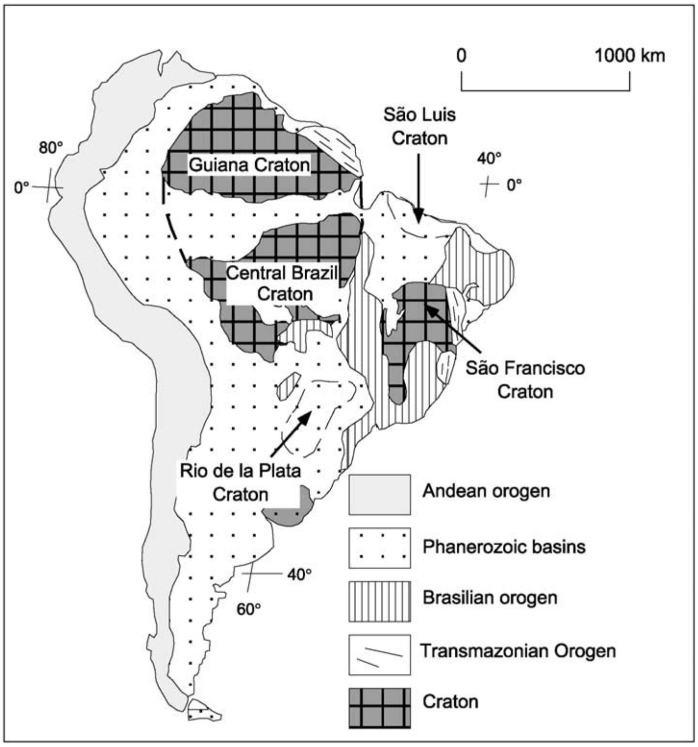


Fig. 3. Main tectonic units of South America (after Alkmim and Marshak, 1998). The Rio de la Plata Craton is dashed because it is poorly exposed.

Feybesse and Milesi, 1994; Ledru et al., 1994), whereas the latter is represented by later NE–SW dextral shear zones, which are widely developed and interfere with the early N–S-trending sinistral strike-slip faults in the southeastern part of the West African Craton (Fig. 4; Ledru et al., 1994). This evolution from an early tangential tectonics to a dominantly transcurrent tectonics is classical in collision tectonics and underlines the oblique character of the collision, at least during the last stages (Ledru et al., 1994). A linear gravity anomaly that underlies the northern part of the Birimian Formation also supports a collisional origin (Bertrand and Jardim de Sá, 1990).

In the Congo Craton, the Ogooué Formation crops out along the western margin (Fig. 4), and includes micaschist and gneiss derived from sedimentary and volcanic rocks. The collisional tectonics of the Ogooué Formation is characterized by large east-verging thrusts in its eastern part and the development of approximately N–S-trending sinistral strike-slip faults (Ledru et al., 1989). Associated with the thrusting and major nappe emplacement was amphibolite to granulite facies metamorphism (Ledru et al., 1989). The mineral assemblages of pelitic rocks from the Ogooué Formation and their P–T estimates define a clockwise P–T–t path with nearly isothermal decompression, which is considered to have resulted from the collision of the Congo Craton in Africa and the São Francisco Craton in South America (Ledru et al., 1989, 1994).

2.3. The Limpopo Belt in Southern Africa

South Africa can be divided into two older (>2.5 Ga) cratonic domains—the Kaapvaal and Zimbabwe Cratons in the eastern half and two younger (<2.5 Ga) cratonic domains—the Angola and Maltahöhe Cratons in the western half (Fig. 5; Anhaeuser, 1990). Separating these cratons are mobile belts: the Limpopo Belt between the Kaapvaal and Zimbabwe

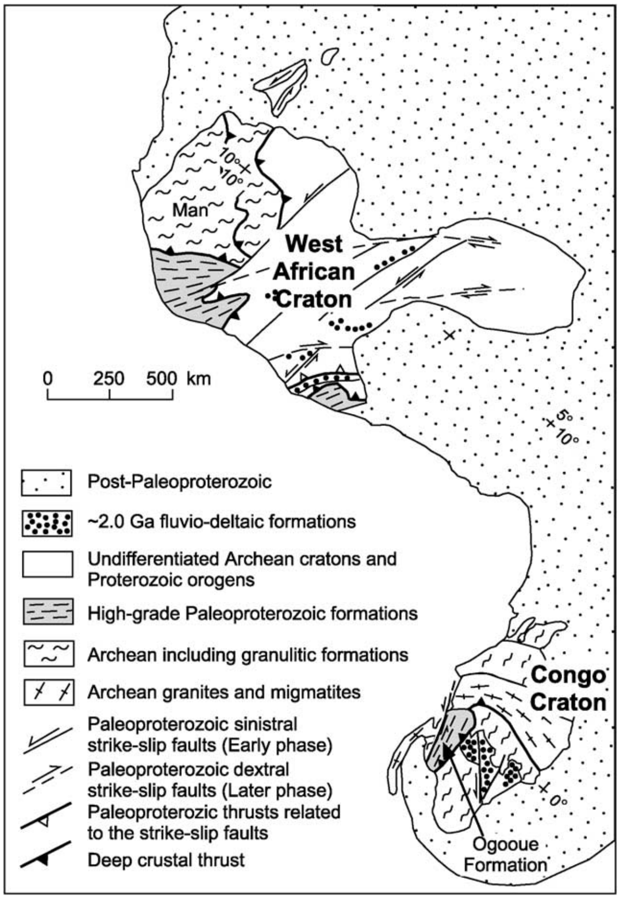


Fig. 4. Tectonic map of West Africa showing the Archean West African and Congo–Chailu Cratons and Paleoproterozoic Eburnian Orogens.

Cratons, and the Damara Belt between the Angola and Maltahöhe Cratons (Fig. 5).

The Limpopo Belt is a high-grade metamorphic orogen that has an ENE–WSW elongation of about 650 km and a width of 200 km. The belt itself has conventionally been subdivided into three zones, a central zone bordered more or less symmetrically by the northern and southern marginal zones, which abut the southern edge of the Zimbabwe Craton and the northern edge of the Kaapvaal Craton, respectively. These zones are separated from each other, and also from the adjacent cratons, by prominent terrane boundaries (Van Reenen et al., 1990; Holzer et al., 1998). The northern marginal zone, interpreted to be reworked granite–greenstone lithologies of the Zimbabwe Craton, is separated from the craton and the central zone by southerly dipping shear zones (Anhaeuser, 1990; Van Reenen et al., 1990). The southern marginal zone, interpreted to be the high-grade equivalents of the adjacent granite–greenstone terrane of the Kaapvaal Craton, is separated from the central zone by the dip-northward Palala shear zone and from the Kaapvaal Craton by the Proterozoic Soutpansberg and Waterberg sediments.

The Limpopo Belt is frequently referred to as a classic example of an Archean collisional belt, resulting from the collision of the Kaapvaal and Zimbabwe Cratons at 2.6 Ga ago (Light, 1982; Van Reenen et al., 1990; Anhaeuser, 1990). Light (1982) proposed that the Kaapvaal and Zimbabwe Cratons may have been separated by more than 1000 km of Limpopo oceanic crust and that this crust was subducted beneath the

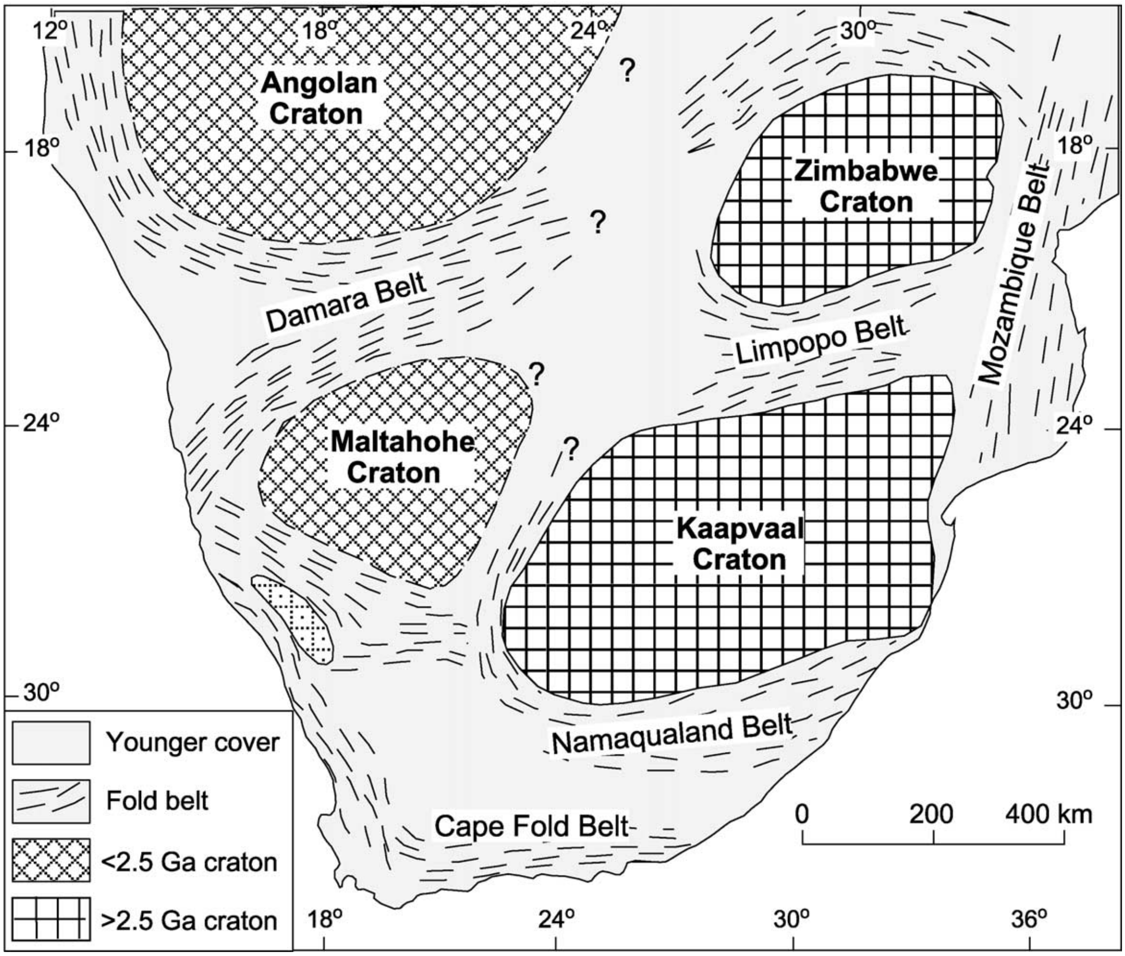


Fig. 5. Simplified geological map showing the main crustal provinces in South Africa, including main cratons and mobile belts (after Anhaeuser, 1990).

Kaapvaal Craton before 2.6 Ga, with the Limpopo Belt formed when the two cratons collided at ∼ 2.6 Ga. Recently, however, a ∼ 2.0–1.9 Ga tectonothermal event was revealed by directly dating garnet, clinopyroxene and titanite using the Pb–Pb and Sm–Nd garnet chronometers and the Ar–Ar step heating technique for amphibole (Kamber et al., 1995), the Pb stepwise leaching for metamorphic minerals (Holzer et al., 1998) and the SHRIMP zircon U–Pb technique (Kröner et al., 1999). Together with lithological, structural and metamorphic data and previously published ages, these new results lead to a reinterpretation of the tectono-metamorphic history of the Limpopo Belt, with the main phase of collision between the Zimbabwe and Kaapvaal cratons occurring between 2.0 and 1.9 Ga. The Late Archean (∼ 2.6–2.5 Ga) low-pressure granulite facies metamorphism of the belt is characterized by a near-isobaric cooling anticlockwise P–T evolution, which reflects deep crustal processes associated with underplating and intrusion of mantle-derived magmas, contemporaneous with vertical crustal growth of the Kaapvaal and Zimbabwe Cratons around 2.6–2.5 Ga, whereas the Paleoproterozoic (∼ 2.0–1.9 Ga) high-pressure granulite facies metamorphism is characterized by a near-isothermal decompression clockwise P–T evolution, involving initial crustal thickening followed by uplift/exhumation, which was caused by Himalayan-style collision of the Kaapvaal and Zimbabwe Cratons (Holzer et al., 1998).

2.4. The Capricorn Orogen in West Australia

The 2.0–1.9 Ga Capricorn Orogen lies between the Yilgarn and Pilbara Cratons which consist predominantly of granites, greenstones and granitic gneisses that formed between 3.7 and 2.6 Ga (Fig. 6; Barley, 1997; Myers and Swagers, 1997; Van Kranendonk and Collins, 1998). On both the southern and northern sides of the orogen, there are Paleoproterozoic ultramafic rocks, tholeiitic basalts, siliciclastics, banded iron formations and carbonates, which are interpreted as forming in a proto-oceanic back-arc setting to retro-arc foreland basin (Myers, 1990). The 2.0–1.9 Ga convergence and continued collision of the Yilgarn and Pilbara cratons resulted in the inversion of the basins, burial metamorphism and multiple progressive compressional deformation (Occhipinti et al., 1998). Smithies and Bagas (1997) establish a steeply decompressive clockwise P–T–t path for the Paleoproterozoic Rudall Complex, which is situated to the southeast margin of the Pilbara Craton and may represent the eastern extension of the Capricorn Orogen. This decompressive clockwise P–T–t path is interpreted to record the thermal history of collision between the Pilbara Craton to the northwest and another continental block (Yilgarn?) to the southeast (Smithies and Bagas, 1997).

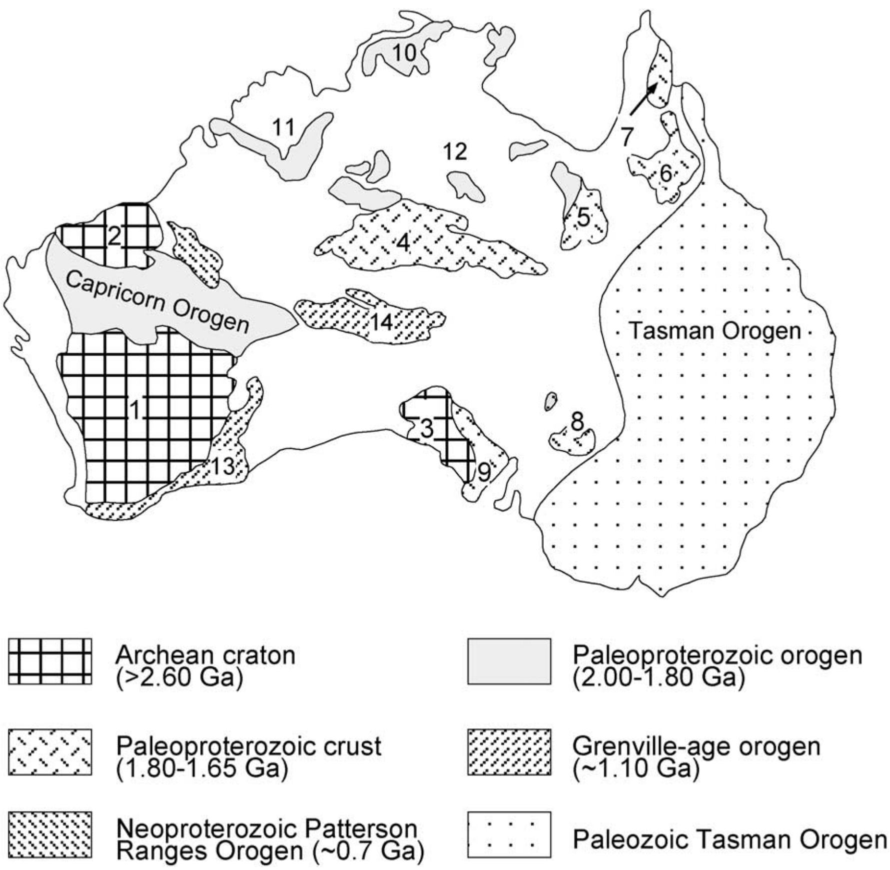


Fig. 6. Precambrian domains in Australia, modified after Myers et al. (1996). 1, Yilgarn Craton; 2, Pilbara Craton; 3, Gawler Craton; 4; Arunta Inlier; 5, Mt. Isa Inlier; 6, Georgetown Inlier; 7, Coen Inlier; 8, Willyama Inlier; 9, Gawler Inlier (1.80–1.65 Ga); 10, Pine Creek Orogen; 11, Halls Creek Orogen; 12, Tennant Creek Inlier; 13, Albany–Fraser Orogen; 14, Musgrave Block.

