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A review of tectonic events in the East Antarctic Shield and their implications for Gondwana and earlier supercontinents

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ABSTRACT—Late Neoproterozoic to Cambrian tectonism in East Antarctica was widely assumed to have been restricted to the Ross Orogen at the Palæopacific margin of the Precambrian shield, but it is now clear that two 'Pan-African age' mobile belts cut across the East Antarctic Shield, the Lützow Holm and Prydz Belts, and these rework, truncate and offset three regions of late Mesoproterozoic to early Neoproterozoic tectonism: the Maud, Rayner and Wilkes Provinces. These three segments were previously assumed to form one single 'Grenville-age' orogen around the coastline, but now appear to represent distinct crustal fragments juxtaposed in the Cambrian. The Lützow Holm Belt is a continuation of the East African Orogen and developed during closure of the Mozambique Ocean. It is unclear whether the Prydz Belt involved ocean closure or regional-scale transcurrent tectonics, but it does juxtapose numerous terranes with different geological histories, and it seems likely that the East Antarctic Shield behaved as a collage rather than a keystone during the amalgamation of Gondwana. Increasing evidence that East Gondwana underwent significant reorganisation during the Cambrian requires changes to current models for both the assembly of Gondwana and the configuration of the late Mesoproterozoic supercontinent of Rodinia. © 2000 Elsevier Science Limited. All rights reserved.

RÉSUMÉ—On supposait généralement que la tectonique dans l'Est-Antarctique s'était restreinte au Néoprotérozoïque supérieur-Cambrien à l'Orogène de Ross, situé sur la bordure paléo-pacifique du bouclier précambrien, mais il est clair à présent que deux chaînes d'âge 'pan-africain' recoupent le Bouclier Est-Antarctique: les chaînes de Lützow Holm et de Prydz. Ces chaînes remobilisent, tronquent et décalent trois régions tectonisées au Mésoprotérozoïque supérieur-Néoprotérozoïque inférieur, les Provinces de Maud, Rayner et Wilkes. On supposait auparavant que ces trois segments formaient au bord de la côte un seul orogène d'âge 'grenvillien', mais il apparaît à présent qu'ils représentent des fragments crustaux distincts juxtaposés au Cambrien. La chaîne de Lützow Holm est le prolongement de l'Orogène Est-Africain et s'est formée au cours de la fermeture de l'Océan du Mozambique. Dans le cas de la chaîne de Prydz, les rôles joués par la fermeture océanique et la tectonique régionale transcurrente ne sont pas clairs, mais la chaîne juxtapose nettement de nombreux terrains d'histoires géologiques différentes et il paraît vraisemblable que le Bouclier Est-Antarctique s'est comporté comme collage plutôt que comme clef de voûte durant l'assemblage du Gondwana. Les arguments de plus en plus nombreux en faveur de la réorganisation significative de l'Est du Gondwana au Cambrien demandent de modifier les modèles actuels sur l'assemblage du Gondwana et la configuration du supercontinent mésoprotérozoïque supérieur de Rodinia. © 2000 Elsevier Science Limited. All rights reserved.

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INTRODUCTION

The notion of Gondwana, a great southern supercontinent, stems from observed patterns in the present-day distribution of Permo-Carboniferous glacial sediments, plant fossils and other geological features (Suess, 1904–1924; du Toit, 1937; Wegener, 1966; Mohana Kumar, 1996), and it is now well established that Gondwana existed throughout much of the Palæozoic and broke apart in the Late Mesozoic, as South America, Africa, India and Australia drifted northwards from Antarctica to their present positions. What is less clear is how and when Gondwana formed. Evidence for the birth of Gondwana and the nature of earlier continental configurations is provided by basement rocks in the southern continents (Fig. 1); and, although our knowledge is limited in many regions by poor exposure and ambiguous age data, these rocks can be crudely divided into Archæan and Palæoproterozoic cratons (ancient continental nuclei that were stabilised before 1600 Ma and behaved as rigid blocks during younger tectonic events) and mobile belts that were formed after 1600 Ma welding the stable cratons together. These mobile belts can be ascribed to three broad tectonic events. The first group developed in the late Mesoproterozoic to early Neoproterozoic (1300–900 Ma) and are commonly referred to as 'Grenville-age' mobile belts after the late Mesoproterozoic Grenville Province of eastern North America, although in Africa they are also known as 'Kibaran' mobile belts. These are truncated by late Neoproterozoic to Cambrian (700–500 Ma) 'Pan-African' mobile belts (following the original definition of Kennedy, 1964), which are known as 'Brasiliano' belts in South America. The third group comprises the Ross-Delamerian Orogen, which developed at the Palæopacific margin of