2.5. Paleoproterozoic orogens in North America

In North America, several Paleoproterozoic orogens surround the Archean Superior, Hearne, Rae, Slave and Wyoming Cratons. These orogens formed between 2.0 and 1.8 Ga and developed as a result of collisions between the abovementioned Archean cratons (Hoffman, 1988, 1989b; Van Kranendonk et al., 1993).

The Trans-Hudson Orogen, the largest and best-exposed Paleoproterozoic orogenic belt in North America, welds together the Archean Superior Province in the southeast and the Rae and Hearne Provinces to the northwest (Fig. 7; Hoffman, 1988, 1989b). The Archean rocks of the Superior, Rae and Hearne Cratons are composed predominantly of 3.0–2.6 Ga low-grade greenstone belts and intrusive granitoids, high-grade gneisses, and clastic sedimentary rocks (Hoffman, 1988). The Trans-Hudson Orogen consists of four principal tectonic domains: Thompson belt, Reindeer zone, Wathaman–Chipewyan batholith and Creek Lake zone (Lucas et al., 1993). Stauffer (1984) proposed that the Reindeer zone represents the closure of a Paleoproterozoic ocean, called the Manikewan Ocean, which separated the Superior and Hearne Cratons which was closed by the collision of the Superior and Hearne Cratons at 1.9–1.8 Ga. Recent paleomagnetic data estimate a 'north–south' width of about 4000 km for the Manikewan Ocean. Isotopic data indicate that oceanic

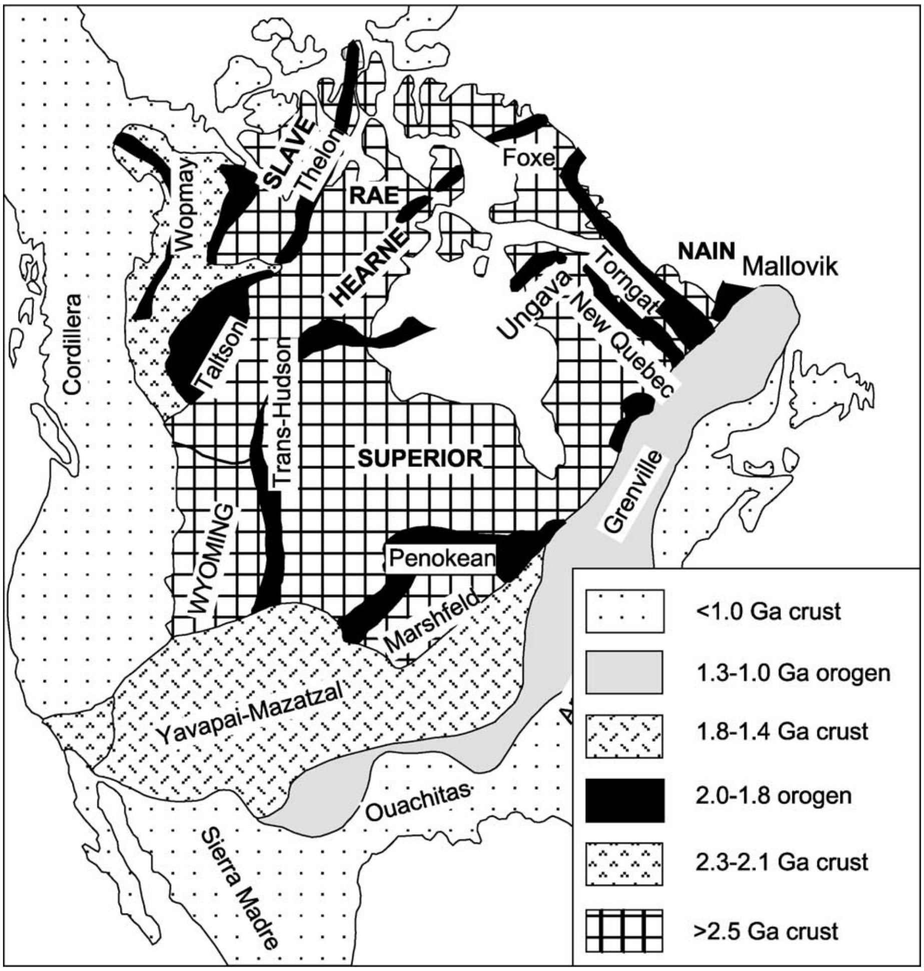


Fig. 7. Schematic tectonic map of North America (after Hoffman, 1988, 1989b).

spreading was initiated about 2.1–2.0 Ga (St-Onge et al., 1992), convergent margin arc magmatism and arc accretion occurred between 1.91 and 1.83 Ga ago (Bickford et al., 1990), and that terminal collision of accreted arcs and the Hearne with the Superior Craton occurred between 1.83 and 1.81 Ga ago (Gordon et al., 1990).

The 1.9–1.8 Ga Penokean Orogen lies along the southern boundary of the Superior Craton, separating it from the Marshfield terrane (Fig. 7). It can be divided into northern, medial and southern belts. The northern belt consists of reworked Archean basement rocks of the Superior Craton and a Paleoproterozoic continental marginal accretionary prism, whereas the medial belt represents an intraoceanic magmatic arc terrane. The southern belt represents an exotic terrane, comprising 3.0–2.8 Ga gneisses which were intruded by 1.9–1.8 Ga tonalites and overlain by Paleoproterozoic volcanic and sedimentary rocks (Windley, 1992). The northern and southern belts are separated from the medial belt by the Niagara and Eau Pleine sutures, respectively (Holm et al., 1988; Hoffman, 1989b; Windley, 1992). Structural investigations reveal multiple deformation and northward-directed nappes during the Penokean orogeny (Holm et al., 1988). Prograde metamorphism occurred simultaneously with early deformation, and peak metamorphism was associated with uplift and exhumation, characterized by increasing temperature associated with decreasing pressure (Holm et al., 1988). This metamorphic evolution is considered to document the tectonothermal history of collision between the northern Archean Superior Craton and the Mashfeld terrane (Holm et al., 1988; Windley, 1992).

The Taltson–Thelon Orogen formed as a result of collision between the Archean Slave and Rae Cratons (Fig. 7; Hoffman, 1988, 1989b). The orogen is composed of three rock assemblages: a 3.2–2.9 Ga reworked basement complex, 2.4–1.9 Ga metasedimentary rocks and 2.0–1.9 Ga granitic plutons. The reworked basement complex represents fragments of the Rae or Slave Craton (Grover et al., 1997), whereas the widespread granitic magmatism occurring between 2.0 and 1.9 Ga is interpreted to indicate an Early Paleoproterozoic magmatic arc related to the subduction of the Slave Craton along an eastward-dipping subduction zone (Hoffman, 1988). The metasedimentary rocks, although volumetrically subordinate, are distributed throughout the orogen and are considered to have been deposited in pre-collisional basins between the Rae and Slave Cratons (Grover et al., 1997). The metamorphic evolution of the Taltson–Thelon Orogen is characterized by high-T granulite-facies peak metamorphism, followed by amphibolite- and greenschist-facies metamorphism, with a clockwise P–T–t path, which is attributed to a combination of both mantle-derived magma and tectonic thickening that resulted from collision of the Slave and Rae Cratons (Grover et al., 1997).

The Wopmay Orogen was a short-lived, 1.95- to 1.84-Ga, belt in NW Canada that developed as a result of collision between the Archean Slave Craton and the Hottah terrane of the Nahanni continental block (Fig. 7; Hoffman and Bowring, 1984). The orogen is made up of three major Paleoproterozoic tectonic units. On the east is the Coronation Supergroup, which represents a 1900–1800 Ma depositional prism on the western margin of the Slave Craton (Hoffman and Bowring, 1984). To the west is the Hottah terrane, a geochronologically exotic metamorphic–plutonic complex inferred to have collided with the Coronation Supergroup at the time of thrusting (Hoffman and Bowring, 1984). Between them is the 100-km-wide Great Bear magmatic zone; a 1875–1840 Ma continental volcano-plutonic arc which is interpreted as the product of eastward subduction of oceanic lithosphere beneath the western margin of the Hottah terrane following its collision with the Slave Province (Hoffman and Bowring, 1984).

In the northeastern part of North America, there are a number of narrow Paleoproterozoic mobile belts, including the New Quebec, Foxe, Makkovik, Ungava and Torngat Orogens (Fig. 7). Here we briefly describe the last two orogens as examples for evaluating the principal features of these orogens.

The Ungava Orogen of northern Quebec is interpreted as a Paleoproterozoic continental–arc–continental collisional belt joining the southeast Rae Craton, Narsajuq arc (Cape Smith Belt) and Northeast Superior Craton (Van Kranendonk et al., 1993; St-Onge et al., 2001). It comprises three tectonic units: (1) parautochthonous reworked Archean (3.22–2.74 Ga) basement of the Superior Craton; (2) autochthonous and allochthonous Paleoproterozoic (2.04–1.92 Ga) sedimentary and volcanic units (Povungnituk and Chukotat Groups); and (3) an allochthonous Paleoproterozoic (~ 2.0 Ga) oceanic assemblage interpreted as an ophiolite suite, represented by Watts Group (St-Onge et al., 2001). The reworked Archean portion corresponds to the lower plate, whereas units (2) and (3) correspond to the collisional upper plate (St-Onge et al., 2001). Convergence and juxtaposition of these tectonic units were accommodated by a thrust fault system that was SW-vergent (St-Onge et al., 2001). The metamorphic evolution of the orogen is characterized by a clockwise P–T path, interpreted as a consequence of decompression and relaxation of isotherms in the thickened crust caused by collision between the Superior Craton and the allochthonous oceanic and arc terranes (St-Onge et al., 2001).

The Paleoproterozoic Torngat Orogen in northern Labrador developed through collision between the Archean Rae and Nain Cratons (Fig. 7; Bertrand et al., 1993; Van Kranendonk, 1996; Van Kranendonk and Wardle, 1996, 1997). It consists predominantly of reworked basement gneisses overlain unconformably by Paleoproterozoic magmatic arc rocks and supracrustal rocks metamorphosed from sub-greenschist to granulite facies, represented by the Lake Harbour, Ramah, Mugford and Ingrid Groups. Detailed geochronology has revealed that Paleoproterozoic arc magmatism took place at 1910–1885 Ma, followed by collision and initial crustal thickening at 1.87–1.86 Ga (Bertrand et al., 1993; Van Kranendonk and Wardle, 1996). Subsequent sinistral shearing occurred at 1845–1822 Ma (Bertrand et al., 1993) under post-peak metamorphic conditions (Van Kranendonk, 1996; Van Kranendonk and Wardle, 1996), and the orogen was partially reworked in an event involving east-directed thrusting in response to collision of the Rae and Superior Cratons across the New Quebec Orogen (Wardle and Van Kranendonk, 1996).

2.6. Paleoproterozoic orogens in Greenland

In Greenland, there are two major Paleoproterozoic orogens surrounding the Early to Late Archean (3.9–2.5 Ga) North Atlantic (Nain) Craton: the ca. 2.0–1.8 Ga Nagssugtoqidian belt to the north and the ca. 1.88–1.74 Ga Ketilidian belt to the south (Fig. 8). These orogens developed as a result of collision between the North Atlantic Craton with other continental blocks (Bridgwater et al., 1990; Van Kranendonk et al., 1993; Park, 1995; Whitehouse et al., 1998).

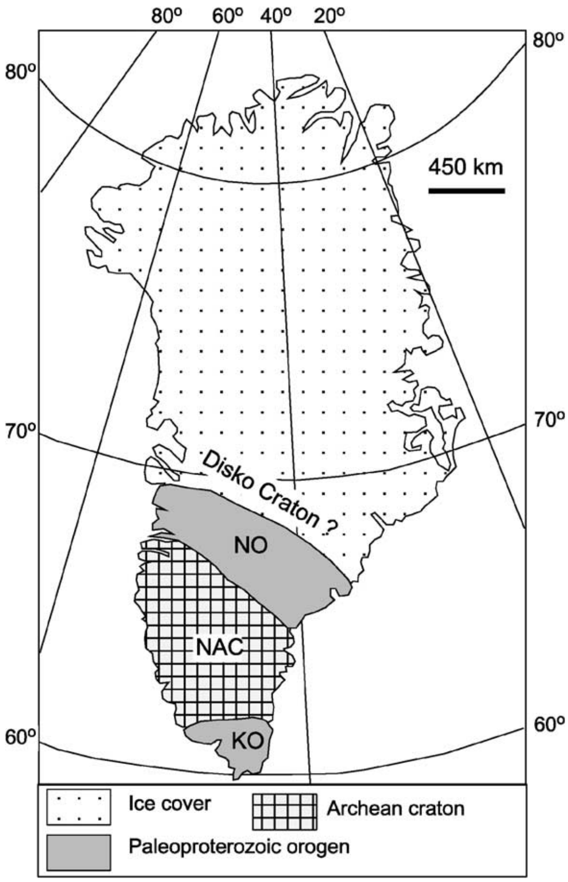


Fig. 8. Distribution of the Archean North Atlantic Craton and Paleoproterozoic Nagssugtoqidian and Ketilidian Orogens. Symbols: NO = Nagssugtoqidian Orogen; NAC = North Atlantic Craton; KO = Ketilidian Orogen.

The Paleoproterozoic Nagssugtoqidian Orogen is an east–west trending belt, developed within the northern margin of the North Atlantic Craton. The orogen can be divided into three units: the Southern, Central and Northern Nagssugtoqidian Orogen (SNO, CNO and NNO, respectively; Whitehouse et al., 1998). The SNO is composed dominantly of 2.85–2.70 Ga Archean gneisses, representing reworked Archean basement of the North Atlantic Craton (Whitehouse et al., 1998). The CNO consists of Paleoproterozoic (2.04–1.80 Ga) metasedimentary rocks, ~ 1.92 Ga calc-alkaline quartz diorites and tonalites, ~ 1.92 Ga charnockites (Sisimiut charnockites) and 1.84–1.80 Ga pink granites (Kalsbeek and Nutman, 1996). These rocks underwent intense polyphase deformation and mylonization along the Nordre Strømfjord shear zone, which can be followed from the west coast over a distance of some 150 km to the Inland Ice. The NNO comprises K-rich Archean granitic gneisses, representing reworked components of a northern cryptic Archean block (Disko Craton), covered by ice in Central and North Greenland (Kalsbeek et al., 1987; Van Kranendonk et al., 1993). The crustal-scale Nordre Strømfjord shear zone in the center of the belt has been interpreted as a suture between the North Atlantic and Disko Cratons (Kalsbeek et al., 1987). Geochronological data indicate that subduction started before ~ 1.92 Ga ago, and lasted until ~ 1.85 Ga when collision occurred, with consequent crustal thickening, high-grade metamorphism and polyphase deformation (Kalsbeek and Nutman, 1996; Whitehouse et al., 1998).

The Paleoproterozoic Ketilidian Orogen lies on the southern margin of the North Atlantic Craton (Fig. 8) and can be divided into four zones, which are from north to south: the Board Zone, the Juliannehaab Batholith, the Psammite Zone and the Pelite Zone (Chadwick and Garde, 1996). The Board Zone consists predominantly of volcano-sedimentary rocks that lie unconformably on the North Atlantic Craton and may have been deposited in a continental foreland setting (Windley, 1992; Chadwick and Garde, 1996; Hamilton, 1997). The Juliannehaab Batholith, separated from the Board Zone by the Kobberminebugt suture zone (Windley, 1992; Chadwick and Garde, 1996), is composed of calc-alkaline granitoids, interpreted to have formed in an Andean-type setting (Watterson, 1978). Pb–Pb and Rb–Sr isotopic age data show that the granitoids in the Juliannehaab Batholith were emplaced episodically within the period 1854–1796 Ma (Chadwick and Garde, 1996; Hamilton, 1997). The Psammite and Pelite Zones, separated from the Juliannehaab Batholith by a shear zone, consist largely of metamorphosed psammitic, semipelitic and pelitic gneisses and schists and a post-tectonic rapakivi granite suite that has an age range of 1.75–1.74 Ga (Gulson and Krogh, 1974). These rocks were deposited in intra-arc between the volcanic to the north and an ocean to the south (Chadwick and Garde, 1996). U–Pb isotopic data indicate that deposition of the psammites took place at ~ 1793 Ma (Hamilton, 1997). Structural evidence reveals the existence of northward-directed sub-horizontal thrust nappes along the Kobberminebugt suture zone (Windley, 1992). U–Pb zircon data obtained from a series of thin appinite sheets, coplanar with neosomal layers which are axial planar to D1/D2 deformation fabrics, give ages between ~ 1793 and 1783 Ma (Hamilton, 1997). The timing of later D3 has been constrained by syn-D3 neosomes that were dated at 1784 ± 2 Ma (Hamilton, 1997). Most supracrustal metasediments from the thrust nappes experienced amphibolite to granulite facies metamorphism, and the pelitic granulites contain various coronas, such as plagioclase + orthopyroxene, cordierite + orthopyroxene, cordierite + quartz and spinel + cordierite developed around garnet grains. These are indicative of decompression that may have resulted from uplift and exhumation following accretion of juvenile island arcs and slices of oceanic crust to the southern margin of the Archean North Atlantic Craton (Dempster et al., 1991).

2.7. Paleoproterozoic orogens in Baltica (Eastern Europe)

The Archean to Paleoproterozoic basement rocks in Baltica (Eastern Europe) are exposed mainly in two prominent shields: the Fennoscandian Shield in the northwest, and Ukrainian Shield in the southwest (Fig. 9). However, recent geophysical data from continental drilling, reflection seismic and aeromagnetic surveys have revealed extensive Archean basement and Paleoproterozoic accretional and collisional orogens beneath the eastern European platform (Bogdanova, 1993, 1999). These data have led to a new three-fold subdivision for the basement of Eastern Europe (Bogdanova, 1993). According to this scheme, the basement of Eastern Europe is made up of the Fennoscandia, Sarmatia and Volgo–Uralia segments (Bogdanova, 1993), which underwent different Archean to Paleoproterozoic evolutionary histories and were brought together along the Paleoproterozoic Volhyn–Central Russian and Pachemel Orogens at 1.9–1.8 Ga (Fig. 9; Bogdanova, 1999). As the basement of Volgo–Uralia and Sarmatia is largely buried beneath a Phanerozoic platform cover, ranging from tens to thousands of meters in thickness, information on the Archean to Paleoproterozoic geology of these two segments is limited and so this review focuses on

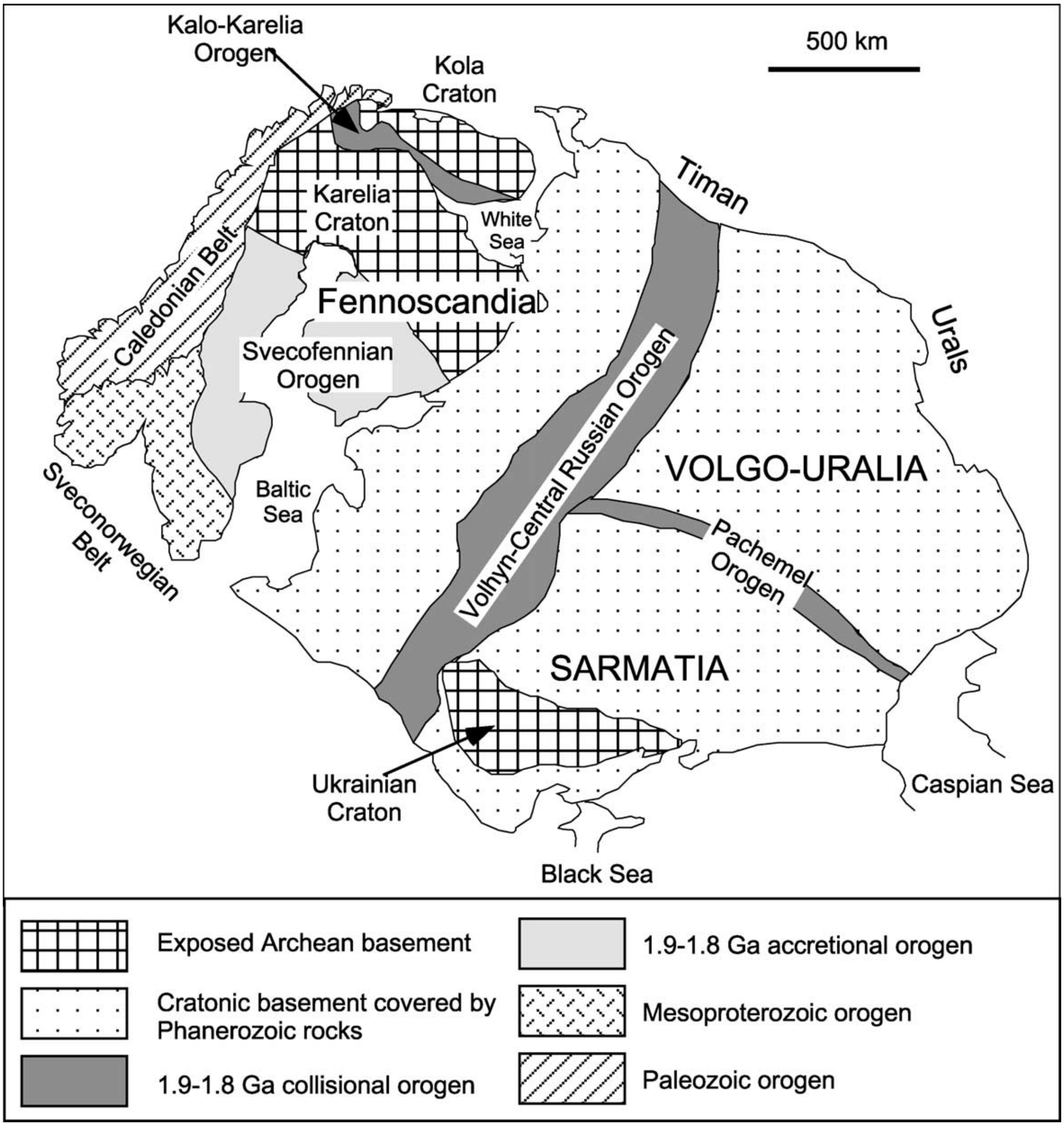


Fig. 9. Simplified geological map showing the major tectonic units in Baltica (including Eastern Europe; revised after Bogdanova, 1993).

the better-known Paleoproterozoic orogens in Fennoscandia.

Fennoscandia consists of two small Archean cratonic blocks, the Kola and Karelia Cratons, and two major Paleoproterozoic orogens, the Kola–Karelian (also known as Lapland–Kola) and Svecofennian Orogens (Fig. 9; Berthelsen and Makers, 1986; Daly et al., 2001). Both the Karelia and Kola Cratons are composed of 2.9–2.6 Ga high-grade gneisses and low-grade granite–greenstone belts. The Kola–Karelia Orogen lies between the two cratons, extending from northern Norway and Finland to the Kola Peninsula in Russia (Fig. 9). It consists of three coeval tectonic belts: the Kola suture belt, Lapland belt and Tanaelv belt, which occur successively from north to south in the eastern segment of the orogen, although the Archean Inari microcontinent separates the two former belts in the western segment (Berthelsen and Makers, 1986). The Kola suture belt is a ca. 500-km-long and ca. 2- to 40-km-wide belt that consistently dips gently to the southwest and is in thrust contact with the surrounding tectonic units. The belt is considered to include a passive continental margin formation along the southern margin of the Kola Craton and an island-arc formation at the northern margin of the Inari microcontinent (Fig. 10a), whereas the 2.36–1.90 Ga Tanaelv and Lapland Belts are considered to have formed in a back-arc environment, with the former consisting mainly of tholeiitic volcanic rocks and the latter consisting predominantly of sedimentary rocks (Fig. 10a; Berthelsen and Makers, 1986). Berthelsen and Makers (1986) proposed an ancient ocean (the Kola ocean) between the Kola Craton and the Inari microcontinent, with a southwest-plunging subduction zone beneath the northern margin of the Inari microcontinent (Fig. 10a). Due to continued subduction and complete consumption of this ocean (Fig. 10b), arc–continent and continent–continent collision occurred at ~ 1.9 Ga. The collision caused widespread thrusting of the Kola Suture Belt over the Kola Craton and the Tanaelv and Lapland Belts over the Karelia Craton, leading to the formation of the Fennoscandia Shield (Fig. 10b; Berthelsen and Makers, 1986).

The Svecofennian Orogen is located to the south of the Karelia Craton (Fig. 9), and is at least 1200 km wide, extending from Central Finland and Sweden southwards to beyond Estonia as far as the Tornquist zone in Poland. It is considered to be magmatic arc accretional orogen joining the Svecofennian arc terrane with the Archean Karelia Craton (Nironen, 1997). The orogen consists of two coeval (2.1–1.8 Ga) but lithologically and structurally different tectonic units: the Svecofennides in the southwest and the Karelides in the northeast. The Svecofennides

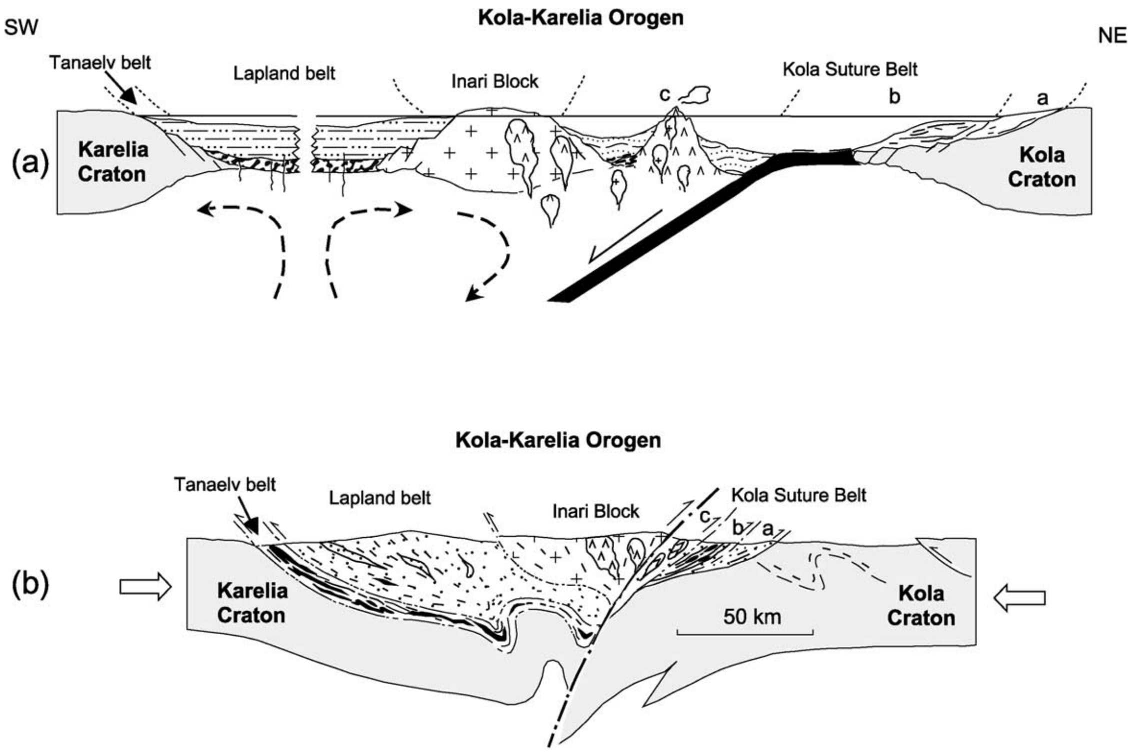


Fig. 10. Sections showing crustal structure and crustal evolution of the Kola–Karelia Orogen (from Berthelsen and Markers, 1986); (a) pre-collisional stage; (b) syn-collisional stage. See text for explanation.

represents a juvenile magmatic arc, whereas the Karelides is considered to have developed in a back-arc basin between the Svecofennian magmatic arc and the Archean Karelia Craton (Park, 1992; Windley, 1992; Nironen, 1997). Separating the Karelides from the Svecofennides is a large lineament zone, called the Luleå–Kuopio thrust zone, extending from the Gulf of Bothnia to Lake Ladoga. The thrust zone is marked by Ni–Cu sulfide-bearing, mafic to ultramafic intrusions, coincident with a positive gravity anomaly, and thus the zone is interpreted as a suture joining the Svecofennian arc terrane with the Karelian belt and the Archean Karelia Craton (Nironen, 1997).

2.8. Paleoproterozoic orogens in Siberia

The Archean to Paleoproterozoic rocks in Siberia are mainly exposed in the Aldan–Stanovik composite craton in the southeast, the Anabar Craton in the north, the Yenisey uplift along the southwest margin and the Akitkan Orogen in the southeast (Fig. 11a). The remainder is covered by Riphean, Vendianand Cambrian sedimentary rocks and the Permian–Triassic flood basalts (Fig. 11a). The Aldan–Stanovik composite craton comprises two major tectonic domains: (1) the Aldan Craton in the north and (2) the Stanovik Belt in the south, which are separated by the Stanovik shear zone (Fig. 11a,b). Both domains consist of 3.3–2.8 Ga granites and greenstones and 3.5–2.7 Ga high-grade gneisses that underwent a regional metamorphic event at ~ 2.7 Ga and then were extensively reworked at 2.0–1.8 Ga (Nutman et al., 1992; Rosen et al., 1994). The tectonic relationships between the Aldan Craton and the Stanovik Belt have not been well constrained. The Anabar Craton can be subdivided to a number of terranes, bounded by major shear zones (Rosen et al., 1994).

The Paleoproterozoic Akitkan Orogen, exposed only along the Baikal uplift, is considered to be a major Paleoproterozoic orogenic belt. Geophysical data suggest that the belt can be traced along strike for 1500 km and is 50–250 km wide (Fig. 11a). The orogen comprises Paleoproterozoic sedimentary and volcanic rocks metamorphosed from greenschist to amphibolite facies and deformed into narrow folds with a northeastern trend. These rocks are intruded by syntectonic granitoids with U–Pb zircon upper-intercept discordia ages of ~ 1.85 Ga (Rosen et al., 1994). Condie and Rosen (1994) proposed that the Akitkan Orogen represents a Paleoproterozoic collisional orogenic belt along which the Archean Anabar and Aldan–Stanovik Cratons were amalgamated to form the Siberia continental block at ~ 1.85 Ga.