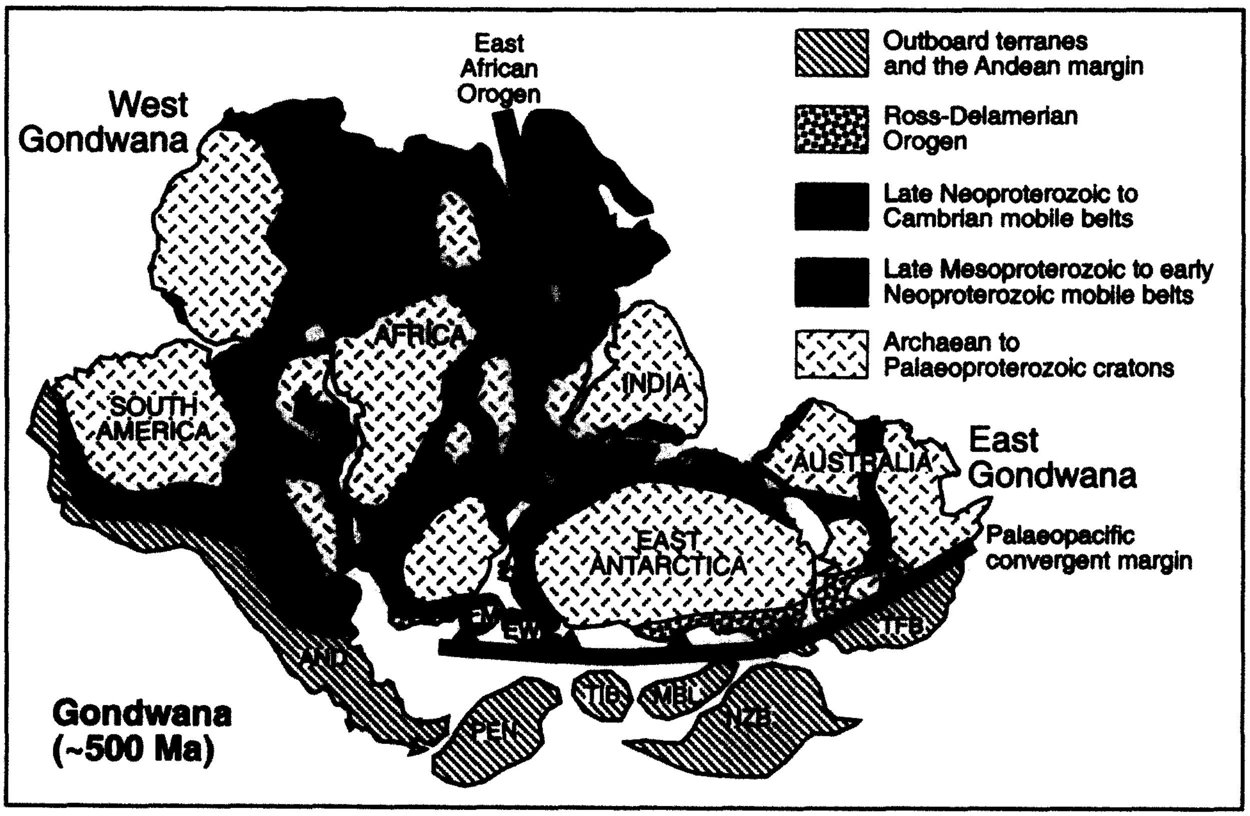

Figure 1. Basement provinces of Gondwana adapted from Hoffman (1991), Trompette (1994) and Unrug (1996). This is representative of many maps published over the last ten years and shows the assumed arrangement of cratons and mobile belts after amalgamation at 500 Ma using the continental fit of Lawver and Scotese (1987) and Dalziel and Grunow (1992). The gap between India and Australia was filled by rocks of unknown age, now consumed by the Himalayan Orogen or buried by the sediments shed by the resulting mountain range. Three possible southern extensions of the East African Orogen are shown and discussed in the text. Lack of evidence for Pan-African tectonism in East Antarctica meant that this orogen was not extended into Antarctica, but new data indicate that it continues into East Antarctica and maps of Gondwana should be revised accordingly. The Tasman Fold Belt (TFB), New Zealand Block (NZB), Marie Byrd Land (MBL), Thurston Island Block (TIB) and Antarctic Peninsula (PEN) are assumed to be outboard of the Ross-Delamerian Arc. Also shown is crustal material accreted to the Andean margin during the Palæozoic (AND). The Saldania Belt at the southern tip of Africa is treated as part of the Ross-Delamerian Orogen (Rozendaal et al.*, 1999). FM: Falkland-Malvinas Block; EW: Ellsworth-Whitmore Block.*

Gondwana (Fig. 1) and preserves evidence of Early Palæozoic tectonism (550–450 Ma). Although partly contemporaneous with the Pan-African event, the Ross-Delamerian Orogeny has a distinct setting (see later in the text) involving strike-slip tectonics, subduction and accretion of outboard terranes (a peripheral orogenic belt using the terminology of Murphy and Nance, 1991). This contrasts with the Pan-African belts, which are typically internal with respect to the supercontinent margins (interior orogens of Murphy and Nance, 1991) and interpreted as zones of collision between major continental blocks during the final amalgamation of Gondwana (Rogers *et al.*, 1995; Unrug, 1996).

Palæomagnetic data and basement geology have been used to support a two-stage assembly of Gondwana (McWilliams, 1981; Rogers *et al.*, 1995; Unrug, 1996). Most published maps indicate an abundance of Pan-African mobile belts within West Gondwana (South America and Africa), consistent with the consolidation of several continental fragments of varying sizes at 700–500 Ma, whereas East Gondwana (India, Australia and East Antarctica) appears to be dominated by Grenville-age mobile belts with little evidence of Pan-African tectonism (Fig. 1). Thus, East Gondwana was assumed to have amalgamated at 1300–900 Ma, and then combined with the fragments of West Gondwana at 700–500 Ma. The East African Orogen, extending from Arabia through Ethiopia, Kenya and Tanzania, is generally assumed to be the principal collision zone between East and West Gondwana (Fig. 1).

Widespread evidence in Gondwana (and the northern continents) for a period of craton amalgamation at 1300–900 Ma is consistent with the existence of a pre-Gondwana supercontinent, which has been named Rodinia (Fig. 2: Hoffman, 1991). Although the details of the Rodinia reconstruction are

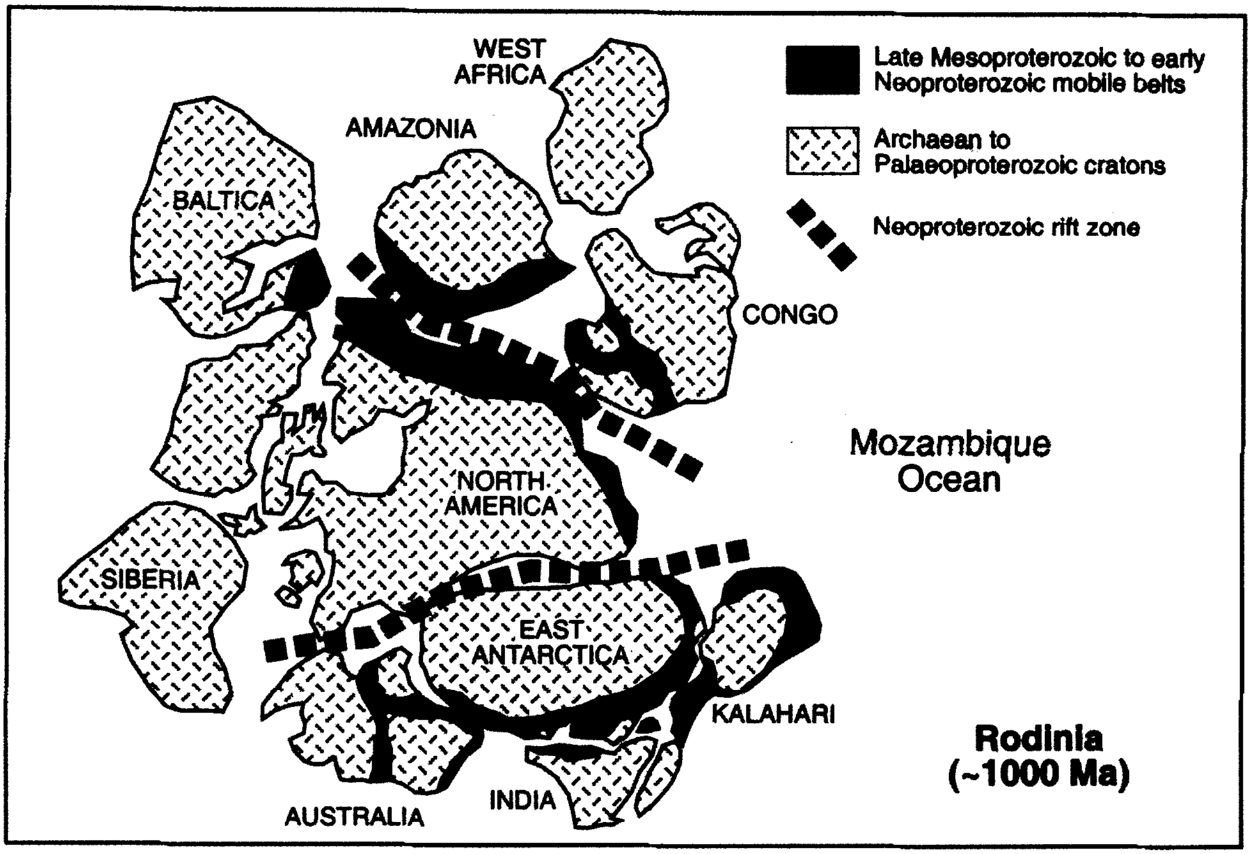

Figure 2. *Rodinia configuration at 1000 Ma (adapted from Hoffman, 1991). Two Neoproterozoic rifts split Rodinia into three parts, and Gondwana assembled by anti-clockwise rotation of the lower part (East Gondwana) and clockwise rotation of the top part (fragments of West Gondwana), closing the Mozambique Ocean. Hoffman (1991) argued that the rifts developed simultaneously, but most workers now favour initial rifting between North America and East Gondwana, followed by rotation of East Gondwana towards the fragments of West Gondwana, and rifting of North America from West Gondwana after collision along the East African Orogen (Dalziel, 1997). This configuration places the Kalahari Craton in East Gondwana at 1000 Ma (consistent with path 1 for the East African Orogen in Fig. 1) but new data indicate that the Kalahari Craton and part of East Antarctica were in West Gondwana and should be located with the other African cratons at the top of this diagram (Gose* et al., *1997). The Kalahari Craton comprises both the Archæan-Palæoproterozoic Kaapvaal-Zimbabwe Craton (shown in Figs 4 and 5) and adjacent Mesoproterozoic belts.*

somewhat speculative, it is commonly assumed to have the broad configuration first proposed by Moores (1991) and Dalziel (1991), which pairs the rifted margin of western North America with a counterpart along the margin of East Gondwana (eastern Australia and the Transantarctic Mountains), and links the late Mesoproterozoic Grenville Orogen of eastern North America with contemporaneous collisional belts in East Gondwana that suture Antarctica with South Africa, India and Australia. The transformation from Rodinia to Gondwana is generally viewed in terms of rifting along the present-day western and eastern margins of North America, leaving a coherent East Gondwana on one side and various unconsolidated West Gondwanan fragments on the other (Fig. 2), which later amalgamated to create Gondwana proper (Hoffman, 1991; Unrug, 1996).

As noted by du Toit (1937), East Antarctica is the 'key piece' of Gondwana about which the other southern continents can be arranged to reconstruct the Palæozoic supercontinent. East Antarctica also plays a vital role at the nucleus of the Rodinia reconstruction and in the notion of a coherent East Gondwana that survived the transition from Rodinia to Gondwana. All of the models proposed for the configuration and amalgamation history of these supercontinents are critically dependent on relationships in the East Antarctic Shield, which remain poorly understood due to limited outcrop and the logistic and financial constraints on fieldwork in this remote and intemperate location. This paper is an attempt to summarise the traditional views of Antarctic geology used to formulate the original models for assembly and dispersion of Rodinia and Gondwana and to give an overview of new data that question some of these models. As with many review papers, this contribution makes some gross simplifications, and the reader is advised to consult primary sources cited throughout the text for the details of each region.

THE EAST ANTARCTIC SHIELD

The Transantarctic Mountains are one of the Earth's major mountain ranges and extend for some 3000 km across the continent between the Ross and Weddell Seas (Fig. 3). This topographic feature marks a boundary between two regions with quite different geological histories, generally referred to as East and West Antarctica (Elliot, 1975; Tingey, 1991 and other chapters in that volume; Dalziel, 1992). This paper focuses on East Antarctica, which comprises a Precambrian to Ordovician basement of igneous and sedimentary rocks, deformed and metamorphosed to varying degrees and intruded by syn- to post-tectonic granites. This basement is locally overlain by undeformed Devonian to Jurassic sediments (the Beacon Supergroup) and intruded by Jurassic tholeiitic plutonic and volcanic rocks (the Ferrar Supergroup). West Antarctica, dominated by the sinuous Antarctic Peninsula, comprises at least four continental blocks (Fig. 3) which have moved relative to each other, and to East Antarctica, throughout the Phanerozoic, and is not considered further here. Traditional models of East Antarctic geology (Fig. 4; Ravich and Kamenev, 1975; Grew, 1982; James and Tingey, 1983; Tingey, 1991) involve a three-stage tectonic history:

i) the stabilisation of various Archæan to Palæoproterozoic cratons before 1600 Ma;

ii) the development of a high-grade late Mesoproterozoic to early Neoproterozoic (1300–900 Ma) mobile belt that follows, more-or-less, the present-day coast of East Antarctica; and

iii) low- to high-grade late Neoproterozoic to Ordovician tectonism (550–450 Ma) in the Ross Orogen, situated at the craton margin in the present-day Transantarctic Mountains, coupled with a static thermal overprint in much of the craton interior.