The Aldan Craton is considered to have formed by amalgamation of several terrains along 1.9 Ga collisional orogenic belts (Rosen et al., 1994; Frost et al., 1998; Jahn et al., 1998). The craton has been divided into four shear-bounded terrains: the Olekma and Batomga granite–greenstone terrains to the west and east, and the intervening Aldan and Uchur high-grade gneiss belts (Fig. 11b; Frost et al., 1998). The north–south-trending Amga and Ulkan shear zones separate the Aldan and Uchur high-grade gneiss belt from the Olekma and Batomga granite–greenstone terrains, respectively (Fig. 11b). Thrusting along these shear zones occurred at ~ 1.9 Ga (Nutman et al., 1992;

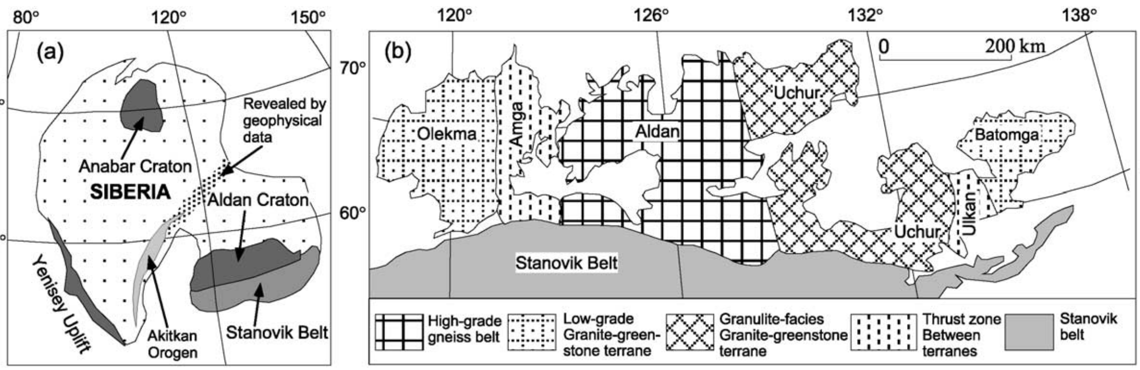


Fig. 11. Sketch map of (a) Siberia and (b) the Aldan Craton (after Frost et al., 1998).

Rosen et al., 1994; Frost et al., 1998). Some ~ 1.9 Ga retrograded eclogites have been found along the east-dipping Amga shear zone, indicating that ca. 30–40 km of crustal thickening occurred along this zone at 1.9 Ga when the Olekma and Batomga granite–greenstone terrains were amalgamated to form the Aldan Craton (Frost et al., 1998; Jahn et al., 1998).

2.9. Paleoproterozoic orogens in Central Australia

In Central Australia, Archean crust is only present in the Gawler Craton and in the Rum Jungle Complex of the Pine Creek Belt (Fig. 6; McCulloch, 1987), and the rest of the Precambrian inliers are dominated by 2.1–1.8 and 1.8–1.6 Ga orogenic belts or accretionary terranes (Myers et al., 1996). The 2.1–1.8 Ga orogens include the Pine Creek, Halls Creek, King Leopold and Tennant Creek belts in northern Australia (Fig. 6), and the basement of some inliers in central and southern Australia (e.g. the Arunta Inlier; Fig. 6). There is currently controversy concerning the tectonic nature of these 2.1–1.8 Ga orogenic belts, with some workers believing that the 2.1–1.8 Ga orogeny was essentially ensialic (Etheridge et al., 1987), whereas others interpret it as a consequence of collision between continental blocks (McCulloch, 1987; Windley, 1992; Myers et al., 1996). The 1.8–1.6 Ga orogenic belts and accretionary terranes in Central Australia include the Arunta, Willyama, Mount Isa, Coen and Georgetown Inliers. The Arunta Inlier is the largest high-grade metamorphic block in Central Australia, covering approximately 200,000 km^2. It comprises igneous and sedimentary rocks that unconformably overlie 2.1–1.8 Ga basement and was formed between 1.80 and 1.65 Ga. The available isotopic data indicate that the other metamorphic blocks in Central Australia have protolith and tectonothermal ages similar to those of the Arunta Inlier, although their lithological, structural and metamorphic histories are still poorly constrained.

2.10. Paleoproterozoic orogens in Antarctica

The Antarctic continent consists of two tectonic units, West and East Antarctica. West Antarctica comprises a series of allochthonous terranes that are interpreted to have been displaced from their original positions during the Paleozoic and Mesozoic (Moores, 1991), whereas East Antarctica contains distinct Precambrian lithotectonic units. Archean basement has only been reported from Enderby Land, Prince Charles Mountains and the Miller Ranger of the Transantarctic Mountains (Moores, 1991). However, the revised SWEAT reconstruction made by Borg and DePalo (1994), based on isotopic mapping, has led to a prediction of extensive Archean basement between the South Pole and Victoria Land. Paleoproterozoic (1.9–1.7 Ga) basement rocks, comprising sedimentary and igneous rocks metamorphosed from greenschist to granulite facies, are predominant in the Shackleton Mountains, Transantartic Mountains, King George V Land and Adélie Land, forming a nearly continuous north-trending belt extending ca. 3500 km (Moores, 1991; Borg and DePalo, 1994), which may represent a Paleoproterozoic collisional mobile belt welding the Archean basement of East Antarctica with the other continental block (Borg and DePalo, 1994).

2.11. The Central Indian Tectonic Zone in India

Recent data reveal that Archean to Paleoproterozoic basement in India can be roughly divided into two major cratonic blocks, namely the South and North Indian Blocks, separated by a linear Paleoproterozoic orogenic belt, named the Central Indian Tectonic Zone (Fig. 12; Yedekar et al., 1990; Jain et al., 1991; Mazumder et al., 2000). The South Indian Block, including the Dhawar, Bastar and Singhbhum Provinces, consists predominantly of early to late Archean TTG gneisses and supracrustal rocks (namely greenstone sequences) with minor Paleoproterozoic rift-related formations. The North Indian Block is a single crustal province, known as the Aravalli-Bundelkhand Province and consists predominantly of Archean basement gneisses and Paleoproterozoic volcanic and sedimentary rocks metamorphosed from amphibolite to granulite facies (Mazumder et al., 2000). Lying between the South and North Indian Blocks is the Central Indian Tectonic Zone, the eastern segment of which extends along the Satpura and Copper Belts, with the western segment buried beneath the Deccan plateau (Fig. 12). The zone is marked by a number of parallel ductile shears zones with a sinuous east–west trend and subvertical to steep northerly dips (Jain et al., 1991). The major lithologies are TTG gneisses, granitic intrusions and supracrustal rocks including quartzites,

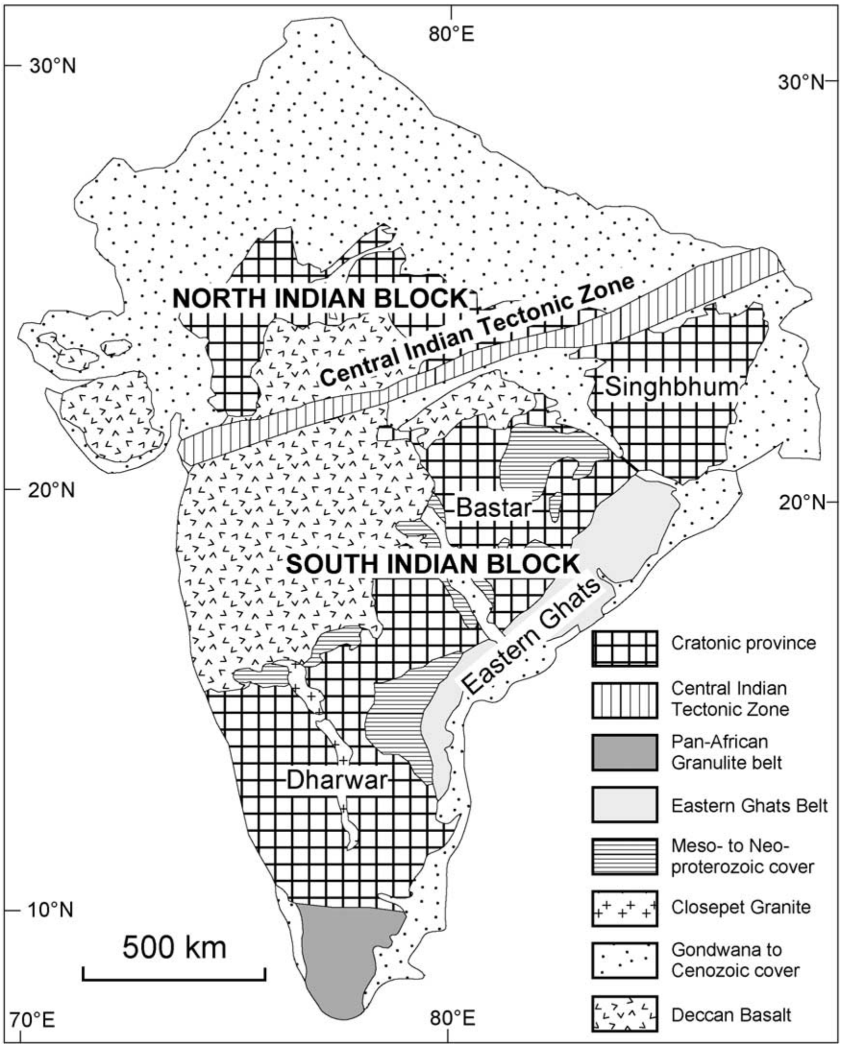


Fig. 12. Tectonic architecture of the Indian Shield, which can be divided into the South and North Indian Blocks, separated by the Central Indian Tectonic Zone (after Mazumder et al., 2000).

mica schists, paragneisses, BIFs, calc-silicates, marbles and basic to acid volcanics, ranging in age from late Archean to Proterozoic and metamorphosed from greenschist to granulite facies (Acharyya and Roy, 2000). Some high-pressure mafic granulites occur as enclaves or boudins within TTG gneisses and preserve mineral assemblages and P–T evolution reflecting initial crustal thickening followed by near-isothermal decompressional exhumation and final cooling (Bhowmik et al., 1999). This is interpreted to have resulted from collision between the South and North Indian Blocks to form the Indian Craton during a poorly defined period between 2.1 and 1.7 Ga (Bhowmik et al., 1999; Mishra et al., 2000).

2.12. The Trans-North China Orogen in North China

China consists of three major cratonic blocks: the North China, South China and Tarim Cratons, separated by younger orogens (Fig. 13). The North China Craton is tectonically divisible into two prominent Archean to Paleoproterozoic blocks, called the East-

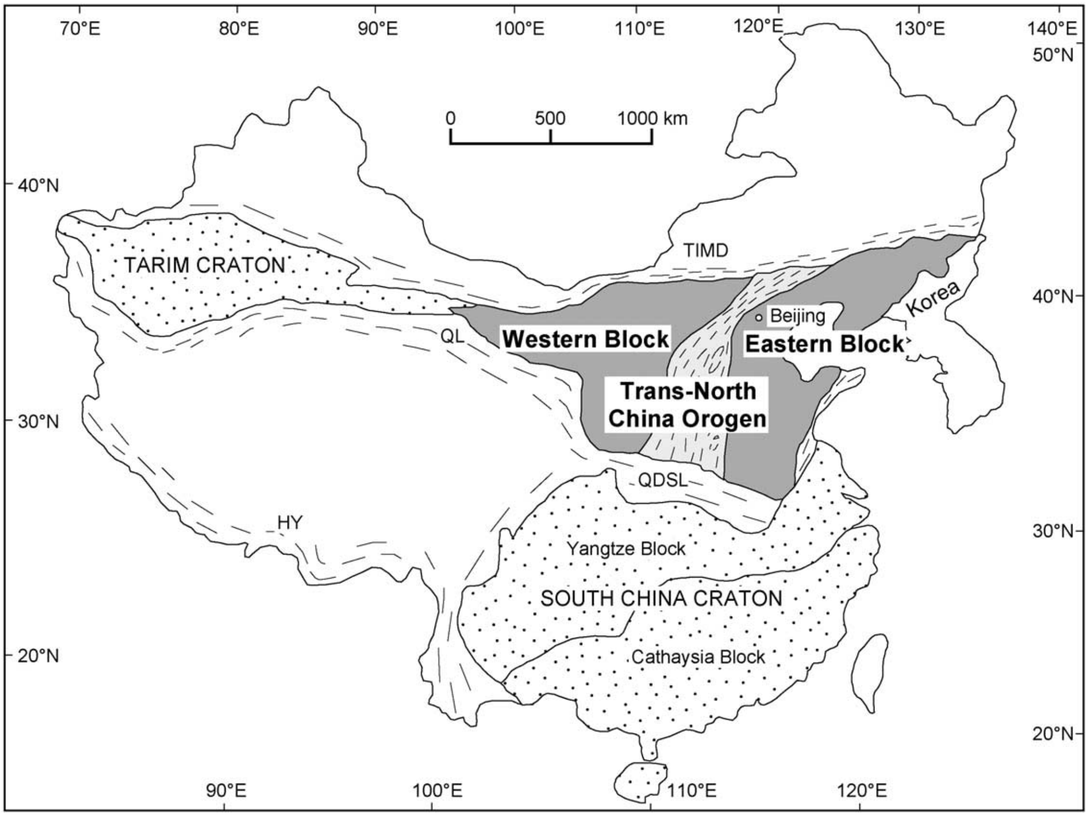


Fig. 13. Schematic tectonic map of China showing the major cratonic blocks (after Zhao et al., 2001a).

ern and Western Blocks, separated by a Paleoproterozoic orogen, called the Trans-North China Orogen (Fig. 13; Zhao et al., 2001a; Wilde et al., 2002). The Eastern Block consists predominantly of 2.7–2.5 Ga TTG gneisses and minor supracrustal rocks ranging in age from 2.8 to 2.5 Ga, with some Early to Middle Archean rocks exposed in local areas. The basement of the Western Block has structural styles and metamorphic histories essentially similar to those of the Eastern Block, but differs in the absence of Early to Middle Archean rocks and in being overlain by, and interleaved with, Paleoproterozoic khondalite sequences (Zhao et al., 1999).

Intervening between the two blocks is the Trans-North China Orogen that forms a roughly north–south trending belt across the central part of the craton (Fig. 13). The basement of the orogen comprises greenschist to granulite facies metamorphic terrains containing reworked Archean basement components derived from the Eastern and Western Blocks, together with juvenile Late Archean to Paleoproterozoic igneous and sedimentary rocks (Sun et al., 1992; Zhao et al., 2000). Geochemical and geochronological data suggest that most igneous rocks in the orogen developed in magmatic arcs (Bai and Dai, 1998; Sun et al., 1992). Collision is mainly characterized by eastward-directed thrusting over the western margin of the Eastern Block and north–south-trending sinistral ductile shear zones. High-pressure granulites and retrograde eclogites are exposed in the northern part of the orogen (Zhao et al., 2001b), and Sm–Nd isotopic analyses on metamorphic garnet, pyroxene and hornblende from these high-pressure rocks yield an isochron age of 1827 ± 18 Ma, interpreted as the approximate age of collision (Guo and Zhai, 2001). Minor amounts of ultramafic to mafic basement rocks have been interpreted to be fragments of ancient oceanic crust (Wu and Zhong, 1998). Based on lithological, structural, metamorphic and geochro-

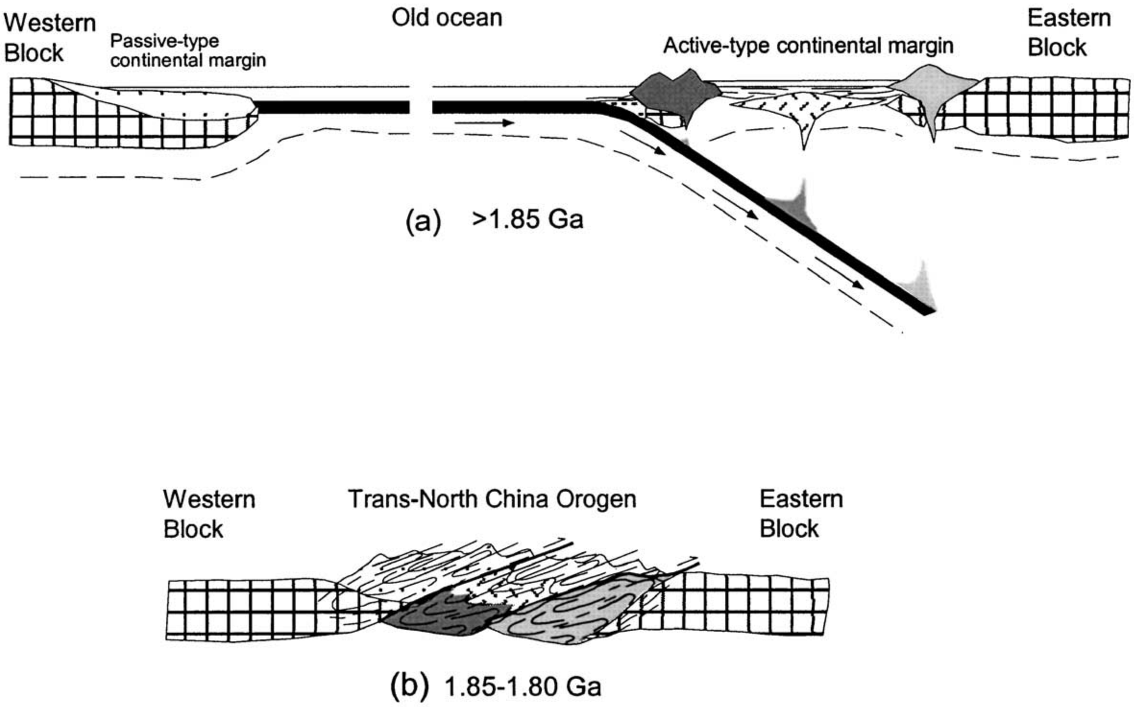


Fig. 14. Sections showing crustal structures and crustal evolution of the Trans-North China Orogen; (a) pre-collisional stage; (b) syn-collisional stage. See text for explanation.

nological data, Zhao (2001) proposed that in the Late Archean to Paleoproterozoic, the Eastern Block had an active-type continental margin on its western side at which continental magmatic arcs and intra-arc basins developed (Fig. 14a), whereas the Western Block had a passive-type continental margin on its eastern side along which stable continental margin sediments were deposited (Fig. 14a). Intervening between the two blocks was an ocean, which was undergoing subduction beneath the western margin of the Eastern Block (Fig. 14a). Final closing of this ocean at ~ 1.85 Ga led to the continent–continent collision between the Eastern and Western Blocks (Fig. 14b) and final assembly of the North China Craton (Zhao, 2001).