Craton stabilisation

The occurrence of relatively ancient cratons within the East Antarctic Shield was originally inferred using a number of field criteria, including the presence of mafic dykes that are absent in surrounding rocks or the development of granulite-facies assemblages in areas that are surrounded by rocks of amphibolite grade (Ravich and Kamenev, 1975; Grew, 1982; James and Tingey, 1983). The application of U-Pb zircon and other dating techniques has shown that many of these areas are indeed Archæan to Palæoproterozoic cratons, although the field criteria do not hold in all cases (Black *et al.*, 1992a). These areas of ancient crust can be divided into an extensive central craton, inferred to occupy much of the continental interior, and various marginal cratons exposed along the coast (Fig. 4).

The inferred central craton is largely hidden by the extensive continental ice sheet, but there is indirect evidence for Archæan to Palæoproterozoic (3.0–1.6 Ga) basement along much of the Ross Orogen, including age data for inherited zircon grains and whole rock Sm–Nd model ages for granite plutons, gneisses and migmatites (Borg *et al.*, 1990; Borg and DePaolo, 1991, 1994; Talarico *et al.*, 1995; Schüssler *et al.*, 1999). Part of this basement is exposed in the Miller Range area of the central Transantarctic Mountains (Borg *et al.*, 1990; Goodge *et al.*, 1991; Borg and DePaolo, 1991, 1994), although these Archæan to

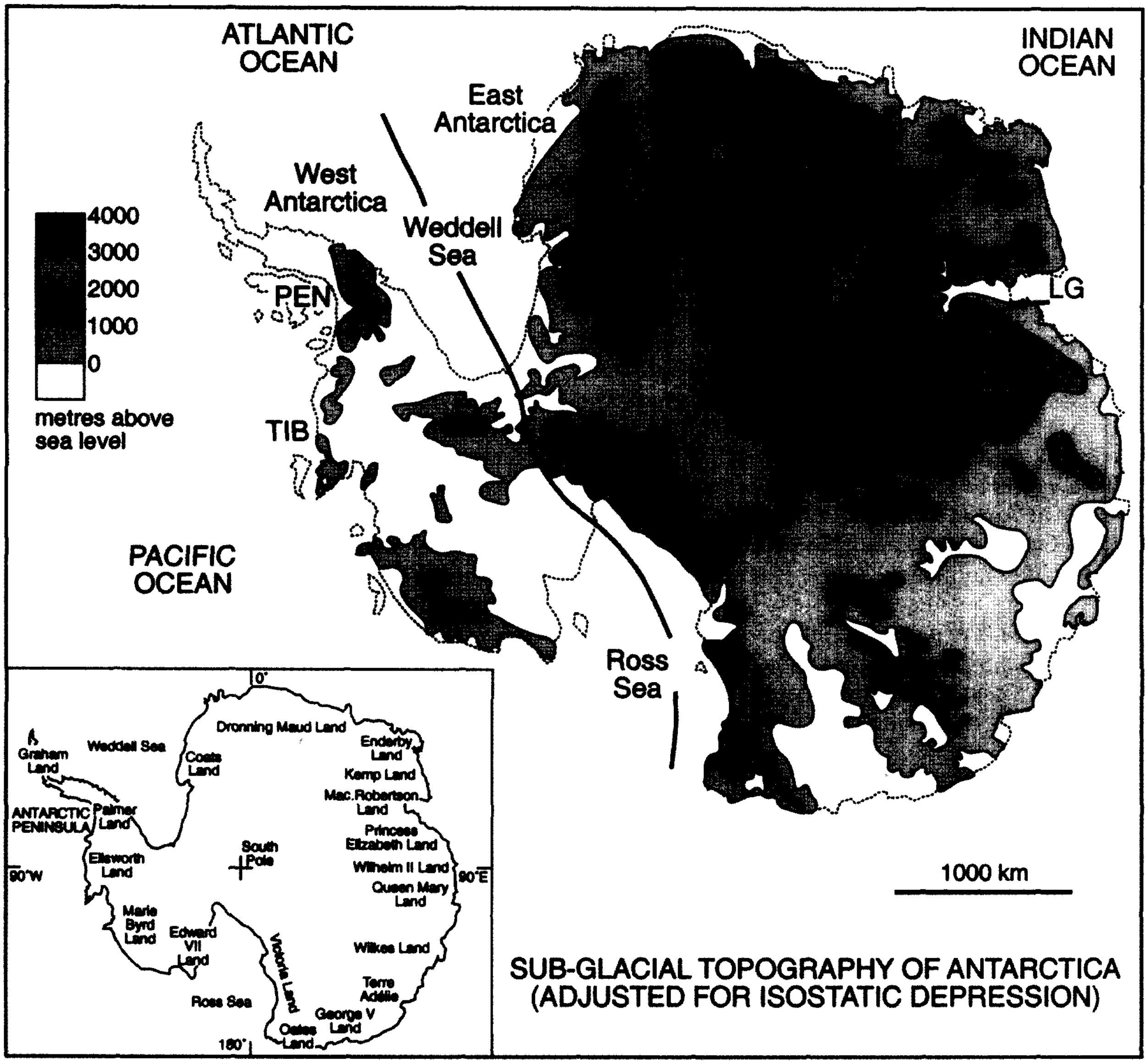

Figure 3. The sub-glacial topography of Antarctica, adjusted for the isostatic depression of the ice cap (after Drewry, 1983). The solid black line joining the Ross and Weddell Seas divides East and West Antarctica. The three most prominent features of East Antarctica are the Lambert Graben (LG), with approximate margins shown by black lines, the Gamburtsev Sub-glacial Mountains (GSM), and the Transantarctic Mountains (TAM). Also shown are the four principal blocks of West Antarctica: MBL: Marie Byrd Land; EW: Ellsworth-Whitmore Block; TIB: Thurston Island Block; PEN: Antarctic Peninsula. The inset depicts the approximate locations of the bewildering geographical divisions of Antarctica, named after a mixture of explorers, their wives, their sponsors, and their sovereigns.