3. Reconstructions

3.1. South America and West Africa

The reconstruction of Archean to Paleoproterozoic cratons in South America and West Africa was constrained first by lithological correlations (Bullard et al., 1965) and then by Paleomagnetic and isotopic data (Onstott and Hargraves, 1981). Bullard et al. (1965) showed that the structure in the Archean–Paleoproterozoic cratons of West Africa can be well correlated with those of Archean–Paleoproterozoic cratons of South America. On the basis of their implied proximity, Bullard et al. (1965) proposed that the São Francisco and São Luis Cratons in South America fitted, respectively, the Congo and West African Cratons in West Africa (Fig. 15). Paleomagnetic and isotopic data indicate that between 2.1 and 1.5 Ga, coeval rocks in the cratons in West Africa and South America recorded similar paleomagnetic polar wander paths, suggesting West Africa and South America were jointed before the Pan-African Orogeny (Onstott and Hargraves, 1981). These fits are further constrained by the similarity or parallelism of major structural features, such as volcanic and orogenic belts or strike-slip faults on each side of the South Atlantic Ocean (Bertrand and Jardim de Sá, 1990) and gravity data (Lesquer et al., 1984). Ledru et al. (1994) noted

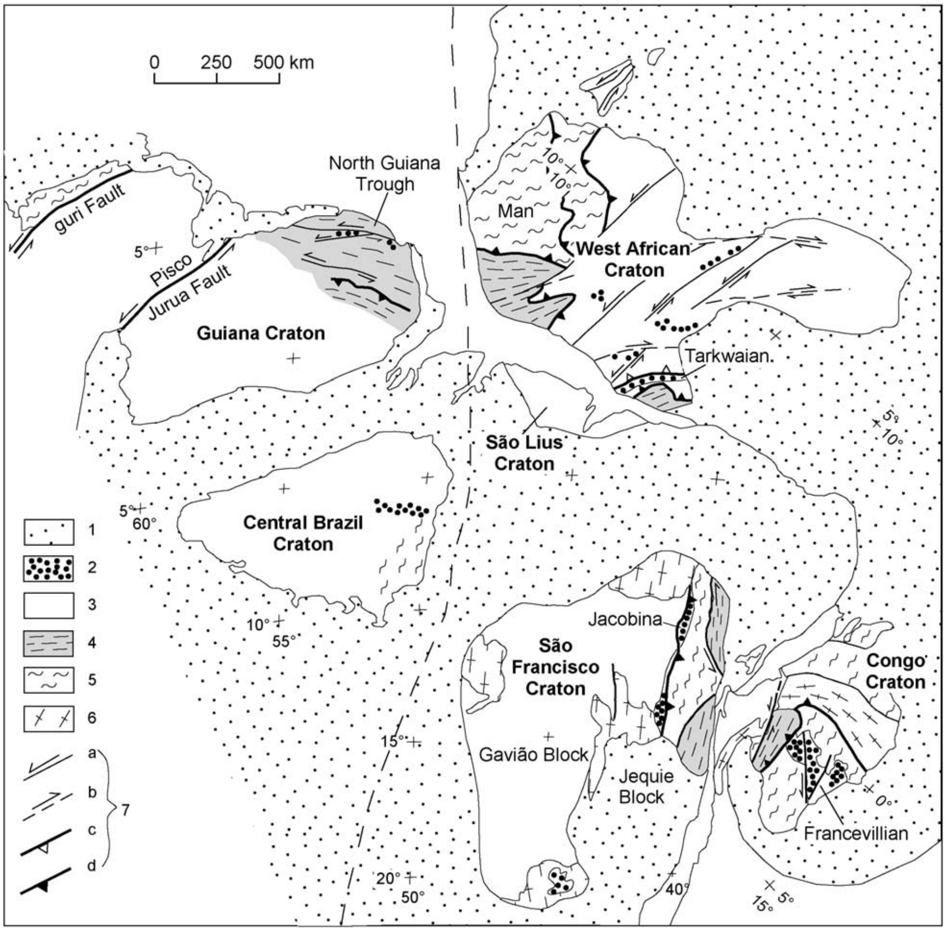


Fig. 15. A fit of circum-South Atlantic Archean–Paleoproterozoic provinces, showing assumed links for the Archean cratons and Paleoproterozoic Transamazonian–Eburnian orogens in West Africa and South America (after Ledru et al., 1994). 1 = Post-Paleoproterozoic; 2 = fluvio-deltaic formations; 3 = undifferentiated Archean and Paleoproterozoic; 4 = high-grade Paleoproterozoic formations; 5 = Archean including granulites; 6 = Archean granites and migmatites; 7 = major structural line of the Paleoproterozoic orogen (a = early sinistral strike-slip faults; b = late dextral strike-slip faults; c = thrusts related to strike-slip faults; d = deep crustal thrusts).

that the ∼ 2.0 Ga fluvio-deltaic formations are exposed in nearly every craton in South America and West Africa (Fig. 15) and that they show a similar structural and metamorphic evolution. These formations either rest directly upon Archean basement, as is the case for the Francevillian Unit in Gabon and the Jacobina Unit in Brazil, or they overlie the upper part of the Paleoproterozoic succession, as with the Tarkwaian in Ghana and the Rosebel Formation in French Guiana (Ledru et al., 1994). These sediments were deposited in foreland basins that formed during the collisional orogeny at ∼ 2.0 Ga. Their tectonic style indicates a frontal collision between the Congo and São Francisco Cratons (Ledru et al., 1994).

The above geological and paleomagnetic data suggest the existence of a Paleoproterozoic landmass in the circum-South Atlantic region. This is further supported by structural and metamorphic data for the Transamazonian Orogens in South America and Eburnean Orogens in West Africa. On the map of the classical Bullard fit of Africa and South America, the structural trend of the Transamazonian Orogen along the eastern margin of the São Francisco Craton is consistent with that of the Eburnean Orogen along the western margin of the Congo Craton, both are north–south trending (Fig. 15). The evolution of both orogens is characterized by early tangential tectonics, marked by large-scale thrusts and sinistral strike-slip faults, followed by later transcurrent tectonics, marked by dextral shear zones (Ledru et al., 1994). Metamorphic evolution of both the orogens involved an initial phase of crustal thrusting and thickening, followed by exhumation and final cooling (Barosa, 1989; Swapp and Onstott, 1989). These imply that they may have belonged to the same orogen joining the São Francisco and Congo Cratons, before the Pan-African orogeny, and their structural and metamorphic features reflect the collision of the two cratons. Recent research has shown that the Transamazonian and Eburnean Orogens are also exposed in northeastern Brazil and in Cameroon, respectively (Ledru et al., 1994). Therefore, the north–south-trending Transamazonian–Eburnean Orogen between the São Francisco and Congo cratons can be connected to the Eburnean Orogen along the eastern margin of the West African Craton, and as Bertrand and Jardim de Sá (1990) suggested, they may be the same Paleoproterozoic transcontinental collisional superbelt suturing the cratons in West Africa and South Africa.

3.2. South Africa and Western Australia

A Precambrian (2.8–2.1 Ga) link between South Africa and Western Australia has been proposed first by Button (1976) and then by Cheney (1996) and Zegers et al. (1998), based on comparisons of sequence stratigraphy, recent U–Pb geochronology and paleomagnetic data. As reviewed by Button (1976) and Cheney (1996), the Kaapvaal and Pilbara Cratons show a three-fold lithostratigraphic similarity between 2.8 and 2.1 Ga. The lowest sequence is 2.77–2.71 Ga arkosic sandstones and basalts that comprise the Pniel/Ventersdorp Supergroup in Kaapvaal and the Fortesque Group in the Pilbara (Fig. 16a). The second sequence consists predominantly of 2.68–2.43 Ga quartz arenites, dolomites and banded iron formations that in the Kaapvaal Craton comprise the Ghaap/Griqualand Groups, and in the Pilbara comprise the Hamersley Group (Fig. 16b). The third sequence is 2.47–2.20 Ga siliciclastic and volcanic units with basal glacigene deposits that in the Kaapvaal Craton comprise the Postmasburg Group (or the lower Pretoria Group), and in the Pilbara comprise the lower part of the Wyloo Group (Fig. 16c). These similarities led Cheney (1996) to propose that the now widely separated Kaapvaal and Pilbara Cratons were once continuous, forming part of a continent, named Vaalbara. In an initial configuration of the reconstructed Vaalbara, Cheney (1996) placed the northwestern margin of the Pilbara Craton along the western part of the southern margin of the Kaapvaal Craton (Fig. 17), based on the spatial match of similar lithostratigraphic sequences in the two cratons. This hypothesis appears to be supported by paleomagnetic data obtained by Zegers et al. (1998) who showed that when the virtual paleomagnetic poles (at ~ 2.87 Ga) of two major igneous layered complexes, the Millinda Complex (2860 ± 20 Ma) in the Pilbara and the Usushwana Complex (2871 ± 30 Ma) in the Kaapvaal, are placed on the present N-pole, the two cratons are brought into close proximity, consistent with Cheney's Vaalbara model.

The amalgamation of Vaalbara with the Zimbabwe Craton along the Limpopo Belt is considered to have resulted in the assembly of a large continent—Zimvaalbara (Cheney, 1996; Aspler and Chiarenzelli, 1998). Zimvaalbara may also include the Yilgarn Craton which was sutured to the Pilbara Craton along the Capricorn Orogen at about 2.0–1.8 Ga (Myers et al., 1996). Based on similar sedimentary and magmatic records and geochronological data, Aspler and Chiarenzelli (1998) recently extend Zimvaalbara to the cratons in India and the circum-South Atlantic provinces including the São Francisco, Amazon, Guiana, Congo and West African Cratons, and propose that these crustal fragments in the southern continents (present-day latitudes) constituted a late Archean to Paleoproterozoic supercontinent.

3.3. Laurentia (North America and Greenland) and Baltica

Pre-Grenvillian connections of Archean to Paleoproterozoic continental blocks in Laurentia and Baltica are constrained by paleomagnetic, isotopic, lithological, structural and geochronological data (Fig. 18; Hoffman, 1988, 1989b; Gower et al., 1990). Early paleomagnetic data indicated that over the period from about 1.8 to 1.3 Ga ago, most cratons in Laurentia and Baltica showed fairly consistent apparent polar wan-

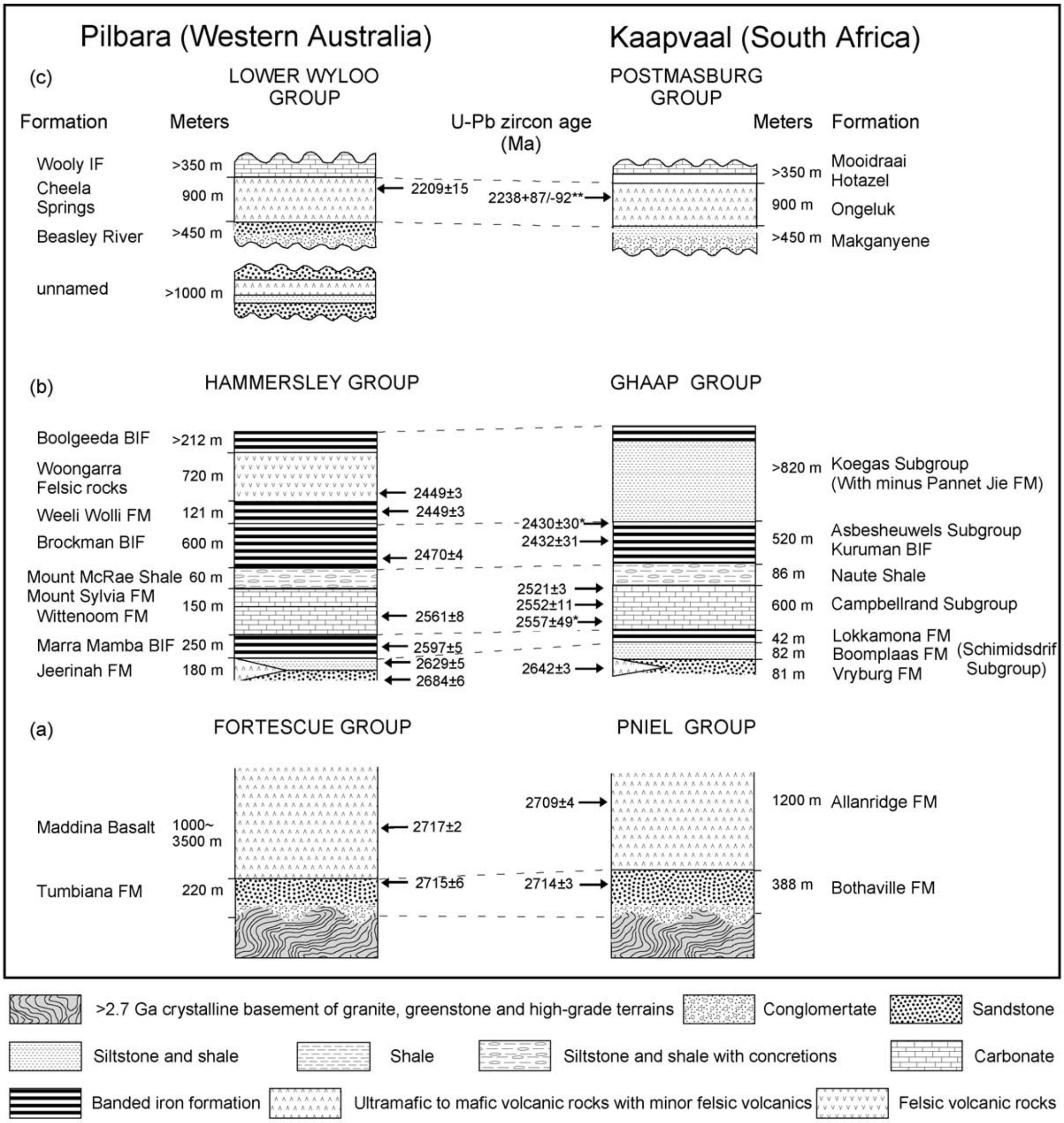


Fig. 16. Comparisons of ∼ 2.–72.0 Ga lithostratigraphies between the Pilbara and Kaapvaal Cratons. (a) Fortescue Group vs. Pniel Group; (b) Hammersley Group vs. Ghaap Group; (c) Lower Wyloo Group vs. Postmasburg Group. All data from Cheney (1996) and Nelson et al. (1999).

dering paths, which were mostly restricted to a $\pm 30°$ paleolatitude range (Poorter, 1976; Patchett et al., 1978; Irving, 1979; Piper, 1982), suggesting that these cratonic blocks existed as a single continental mass at this period. For example, by comparing Baltica and Laurentia APWPs of Svecofennian/Hudsonian to Jotnian/Mackenzie age, Poorter (1976) proposed a 1.9–1.2 Ga reconstruction with northern Baltica adjacent to southwestern Greenland and southern Labrador. Patchett et al. (1978) obtained a similar fit by using 1.26–1.19 Ga Jotnian paleopoles of Baltica and Mackenzie-aged paleopoles of Laurentia. These

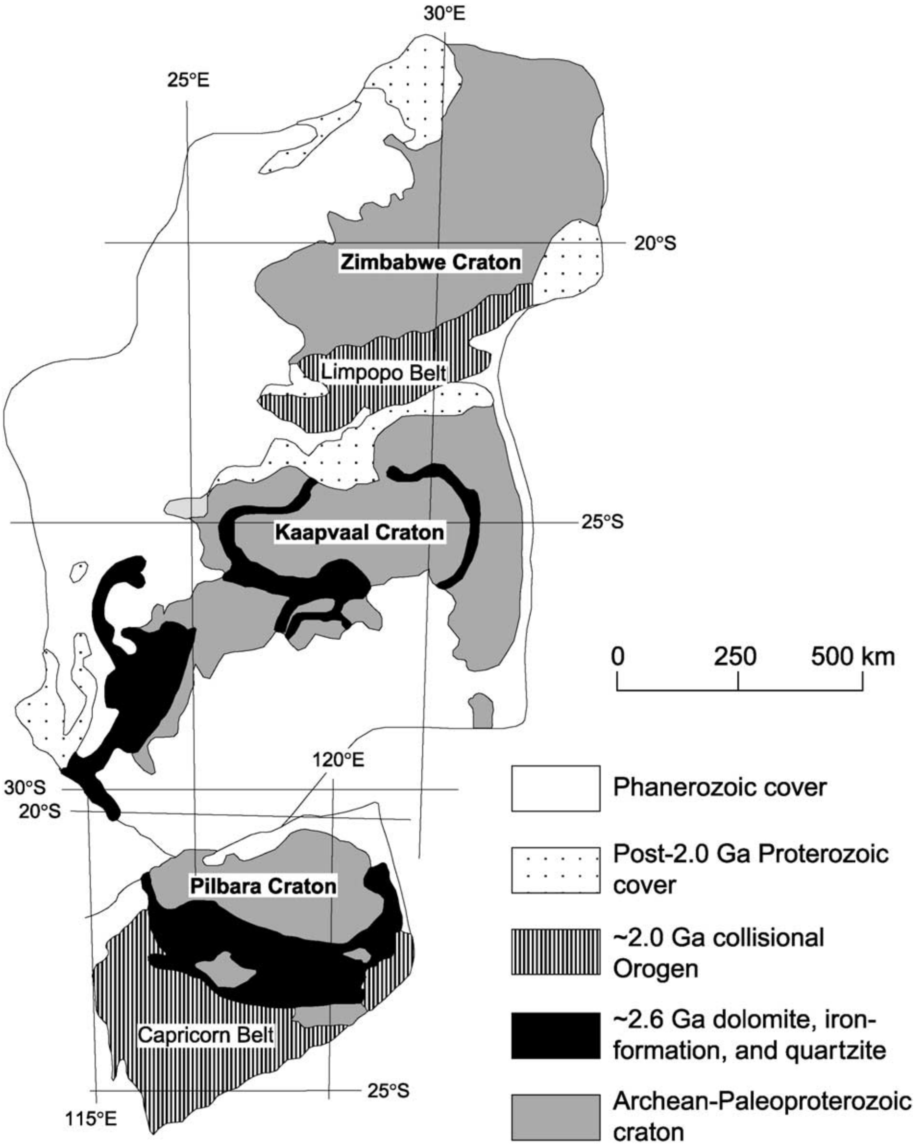


Fig. 17. Cheney's (1996) fit of the Kaapvaal and Pilbara Cratons.

reconstructions were further supported by many more recent paleomagnetic data obtained for Laurentia and Baltica between 1.9 and 1.2 Ga (Symons, 1991; Elming, 1994; Smethurst et al., 1998; Gala et al., 1998; Buchan et al., 2000). Paleomagnetic investigations also suggest a 'north–south' width of about 4000 km for the Manikewan Ocean between the Superior Craton and the Hearne and Rae Cratons before 1.85 Ga (Symons, 1991; Gala et al., 1998). This implies that these Archean blocks were not connected until 1.85 Ga.

The pre-Grenvillian paleomagnetic connection of Laurentia and Baltica is supported by evidence for the widespread existence of a late Paleoproterozoic to Mesoproterozoic subduction-related magmatic arc system extending from North America, throughout southern Greenland, to Baltica, and bordering the present southern margin of the Wyoming, Superior,

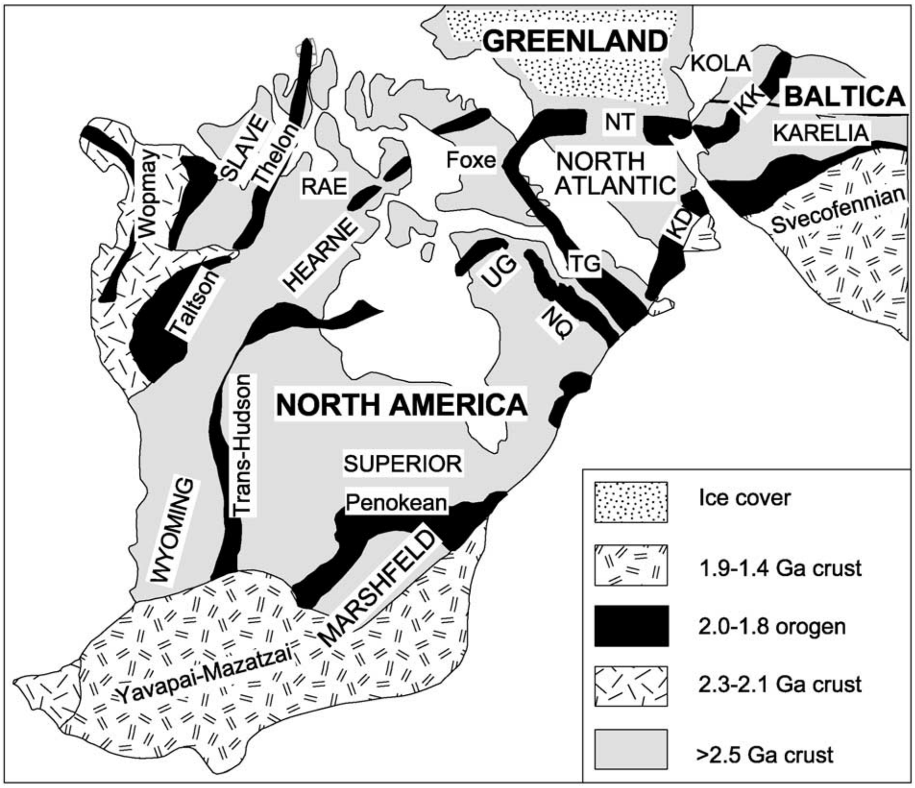


Fig. 18. Paleoproterozoic reconstruction of the cratonic blocks in North America, Greenland and Baltica (revised after Hoffman, 1988, 1989b; Gower et al., 1990; Van Kranendonk et al., 1993). Abbreviations: MK—Makkovik–Ketilidian Orogen; KK—Kola–Karelia Orogen; NQ—New Quebec Orogen; NT—Nagssugtoqidian Orogen; TG—Torngat Orogen; UG—Ungava Orogen.

North Atlantic and Karelia Cratons (Fig. 19; Patchett and Arndt, 1986; Winchester, 1988; Hoffman, 1989b; Park, 1992; Åhäll and Connelly, 1998). Coeval plutonic rocks were also discovered in southwestern and northwestern Scotland (Muir et al., 1992; Cliff et al., 1998), northwestern Ireland and the Rockall bank (Morton and Taylor, 1991), now completing the link through the British Isles (Fig. 19; Park, 1994). The occurrence of temporally and petrologically similar rocks across a distance of 2000 km between these cratonic blocks strongly supports the existence of a continental mass that includes the Archean to Paleoproterozoic cratonic blocks in Laurentia and Baltica (Hoffman, 1989b; Gower et al., 1990; Park, 1992, 1994, 1995; Åhäll and Connelly, 1998).

Connections between the 2.1–1.8 Ga orogens surrounding these Archean blocks have also been established (Winchester, 1988; Hoffman, 1989b; Bridgwater et al., 1990; Gower et al., 1990; Park, 1992; Van Kranendonk et al., 1993; Van Kranendonk and Wardle, 1996; Åhäll and Connelly, 1998; Daly et al., 2001). The timing and tectonic evolution of the Torgat and Nagssugtoqidian Orogens are remarkably similar. The Torngat Orogen formed during the 1.9–1.8 Ga collision between the North Atlantic (Nain) and southeastern Rae Cratons (Van Kranendonk et al., 1993; Van Kranendonk and Wardle, 1996; Wardle and Van Kranendonk, 1996), while the Nagssugtoqidian Orogen developed during the 1.9–1.8 Ga collision between the North Atlantic and Disko Cratons (Kalsbeek et al., 1987; Van Kranendonk et al., 1993). As discussed by Bridgwater et al. (1990) and Van Kranendonk et al. (1993), the ~1910 Ma arc rocks and ~1895 Ma charnockites in the Torgat Orogen formed contemporaneously with the ~1920 Ma volcanic arc granitoid suite and ~1886 Ma Ammassalik igneous complex in the Nagssugtoqidian Orogen (Table 1). They are considered to have developed in

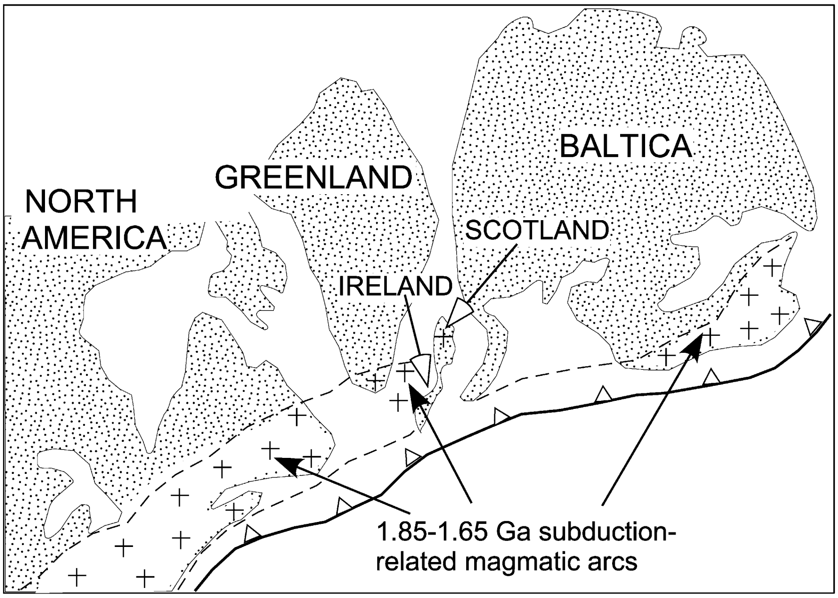


Fig. 19. Spatial distribution of late Paleoproterozoic to Mesoproterozoic subduction-related magmatic arcs along the margin of the reconstructed continental mass consisting of cratonic blocks in North America, Greenland, Scotland, Ireland and Baltica (after Park, 1992).

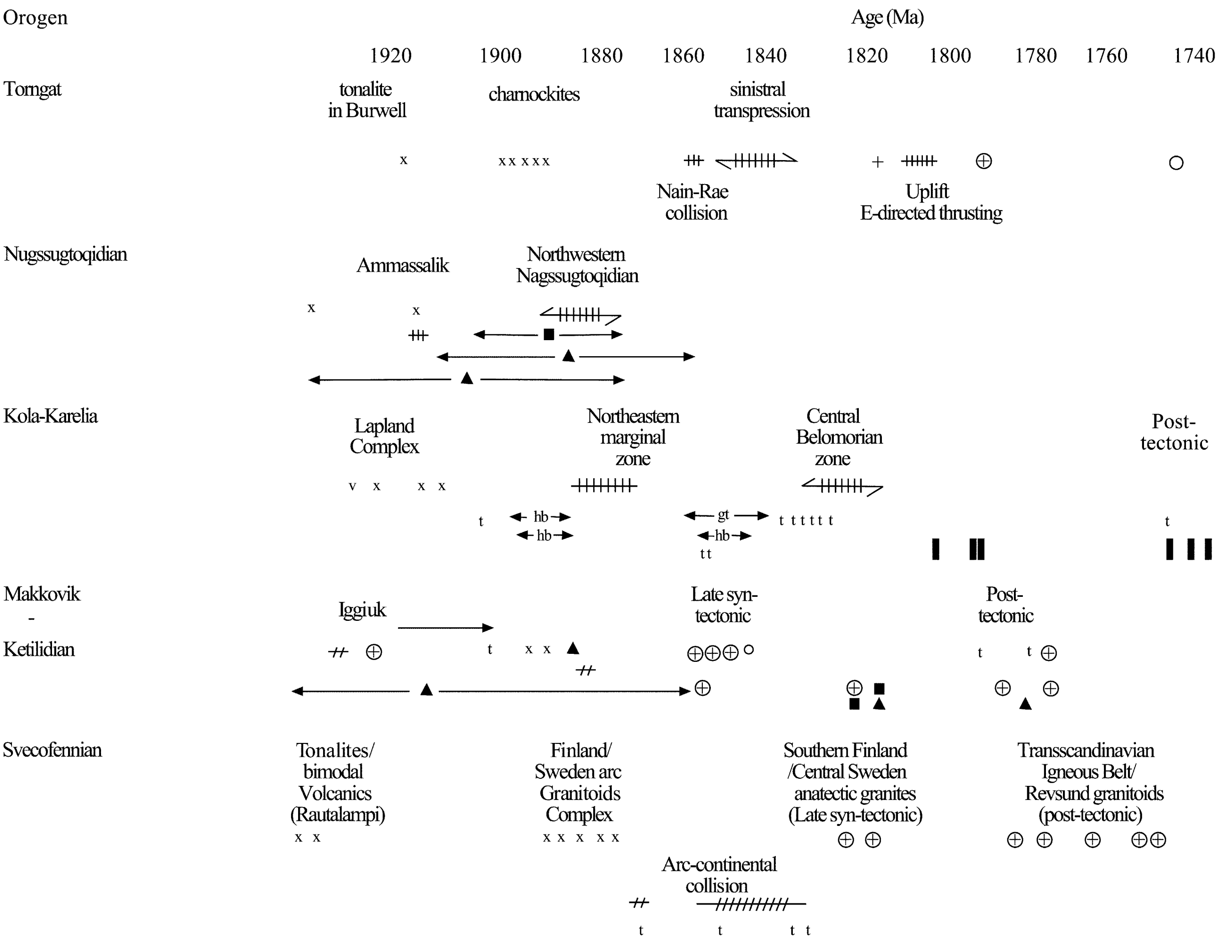
the same orogen, bounding the western and northern margins of the North Atlantic (Nain) Craton (Bridgwater et al., 1990; Van Kranendonk et al., 1993). On the basis of similarities in age, composition and tectonic setting, Gower et al. (1990) suggested that the Kola–Karelia Orogen in Baltica represents the eastern extension of the Torgat and Nagssugtoqidian Orogens across the Atlantic (Fig. 18). This connection provides a reasonable temporal and spatial match of similar lithologies (e.g. enderbites, charnockites, mafic granulites, Al-rich gneisses, etc.) and tectonic events in these orogens (Table 1). In addition, the Makkovik Orogen in northeastern North America has been well correlated with the Ketilidian Orogen in Greenland and the Svecofennian Orogen in Baltica (Fig. 18; Hoffman, 1989b; Park, 1992; Van Kranendonk et al., 1993); they are all accretionary orogens in a large subduction-related magmatic arc system bordering the margin of the Archean cratonic blocks of Laurentia and Baltica (Table 1; Hoffman, 1988, 1989b; Windley, 1992; Park, 1992; Van Kranendonk et al., 1993). Gower et al. (1990) and Van Kranendonk et al. (1993) have discussed the detailed lithological and geochronological correlations between these orogens.