Palæoproterozoic protoliths have been reworked during high-grade late Neoproterozoic to Cambrian deformation and metamorphism of the Ross Orogeny (Goodge and Dallmeyer, 1992, 1996; Goodge *et al.*, 1992, 1993b; Goodge and Fanning, 1999). Other edges of this inferred central craton may be exposed in the Shackleton Range (Pankhurst *et al.*, 1983; Tessensohn *et al.*, 1999), where Palæoproterozoic protoliths (2.5–1.7 Ga) are variably overprinted by Cambrian tectonism, and the southern Prince Charles Mountains (Halpern and Grikurov, 1975; Tingey, 1982, 1991; Kovach and Belyatsky, 1991; Sheraton *et al.*, 1996), where Archæan granitic basement (3.2–2.5 Ga) is exposed with younger metasediments. It should be noted that the southern Prince Charles Mountains are arguably the least understood region of East Antarctica and still lack a sound geochronological framework. Neoarchæan to Palæoproterozoic outcrops (2.8–1.6 Ga) on the coast of Adélie and King George V Lands (Oliver *et al.*, 1983; Stüwe and Oliver, 1989; Tingey, 1991; Peucat *et al.*, 1999) are also regarded as part of the central craton, as are similar aged rocks of the Gawler Craton in southern Australia (Fanning *et al.*, 1988; Oliver and Fanning, 1997). Fanning *et al.* (1995, 1996) have named this extensive region of Archæan to Palæoproterozoic crust the Mawson Continent, which would have been contiguous with the North American Shield in the Rodinia configuration, although suggested correlations between specific provinces in the two shields remain speculative (Borg and DePaolo, 1994).

A number of marginal Archæan cratons occur around the East Antarctic coastline (Fig. 4), and are correlated with similar cratons in continents that rifted from Antarctica in the Late Mesozoic. The Grunehogna Province of western Dronning Maud Land, comprising Archæan basement (3.0–2.8 Ga) and Mesopro-terozoic cover sediments, is widely assumed to be a rifted fragment of the Kaapvaal–Zimbabwe Craton of southern Africa (Barton *et al.,* 1987; Groenewald *et al.*, 1991, 1995; Moyes *et al.*, 1993, 1995). The Archæan Napier Complex (4.0–2.5 Ga) of Enderby and Kemp Lands (Sheraton *et al.*, 1980, 1987; Harley and Black, 1997) is correlated with Archæan terranes of southern India (Fedorov *et al.*, 1982b; Yoshida *et al.*, 1992), although Mezger and Cosca (1999) have noted that none of the formerly contiguous Indian terranes have yet yielded ages that closely match those of the Napier Complex. The Neoarchæan Vestfold Hills block (2.8–2.5 Ga) of Princess Elizabeth Land (Oliver *et al.*, 1982; Collerson and Sheraton, 1986; Black *et al.*, 1991; Snape *et al.*, 1997) is also likely to be related to the Precambrian rocks of India, although again an exact correlative has yet to be identified and could be hidden beneath the deposits of the Ganges and Brahmaputra Rivers.

There is evidence for reworked Archæan to Palæoproterozoic material within the younger metamorphic belts that fringe the cratons. Much of the Proterozoic Rayner Complex, which wraps around the southern margin of the Archæan Napier Complex, has been interpreted as reworked Napier material (Sheraton *et al.*, 1980; Sheraton and Black, 1983). This was based on the similarity of rock compositions in the two areas, the occurrence of deformed and metamorphosed mafic dykes in the Rayner Complex that were correlated with undeformed mafic dykes in the Napier Complex and the locally transitional nature of the boundary between the two. However, subsequent isotopic work has indicated that much of the Rayner Complex is relatively juvenile Proterozoic crust and the amount of reworked Archæan material is rather limited (Black *et al.,* 1987; Sheraton *et al.*, 1987; Shiraishi *et al.*, 1997).

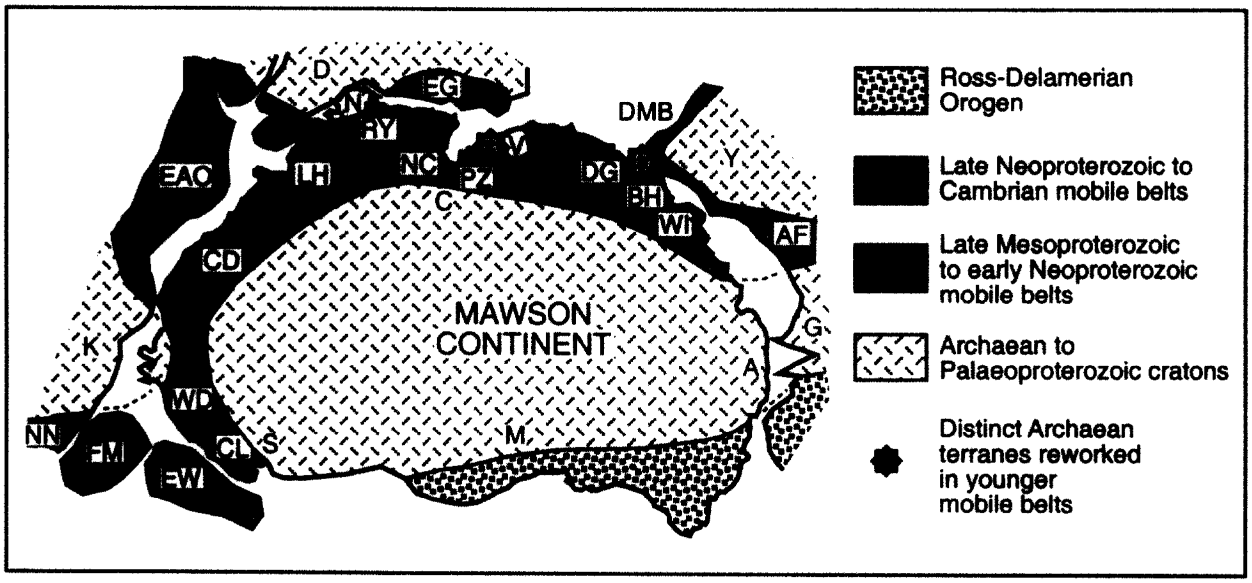

Figure 4. *A tectonic map of East Antarctica and adjacent parts of Gondwana, assuming the traditional view of Antarctic geology (Tingey, 1991) and a continental fit after Lawver and Scotese (1987). Archæan to Palæoproterozoic cratons have single letter labels. K: Kaapvaal-Zimbabwe Craton and its Antarctic extension (Grunehogna Province, unlabelled); D: Dharwar Craton and N: its Antarctic extension, the Napier Complex; V: Vestfold Hills; Y: Yilgarn Craton; and a central craton (the Mawson Continent) exposed in M: the Miller Range; S: Shackleton Range; C: southern Prince Charles Mountains; A: Terre Adélie and King George V Land; G: Gawler Craton of South Australia. Reworked Archæan cratons occur in the Rauer Group (R); and Denman Glacier region (D). Grenville-age regions have two letter labels. NN: Namaqua-Natal Province; FM: Falkland–Malvinas Block; EW: Ellsworth–Whitmore Block; EG: Eastern Ghats; AF: Albany-Fraser Orogen; and the coastal belt of Antarctica exposed in CL: Coats Land; WD: western Dronning Maud Land; CD: central Dronning Maud Land; LH: Lützow Holmbukta; RY: Rayner Complex; NC: northern Prince Charles Mountains; PZ: Prydz Bay coast; DG: Denman Glacier region; BH: Bunger Hills; WI: Windmill Islands. Pan-African mobile belts have three letter labels. DMB: Darling Mobile Belt; EAO: East African Orogen. A revised version of this diagram, incorporating new age data, is given in Fig. 5.*

Rocks with Archæan protoliths also occur in the Rauer Group of Princess Elizabeth Land, where they are interleaved with younger Proterozoic material (Sheraton *et al.*, 1984; Kinny *et al.*, 1993; Harley *et al.*, 1998). The Rauer Group is adjacent to the Archæan Vestfold Hills, and the Archæan component of the Rauer Group was previously held to be a reworked equivalent of the Vestfold Hills due to a dominance of felsic orthogneiss in both areas and the occurrence of deformed and metamorphosed mafic dykes in the Rauer Group correlated with undeformed mafic dykes in the Vestfold Hills (e.g. Sheraton and Collerson, 1983; Sheraton *et al.*, 1984), but these terranes are now known to have quite different geological histories. Archæan rocks of the Rauer Group are significantly older (3.3–2.8 Ga) than any crust exposed in the Vestfold Hills, indicating that these two regions are distinct continental fragments (Kinny *et al.*, 1993; Harley and Fitzsimons, 1995; Harley *et al.*, 1998). The geology of the Rauer Group is complex, with evidence of tectonic activity in the late Mesoproterozoic and Cambrian as well as the Archæan, and is discussed in more detail later.

Partly reworked Archæan crust is also exposed in the Denman Glacier region of Queen Mary Land. Orthogneisses at Cape Charcot, immediately west of the Denman Glacier, and the Obruchev Hills, immediately east of the Denman Glacier, have 3.0–2.9 Ga and 2.6 Ga protolith ages, respectively (Black *et al.*, 1992b; Sheraton *et al.*, 1993, 1995), and both could be reworked parts of the formerly adjacent southwestern Yilgarn Craton of Australia (Fig. 4; Wilde *et al.*, 1996). As with the Rauer Group, this poorly understood area is a complex mix of Archæan, Proterozoic and Cambrian rocks and is discussed in more detail later.

Late Mesoproterozoic to early Neoproterozoic tectonism

1300–900 Ma isotopic ages, determined originally by whole rock Rb-Sr techniques and confirmed with U-Pb zircon data, have been retrieved from amphibolite- to granulite-facies rocks in the Maud Province of Coats Land and western Dronning Maud Land (Moyes and Barton, 1990; Arndt *et al.*, 1991), the Rayner Complex of Enderby and Kemp Lands (Grew, 1978; Black *et al.*, 1987; Grew *et al.*, 1988), the adjacent Mawson Coast (Young and Black, 1991) and northern Prince Charles Mountains region of Mac.Robertson Land (Tingey, 1982; Kinny *et al.*, 1997; Boger *et al.*, 1999), the Rauer Group on the coast of Prydz Bay, Princess Elizabeth Land (Tingey, 1981; Kinny *et al.*, 1993), and the Bunger Hills (Sheraton *et al.*, 1992, 1993, 1995) and Windmill Islands (Blight and Oliver, 1977; Williams *et al.*, 1983; Post *et al.*, 1997) region of Wilkes Land. These areas comprise rocks with both igneous and sedimentary precursors but are dominated by orthogneiss units recording a prolonged history of early subduction-related magmatism followed by syn-collisional magmatism and high-grade metamorphism (e.g. Sheraton *et al.*, 1992, 1996; Groenewald *et al.*, 1995).

Until recently, no isotopic data (other than relatively easily reset Rb-Sr and K-Ar ages) were available for outcrops between the Maud Province and Rayner Complex. Robust age data were similarly absent for outcrops between the Prince Charles Mountains and the Rauer Group-Vestfold Hills region, and between the latter and the Bunger Hills-Windmill Islands area of Wilkes Land. However, the identification of 1300–900 Ma tectonism in all of those segments with reliable age data was taken as evidence for a continuous late Mesoproterozoic to early Neoproterozoic mobile belt skirting the coast of East Antarctica (Fig. 4) from Coats Land at the edge of the Weddell Sea, through Dronning Maud Land, the Rayner Complex in Enderby and Kemp Lands and northern Prince Charles Mountains of Mac.Robertson Land, into the coastal outcrops of Prydz Bay in Princess Elizabeth Land, the Denman Glacier region of Queen Mary Land and at least as far as the Bunger Hills and Windmill Islands of Wilkes Land. This Grenville-age belt has been given a number of names, including the Wegener-Mawson Mobile Belt (Kamenev, 1993) and the Circum East Antarctic Mobile Belt (Yoshida, 1995) and is a prominent feature of most tectonic maps of Antarctica. It can also be extended into formerly adjacent continents: the Maud Province correlates with the Namaqua-Natal Province of South Africa, rocks in the Rayner Complex and northern Prince Charles Mountains are an extension of the Eastern Ghats of India, and relationships in the Bunger Hills-Windmill Islands correspond closely with those in the Albany-Fraser Orogen of Western Australia. These correlations, and details of the age data from each area, are discussed in more detail later.

This apparent swathe of Grenville-age tectonism affecting juvenile magmatic rocks and locally reworking older cratons is widely interpreted as a suture between the inferred central Antarctic-South Australian Craton (the Mawson Continent) and the marginal cratons that make up much of southern Africa, India and Western Australia. Geochemical evidence for subduction before high-grade tectonism in all of these outcrops is consistent with a convergent collisional setting, as is structural evidence for collision tectonics with juxtaposition of various crustal terranes during transpression (e.g. Jacobs *et al.*, 1993, 1996).