In summary, both geological and paleomagnetic data have shown that Laurentia and Baltica had very similar geological histories from the Paleoproterozoic to Mesoproterozoic, implying that they existed as a single cratonic landmass (named ‘Nena’ by Gower et al., 1990). The widespread occurrence of Late Mesoproterozoic (~ 1.3 Ga) mafic to ultramafic dyke swarms, represented by the Mackenzie dykes in Laurentia and the Orust dykes in Baltica, is considered to mark the commencement of rifting and breakup of this cratonic landmass, resulting in the detachment of Baltica from Laurentia (Park, 1992; Buchan et al., 2000).

3.4. Siberia and Laurentia

Archean to Paleoproterozoic connections between Paleoproterozoic orogens and cratonic blocks in Siberia and those in Laurentia have been proposed for a long time, on the basis of paleomagnetic and geological correlations (Sears and Price, 1978, 2000; Piper, 1982, 2000; Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Smethurst et al., 1998; Ernst et al., 2000). Paleomagnetic data indicate that during the Mesoproterozoic, Siberia was at low

Table 1
Summary of geological data for the Torgat, Nagssugtoqidian, Kola–Karelia, Makkovik–Ketilidian and Svecofennian Orogens



Data sources for the Torgat, Nagssugtoqidian and Makkovik–Ketilidian Orogens are given by Van Kranendonk et al. (1993) and references therein. Hornblende Ar/Ar, garnet–whole rock Sm–Nd and zircon, titanite and rutile U–Pb age data for the Kola–Karelia Orogen are from Daly et al. (2001) and Bibikova et al. (2001). References and age data for the Svecofennian Orogen are given by Lahtinen and Huhma (1997), Nironen (1997) and Högdahl and Sjöström (2001). Symbols: ⫽ = arc–continent collision; ○ = U–Pb age on monazite; ┼┼┼┼┼┼ = continental collision; ▮ = U–Pb age on rutile; ⟨——⟩ = high-grade shearing; ▲ = Rb–Sr age; ← ■ → = zircon Pb–Pb age (with error); × = calc-alkaline arc magmatism; ← hb → = hornblende Ar/Ar age (with error); + = granite plutonism; ← gt → = garnet Sm–Nd age (with error); ⊕ = post-tectonic granite; t = U–Pb age on titanite; v = mafic volcanism.

latitudes between 5°N and 20°N (Piper, 1982; Smethurst et al., 1998; Ernst et al., 2000), broadly similar to latitudes determined for Laurentia (Irving, 1979; Piper, 1982; Elming, 1994; Gala et al., 1998; Buchan et al., 2000). As paleomagnetic data cannot constrain longitude, different geological reconstruction models have been postulated. Sears and Price (1978) suggested that the Aldan Craton in Siberia should be linked to the Wyoming Craton of North America, but their model has been largely neglected in the reconstructions of Rodinia (Dalziel, 1991; Hoffman, 1991; Moores, 1991). Recently, however, Sears and Price (2000) and Piper (2000) have provided several new lines of lithostratigraphic, structural, geochronological and paleomagnetic evidence for this fit. Hoffman (1991) proposed that the Aldan Shield lay on the distal side and need not have been attached to any portion of North America (Fig. 20a), whereas Condie

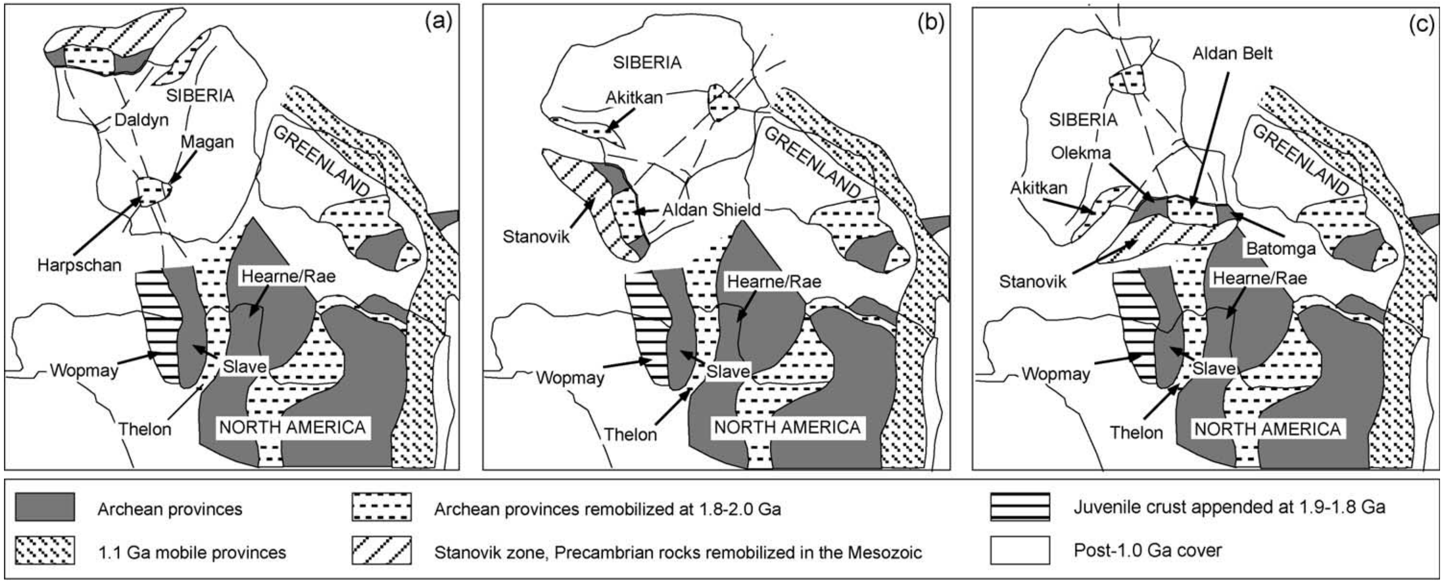


Fig. 20. Possible alternatives for the reconstruction of the North America and Siberia connection (after Frost et al., 1998). (a) Reconstruction of Hoffman (1991). (b) Reconstruction of Condie and Rosen (1994). (c) Reconstruction of Frost et al. (1998).

and Rosen (1994) suggested that the Aldan Craton and Akitkan fold belt were continuous with the Slave Craton and the Taltson–Thelon Orogen, respectively, in North America (Fig. 20b). Recently, based on lithological and geochronological correlations, Frost et al. (1998) postulated a connection in which the Olekma and Batomga granite–greenstone terrains are continuations, respectively, of the Slave and Hearne/Rae Cratons, and the Aldan high-grade gneiss belt is a continuation of the Taltson–Thelon Orogen (Fig. 20c). This connection seems reasonable because the Olekma and Batomga granite–greenstone terrains, like the Slave and Hearne/Rae Cratons, are dominated by amphibolite-facies, rather than granulite facies gneisses, and both the Aldan high-grade gneiss belt and Taltson–Thelon Orogen are 1.9 Ga granulite facies collisional belts.

3.5. Central Australia and Laurentia

Recent reconstructions of Rodinia have proposed that Central Australia was connected to northwestern Laurentia and East Antarctica before the assembly of Rodinia (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Ross et al., 1992; Borg and DePalo, 1994; Burrett and Berry, 2000). In the SWEAT (Southwest U.S.–East Antarctic) reconstruction, Moores (1991) postulated that the Wopmay and Taltson Orogens of North America might originally have continued into Central Australia (Fig. 21a). However, Ross et al. (1992) argued that this configuration did not provide a continental counterpart to the rifted margin of the northwestern United States and adjacent Canada, where the U–Pb, Sm–Nd and stratigraphic data for the Belt basin (the Belt Supergroup) imply a western continental source area that was composed largely of a 1.8–1.6 Ga Paleoproterozoic juvenile crust. On the basis of stratigraphic, geochemical and geochronological correlations, Ross et al. (1992) found that there is a match between the Paleoproterozoic basement of Central Australia and the provenance of the Belt Supergroup in the northwestern United States. This led Ross et al. (1992) to propose a left-lateral displacement of about 1500 km between Central Australia–East Antarctic and Laurentia to bring the Gawler block in Central Australian closer to the Belt basin in the northwestern United States and adjacent Canada. Borg and DePalo (1994) also suggested a similar displacement, but to a lesser extent (Fig. 21b), to obtain a reasonably good match of isotopic provinces in Central Australia, Laurentia and East Antarctica. Most recently, based on a comparison of the major geological provinces, belts, and lineaments of Proterozoic Laurentia and eastern Central Australia, Burrett and Berry (2000) proposed a new reconstruction that fits the Mojave terrane of California–Nevada into a reentrant of the Tasman Line of eastern Australia. This reconstruction also provides suitable intercontinental source terranes for zircons in Tasmania (eastern Australia) and the Belt basin (southwestern Laurentia).

3.6. East Antarctica and Laurentia

The similarity in lithological compositions and radiometric ages between the Paleo- to Mesoproterozoic Transantarctic Mountains and Shackleton Range Orogens of East Antarctica and Yavapai–Mazatzal and Mojavia Orogens of southwestern North America (Laurentia) led Moores (1991) to propose that the now widely separated Antarctica and Laurentia blocks were originally continuous (Fig. 21a). This connection was further tested through computer-simulated reconstruction and isotopic match of these two continents (Fig. 21b; Dalziel, 1991; Borg and DePalo, 1994). Also, this linkage can satisfactorily provide a western continental source region for Paleoproterozoic sedimentary rocks in the Mojavia province of southwestern Laurentia. As noted by Bennet and DePaolo (1987), basement rocks with T_{DM} ages of 2.0–2.4 Ga are normally adjacent to Archean cratons. However, there is no adjoining Archean craton for the westernmost part of the Mojavia Province. Bennet and DePaolo (1987) hypothesized that originally adjacent Archean cratons had drifted away during rifting in late Precambrian time and should be found in some other continent. Based on the above reconstruction, Archean crust in Antarctica adjacent to the Transantarctic Mountains may represent a potential continental source area to the 2.0–2.4 Ga basement of the Mojavia province (Fig. 21b; Borg and DePalo, 1994).

3.7. North China and India

Controversy has surrounded the Precambrian connection of the North China Craton with other cratonic

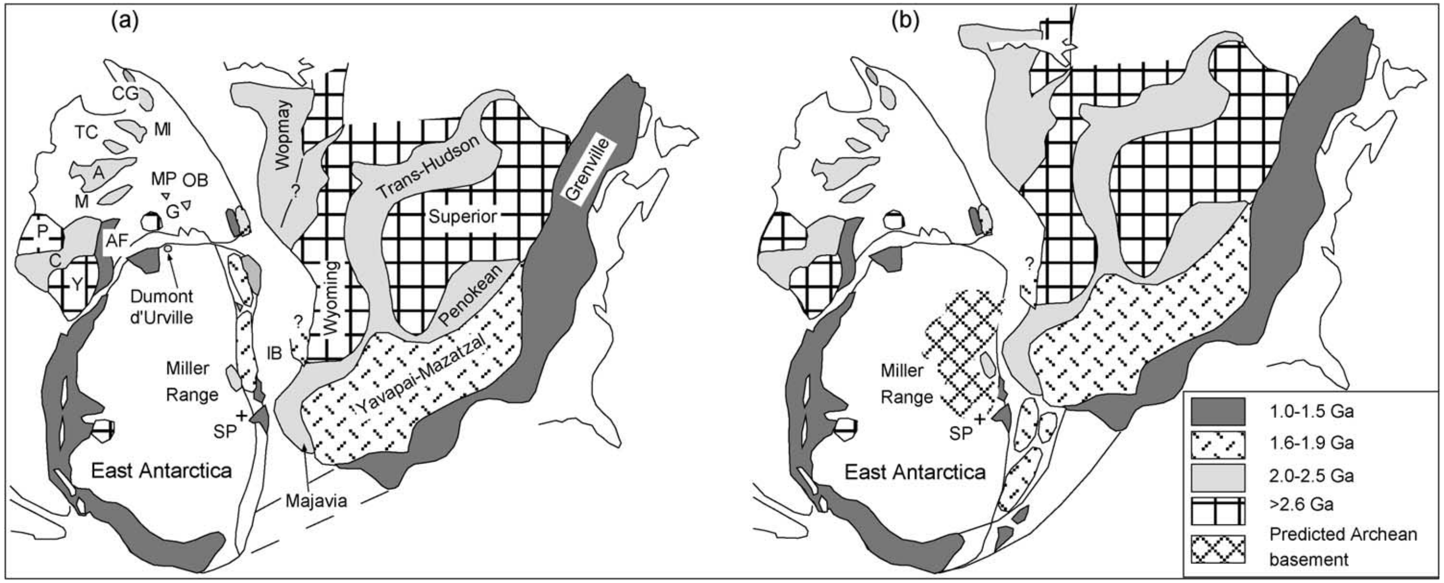


Fig. 21. Possible alternatives for the reconstructions of the North America–Australia–Antarctica connection (after Borg and DePalo, 1994). (a) Reconstruction of Moores (1991). (b) Reconstruction of Borg and DePalo (1994). Abbreviations: A = Arunta Inlier; AF = Albany–Fraser Orogen; C = Capricorn Orogen; CG = Coen–Georgetown Inlier; G = Gawler Craton; M = Musgrave Orogen, MI = Mt. Isa Inlier; MP = Mt. Painter Inlier; OB = Olary–Broken Hill Inlier; P = Pilbara Craton; TC = Tennant Creek Inlier; SP = South Pole; Y = Yilgarn Craton.

blocks (Wilde et al., 2002). Li et al. (1996) proposed that the North China Craton was once connected to Siberia during the Paleo- and Mesoproterozoic. Alternatively, Qian (1997) proposed a link between the North China Craton and the Baltic Shield. However, the striking geological differences in Archean geology between these continental blocks discourage the above hypotheses. For example, the Aldan and Baltic Shields experienced their main Archean crust-formation events at some time before ~ 2.60 Ga (Rosen et al., 1994), whereas most Archean basement rocks in the North China Craton formed between 2.6 and 2.5 Ga (Kröner et al., 1998).

Recently, Kröner et al. (1998) noticed that the Eastern Block of the North China Craton and the South Indian Block of the Indian Shield are two unique cratonic blocks in the world that experienced a major Archean crust-forming event between 2.6 and 2.5 Ga. Both the blocks are characterized by the near-contemporaneity of late Archean granitoid intrusive and metamorphic events, with the peak of metamorphism reached shortly (< 50 Ma) after the widespread intrusion of granitoid suites (Jahn and Zhang, 1984; Kröner et al., 1998). Moreover, dome-and-basin structures are dominant in both the blocks (Zhao et al., 2001a; Chardon et al., 1998), and anticlockwise $P-T$ paths characterize the metamorphic evolution of the late Archean granulites from both the blocks (Raith et al., 1990; Liu, 1991; Zhao et al., 2001a; Jayananda et al., 2000). These similarities led Kröner et al. (1998) to postulate that the two blocks may have constituted part of a single major active plate margin along which juvenile crust was accreted onto an older landmass. This hypothesis can also explain similar Paleoproterozoic formations between the two blocks. For example, Paleoproterozoic (2.5–1.8 Ga) sedimentary–volcanic successions in both the blocks comprise lower clastic-rich, middle volcanic-rich and upper clastic + carbonate sequences, represented by the Liaohe Group in the Eastern Block and the adjoining Singhbhum, Dhanjori and Kolhan Groups in the South Indian Block (Naqvi and Rogers, 1987; Cao et al., 1994).