Geological relationships in the Maud Province–Namaqua-Natal region are consistent with subduction beneath the central Antarctic Craton before collision rather than beneath the Kaapvaal-Zimbabwe Craton (Groenewald *et al.*, 1995; Jacobs *et al.*, 1996), but no constraints on subduction polarity have been reported for the other Grenville-age outcrops of East Antarctica.

The Ross Orogen and a contemporaneous thermal overprint

The Ross Orogen comprises a deformed sequence of Neoproterozoic to Cambrian sediments, described in numerous publications (see the review by Stump, 1995). These sediments were deposited at a passive margin, probably developed during the rifting of North America from the East Antarctic Shield, and were subsequently deformed and metamorphosed at low- to medium-grade and intruded by syn- to post-tectonic granitoids, although high-grade amphibolite to granulite assemblages occur locally. U-Pb zircon and monazite data indicate that deformation, plutonism and metamorphism commenced at about 550 Ma with peak metamorphism at 540–535 Ma in the central Transantarctic Mountains (Goodge *et al.*, 1993b) and 500–485 Ma in Victoria Land (di Vincenzo *et al.*, 1997; Schüssler *et al.*, 1999), and the post-tectonic Granite Harbour Intrusives were emplaced at 500–480 Ma as the orogen cooled (Stump, 1995). These events are generally interpreted in terms of oblique subduction of oceanic crust beneath a continental margin, with evidence for tectonic shortening during sinistral transpression (Goodge *et al.*, 1991, 1993a; Goodge, 1997), spatial geochemical and geological variations reflecting subduction and accretion of outboard terranes (Borg and DePaolo, 1991; Encarnación and Grunow, 1996) and the occurrence of eclogites at terrane boundaries (Peacock and Goodge, 1995; Ricci *et al.*, 1996; di Vincenzo *et al.*, 1997; Capponi *et al.*, 1997). In the past, it was unclear whether high-grade metamorphic rocks in the Ross Orogen, including relatively low pressure granulite-facies rocks and high pressure eclogites, are relics of the craton or whether they stabilised during the Ross tectonic event. It now seems likely that most, if not all, metamorphic assemblages in the Transantarctic Mountains reflect Ross tectonism (e.g. Adams and Höhndorf, 1987; Goodge *et al.*, 1993b; di Vincenzo *et al.*, 1997; Schüssler *et al.*, 1999), although there is local isotopic evidence that some rocks in the central Transantarctic Mountains were derived from Palæoproterozoic precursors (Goodge and Fanning, 1999).

It has long been recognised that Early Palæozoic tectonism in the Ross Orogen was contemporaneous with an isotopic overprint throughout much of East Antarctica. Indeed, 550–450 Ma K-Ar and Rb-Sr mineral ages formed the bulk of geochronological data for East Antarctica until recently (e.g. Picciotto and Coppez, 1963, 1964; Angino and Turner, 1964; Ravich and Krylov, 1964; Webb *et al.*, 1964; Krylov, 1972; James and Tingey, 1983; Tingey, 1991). Given the relatively low blocking temperature for K-Ar and Rb-Sr diffusion in mineral systems, these data were ascribed to a medium-grade thermal overprint associated with granitoid plutonism and pegmatite emplacement (Tingey, 1981, 1982, 1991; James and Tingey, 1983; Sheraton and Black, 1988; Grantham *et al.*, 1991). Deformation was thought to be restricted to local greenschist or amphibolite grade shear zones and mylonites, and the Early Palæozoic event in East Antarctica was thus interpreted as a static intraplate thermal overprint, perhaps related to magmatic underplating of the crust (Moyes *et al.*, 1993; Stüwe and Sandiford, 1993).

A CHALLENGE TO THE TRADITIONAL VIEW

The belief that Pan-African events in East Antarctica, and elsewhere in East Gondwana, were limited to granite plutonism and a low- to medium-grade thermal overprint associated with localised shearing has been challenged by new age data indicating that much of the high-grade metamorphism and deformation in the East Antarctic Shield is late Neoproterozoic to Cambrian in age (Fig. 5). This tectonism is best preserved within Dronning Maud Land and Prydz Bay, but there is also a poorly constrained Cambrian overprint in the Denman Glacier region.

Dronning Maud Land: an extension of the East African Orogen?

It is widely accepted that amalgamation of East and West Gondwana occurred by closure of the Mozambique Ocean (Fig. 2), and that this collision is marked by the 700–500 Ma East African Orogen (Shackleton, 1986), but the southern extension of this belt from Kenya and Tanzania has been problematic (Fig. 1). Hoffman (1991) favoured a southwestwards continuation (present-day African co-ordinates) through the Zambezi and Damara Belts (path 1 in Fig. 1), whereas others argued for a southern or southeastern continuation towards Antarctica (paths 2 and 3: Stern, 1994; Shackleton, 1996) in line with increasing evidence for high-grade Pan-African metamorphism and deformation in Madagascar (Paquette *et al.*, 1994; Kröner *et al.*, 1996), southern India (Choudhary *et al.*, 1992; Bartlett *et al.*, 1998) and Sri Lanka (Kröner and Williams, 1993; Hölzl *et al.*, 1994). The apparent