Fig. 22 shows a possible fit for the North China Craton and Indian Shield, where the north margin of the Eastern Block is placed adjacent to the western margin of the South Indian Block, with the Trans-North China Orogen and Western Block of the North China Craton representing the continuations, respectively, of the Central Indian Tectonic Zone and North Indian Block. This fit suggests that the Eastern Block + South Indian Block and the Western Block + North Indian Block represent two discrete continental blocks that developed independently during the Archean and Paleoproterozoic, and joined along the Trans-North China Orogen and Central Indian Tectonic Zone during a Paleoproterozoic collisional event. Although detailed correlations between the Trans-North China Orogen and Central Indian Tectonic Zone and between the Western Block and North Indian Block cannot be made at present because of the paucity of reliable geochronological data, the available data show that the Trans-North China Orogen and Central Indian Tectonic Zone share similar structural styles, lithotectonic assemblages and tectonothermal histories. Structurally, both the orogens have undergone large-scale thrusting and ductile shear deformation, forming a series of east-verging thrusts and north–south-trending ductile shear zones in the Trans-North China Orogen (e.g. the Longquanguan shear zone) and south-verging thrusts and east–west-

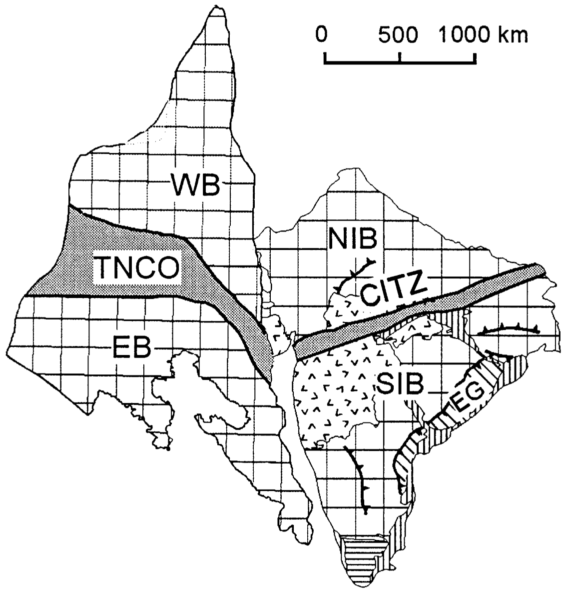


Fig. 22. A proposed fit of the North China Craton and India Shield, based on similar Archean to Paleoproterozoic sedimentary and magmatic features between the Eastern Blocks of the North China Craton and the South Indian Block of the Indian Shield. See text for detailed discussion.

trending ductile shear zones in the Central Indian Teconic Zone (e.g. the Central Indian shear zone). Both the orogens consist of low-grade volcanic–sedimentary (greenstone) sequences and granitoids in the center, flanked by high-grade granulite–gneiss terrains on both the margins (Zhao et al., 2000; Mazumder et al., 2000). Moreover, high-pressure mafic granulites (retrograded eclogites) have been discovered in the two orogens (Zhai et al., 1992; Bhowmik et al., 1999; Guo and Zhai, 2001; Zhao et al., 2001b). These high-pressure granulites contain peak high-pressure and post-peak decompression and cooling mineral assemblages, which, along with their P–T estimates, define near-isothermal decompressional, clockwise P–T paths (Zhao et al., 2001b; Bhowmik et al., 1999). These P–T paths suggest that the two zones underwent a similar tectonothermal process involving initial crustal thickening, subsequent rapid exhumation, and cooling, which may record a major phase of collision between the Eastern Block + South Indian Block and the Western Block + North Indian Block.

4. Implications for a pre-Rodinia supercontinent

This review shows that most 2.1–1.8 Ga orogens in the world represent continental collisional belts suturing Archean to Paleoproterozoic cratonic blocks. Based on the available lithological, tectonothermal, geochronological and paleomagnetic data, we have summarized the connections proposed for those cratonic blocks that are joined by 2.1–1.8 Ga collisional orogens. In particular, we have examined the links between South America and West Africa; South Africa and Western Australia; Laurentia and Baltica; Siberia and Laurentia; Central Australia and Laurentia; East Antarctica and Laurentia; and North China and India. These links lead us to infer the existence of a pre-Rodinia supercontinent, referred to herein as Columbia, a name recently proposed by Rogers and Santosh (2002) for a Paleo-Mesoproterozoic supercontinent. Fig. 23 shows a tentative reconstruction for the proposed Columbia Supercontinent, based on the connections discussed above.

The positions of some cratonic blocks (e.g. South China, Tarim, North China + India and South America + West Africa) remain unknown in this tentative reconstruction. Li et al. (1995) postulated that the South China Block lay between eastern Australia and western Laurentia, but paleomagnetic data do not fully support this hypothesis (Zhang and Piper, 1997). Li et al. (1996) also proposed that the Tarim Craton of China was connected to the Kimberley Block of Northern Australia from the Paleoproterozoic to Early Cambrian, since the two blocks have similar Paleoproterozoic basement rocks and little-metamorphosed Meso- to Neoproterozoic sedimentary successions. This hypothesis needs further testing by geological and paleomagnetic data. Some researchers argued that the 1.6–1.0 Ga Eastern Ghats Belt of India was fragmented from the eastern margin of East Antarctica (Grew and Manton, 1986; Mazumder et al., 2000); Rogers (1996) believed that India, East Antarctica and Australia had existed as a single continental block (called ‘Ur’) since 3.0 Ga ago and had not separated from each other until the break-up of Pangea, whereas other workers suggested that India and East Antarctica were amalgamated during the final assembly of Rodinia at ~1.0 Ga (Hoffman, 1991; Dalziel, 1991; Moores, 1991). Sadowski and Bettencourt (1996) proposed a Paleo-Meoproterozoic link between the northwestern margin of South America and the southeastern margin of Laurentia, based on comparisons of tectonostratigraphy and new U–Pb geochronology. However, this link cannot explain the existence of the Paleoproterozoic Makkovik–Ketilidian accretionary orogen in eastern Laurentia and a Paleo-Mesoproterozoic subduction-related magmatic arc system extending along the southeastern margin of Laurentia (see the following).

The effect of a supercontinent should be reflected in world-scale magmatic and sedimentary records. In South America and West Africa, the ~2.0 Ga fluvio-deltaic intracontinental basins developed within all cratonic blocks (Ledru et al., 1994; Windley, 1995; Rogers, 1996). The basins show nearly similar compositional features, being composed mainly of conglomerate and sandstone and ranging from fluviatile, locally with debris flows, to deltaic (Fig. 14; Ledru et al., 1994). The sedimentary formations include the Francevillian Unit in the Congo, the Tarkwaian Formation in West Africa, the Rosebel Formation in Guiana, the Jacobina Unit in the São Francisco Craton, and they either rest directly upon Archean basement or overlie the upper part of the Paleoproter-

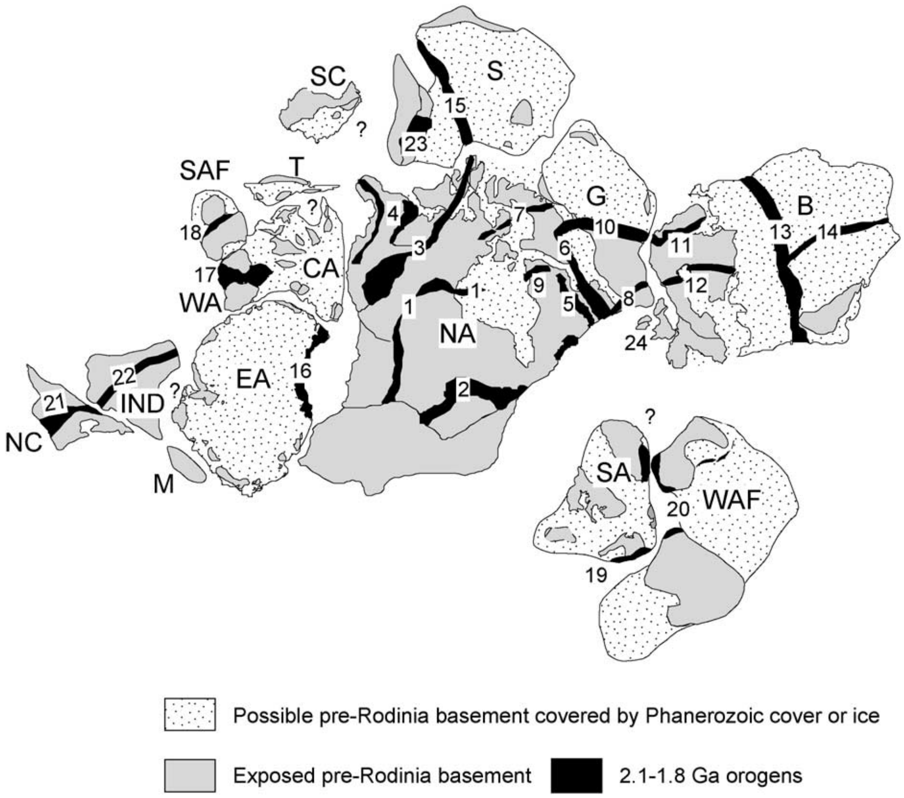


Fig. 23. Reconstruction of the proposed Columbia Supercontinent. The restoration of Laurentia–Baltica is based on Hoffman (1988, 1989b, 1991), Gower et al. (1990) and Van Kranendonk et al. (1993). Eastern Antarctica–Laurentia from Moores (1991), Dalziel (1991) and Borg and DePalo (1994), Central Australia–Laurentia from Moores (1991) and Ross et al. (1992), Siberia–Laurentia from Condie and Rosen (1994), South America–West Africa from Bullard et al. (1965) and Ledru et al. (1994), South Africa–Western Australia from Cheney (1996), and North China–India (Kröner et al., 1998 and this study). See text for discussion on the loose connections of South China, Tarim and the adjoining North China + India and South America + West Africa with others fragments. Symbols: B—Baltica (including Eastern Europe); CA—Central Australia; EA—East Antarctica; G—Greenland; IND—India; M—Madagascar; NA—North America; NC—North China; S—Siberia; SA—South America; SAF—South Africa; SC—South China; T—Tarim; WA—West Australia; WAF—West Africa; 1—Trans-Hudson Orogen; 2—Penokean Orogen; 3—Taltson–Thelon Orogen; 4—Wopmay Orogen; 5—New Quebec Orogen; 6—Torngat Orogen; 7—Foxe Orogen; 8—Makkovik–Ketilidian Orogens; 9—Ungava Orogen; 10—Nugssugtoqidian Orogen; 11—Kola–Karelian Orogen; 12—Svecofennian Orogen; 13—Volhyn–Central Russian Orogen; 14—Pachelma Orogen; 15—Akitkan Orogen; 16—Transantarctic Orogen; 17—Capricorn Orogen; 18—Limpopo Orogen; 19—Transamazonian Orogen; 20—Eburnian Orogen; 21—Trans-North China Orogen; 22—Central Indian Tectonic Zone; 23—Central Aldan Orogen Zone; 24—Scotland.

ozoic sequence (Ledru et al., 1994). These sedimentary rocks were deposited after the initial stage of the collision between the Congo and São Francisco cratons and between the West African and Amazonian cratons (Ledru et al., 1994; Rogers, 1996), during the assembly of Columbia. In Laurentia and Baltica, as discussed earlier, a 1.80–1.30 Ga subduction-related magmatic belt extends from Arizona through Colorado, Michigan, South Greenland, Sweden, Finland to western Russia, bordering the present southern margin of the North America, Greenland and Baltica (Winchester, 1988; Hoffman, 1989b; Bridgwater et al., 1990; Gower et al., 1990; Park, 1992; Åhäll and Connelly, 1998). Coeval magmatic rocks are also present in southwestern Scotland (Muir et al., 1992), Central Australia (McCulloch, 1987), and North China (Ma et al., 1987). The occurrence of temporally and petrologically similar rocks across a distance of thousands of kilometers between these continents is impressive and supports the existence of the Columbia

Supercontinent. Nd isotopic studies indicate that this large magmatic belt consists of volcanic and plutonic rocks resembling those of present-day island arcs and continental margins (Patchett and Arndt, 1986), and they may represent a subduction-related igneous belt along the margins of the Columbia Supercontinent.

Throughout much of Columbia, especially in North America, Greenland, Baltica, South America and North China, the 1.6–1.2 Ga age range is characterized by a wide spectrum of anorogenic magmatism including eruption of rhyolite and emplacement of anorthosite-mangerite-charnockite-granite (AMCG), rapakivi, carbonatite and alkaline intrusives (Anderson, 1983; Anderson and Morrison, 1992; Windley, 1995; Åhäll and Connelly, 1998). Mesoproterozoic AMCG and rapakivi granites are exposed in a huge belt that trends across North America and southern Greenland into the Baltic region of northern Europe to as far east as the Ukraine Ural Mountains and North China (Anderson, 1983; Yu et al., 1994; Emslie et al., 1994; Rämö and Haapala, 1995). The anorogenic igneous activity was probably related to an extensive underplating mechanism that preceded the dispersion of the fragments of a supercontinent (Gower et al., 1990; Windley, 1995). In addition, 1.4–1.2 Ga mafic dyke swarms have been widely reported from North America (Le Cheminant and Heaman, 1989), Greenland (Cadman et al., 2001), Baltica (Park, 1992), North China (Hall et al., 2000), East Antarctica (Sheraton et al., 1990) and Central–South Australia (Mortimer et al., 1988). One of the most widely distributed dyke swarms is the MacKenzie swarm that has a well-defined intrusion age of 1.27 Ga (Le Cheminant and Heaman, 1989). These mafic dyke swarms constitute a plate-wide extensional episode that may mark the youngest piercing points at which these cratonic blocks in the Columbia Supercontinent can be paleomagnetically and geologically linked (Park, 1992). This episode of extension is regarded as having signaled the commencement of the rifting and breakup of Columbia.

Global-scale Mesoproterozoic anorogenic magmatism is also recorded by widespread presence of alkaline ultrabasic rocks represented by kimberlites, lamproites and carbonatites. Milanovski and Malkov (1980) showed that kimberlite activity on a global scale coincided with periods of crustal spreading. Few Paleoproterozoic kimberlites have been reported from the cratonic blocks, but the emplacement of Mesoproterozoic kimberlites and lamproites took place at numerous points within the cratonic blocks in West Africa, South Africa, India, South America and Western Australia (Dawson, 1989), beginning with the 1.6 Ga intrusion in Kuruman, situated on the margin of the Kaapvaal Craton (Bristow et al., 1986). Middle Mesoproterozoic (~ 1.4 Ga) kimberlites are reported from Gabon, on the west margin of the Congo Craton, and from Liberia, on the southwest margin of West African Craton (Haggerty, 1982). Particularly extensive kimberlite–lamproite magmatic activity appears to have taken place in the late Mesoproterozoic (~ 1.2 Ga), widely distributed in the Western Australia (e.g. Kimberley area; Pidgeon et al., 1989), West African Craton (e.g. Mali; Haggerty, 1982), Indian Shield (e.g. Majhgawan; Paul et al., 1975), and Kaapvaal Craton (e.g. Premier; Phillips et al., 1989). This plate-scale kimberlite activity may represent an important mantle upwelling episode that resulted in the final breakup of Columbia.

Although several lines of evidence strongly support the hypothesis that the Columbia Supercontinent existed in the Paleo-Mesoproterozoic, a full reconstruction for this supercontinent is not possible at present because of the lack of reliable paleomagnetic data matched to high-precision ages, as well as detailed correlations and connections established for various major 2.1–1.8 Ga collisional orogens and related Archean to Paleoproterozoic cratonic blocks. Nevertheless, we believe there is sufficient evidence to conclude that there existed such a pre-Rodina supercontinent that resulted from the amalgamation of Archean to Paleoproterozoic cratonic blocks by a global-scale collisional orogeny at 2.1–1.8 Ga.

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