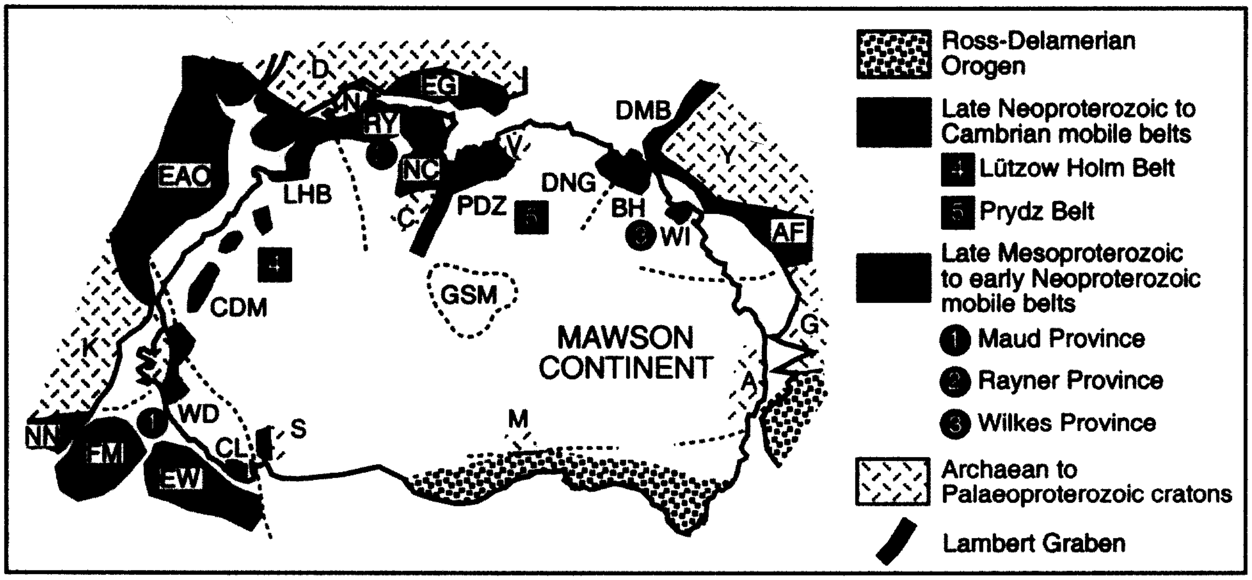

Figure 5. *Tectonic provinces in East Antarctica and adjacent parts of Gondwana, taking into account new evidence for Pan-African tectonism in East Gondwana. Cratons are labelled as in Fig. 4 (single letter labels), but the two reworked cratons depicted in Fig. 4 have been omitted for clarity. Late Mesoproterozoic to early Neoproterozoic belts (two letter labels) are exposed in three main Antarctic segments: the Maud Province comprising Coats Land (CL) and western Dronning Maud Land (WD), contiguous with the Namaqua-Natal Province (NN) and the Falkland-Malvinas (FM) and Ellsworth-Whitmore (EW) Blocks; the Rayner Province comprising the northern Prince Charles Mountains (NC) and Rayner Complex (RY), and contiguous with the Eastern Ghats (EG); and the Wilkes Province comprising the Windmill Islands (WI) and Bunger Hills (BH), and contiguous with the Albany-Fraser Orogen (AF). Evidence of Grenville-age tectonism in the Rauer Group of Prydz Bay (unlabelled) has been noted, even though these protoliths may have been intensely reworked by Cambrian events. These Grenville-age segments are separated by two regions of high-grade Pan-African tectonism (three letter labels). The Lützow Holm Belt is the extension of the East African Orogen (EAO) into Lützow Holmbukta (LHB), central Dronning Maud Land (CDM), and the Shackleton Range. The Prydz Belt is an extension of the Darling Mobile Belt (DMB), and comprises the Prydz Bay coast (PDZ) and Denman Glacier region (DNG), and may extend southwards along the eastern margin of the Lambert Graben towards the unexposed Gamburtsev Sub-glacial Mountains (GSM). Unshaded parts of Antarctica: areas of no exposure; dashed lines: possible province boundaries across these areas. Boundaries depicted for the Pan-African mobile belts are somewhat arbitrary as they overprint and are transitional with high-grade Grenville-age belts. In general, they mark the edges of high-grade Cambrian tectonism, defined by the limit of U-Pb resetting in zircon, although the boundary shown between the Maud Province and Lützow Holm Belt is the limit of low-grade Cambrian tectonism (defined by the K-Ar system) and follows the Heimefront Shear Zone.*

termination of this orogen within Africa (rather than continuing into Antarctica) was attributed to closure of the Mozambique Ocean about a pivot in South Africa (Hoffman, 1991; Stern, 1994).

The perceived absence of pervasive Pan-African tectonism in East Antarctica was first challenged by 550–530 Ma U-Pb zircon ages from granulite-facies gneisses in the Lützow Holmbukta region of eastern Dronning Maud Land (Shiraishi *et al.*, 1994), suggesting that the East African Orogen did indeed extend into Antarctica (Rogers *et al.*, 1995). This was confirmed by U-Pb zircon data from central Dronning Maud Land, where charnockite and anorthosite emplacement at 600 Ma was followed by high-grade tectonism and magmatism at 590–550 Ma and 530–515 Ma (Mikhalsky *et al.*, 1997; Jacobs *et al.*, 1998). Although all high-grade minerals and fabrics in Lützow Holmbukta and central Dronning Maud Land developed at 550–500 Ma, these gneisses also preserve evidence for late Mesoproterozoic tectonic events that were later overprinted by Pan-African tectonism. Zircons with a relatively poorly defined age range of 1020–1000 Ma in paragneisses of the Lützow Holm Complex are interpreted as detrital grains (Shiraishi *et al.*, 1994), and protolith zircons in metavolcanics and orthogneiss from central Dronning Maud Land indicate felsic volcanism at ~1130 Ma and granitoid magmatism and metamorphism at ~1080 Ma (Jacobs *et al.*, 1998).

Pan-African reworking of Mesoproterozoic magmatic rocks in central Dronning Maud Land, and of sediments in Lützow Holmbukta derived from Grenville-age protoliths, decreases markedly in intensity both westwards into the Maud Province and eastwards into the Rayner Complex. Outcrops in western Dronning Maud Land and Coats Land preserve an east to west transition from late Mesoproterozoic rocks deformed and metamorphosed under amphibolite conditions at 600–450 Ma to late Mesoproterozoic rocks with no younger isotopic overprint, even in the K-Ar system (Jacobs *et al.*, 1995, 1996; Groenewald *et al.*, 1995; Moyes and Groenewald, 1996). A similar orientation of Grenville-aged and Pan-African structures makes it difficult to delimit the extent of Pan-African tectonism, but Jacobs *et al.* (1995, 1996, 1997b) have proposed that the western boundary is marked by the Heimefront Shear Zone. A less well-defined transition has been identified in the Rayner Complex to the east of Lützow Holmbukta (Black *et al.*, 1987; Shiraishi *et al.*, 1997). Orthogneiss in the Thala Hills (300 km east of Lützow Holmbukta) has a Grenville-age protolith, but granulite-facies assemblages and fabrics in these rocks developed at 540–520 Ma, when there was new zircon growth and significant resetting of U-Pb isotopes in pre-existing zircon. In contrast, gneisses in the Nye Mountains (400 km east of Lützow Holmbukta) yield 980–910 Ma zircon ages with no U-Pb evidence of a Pan-African overprint, implying that high-grade assemblages and fabrics in these rocks reflect Grenville-age tectonism. 570–450 Ma Rb-Sr biotite and whole rock ages from the Rayner Complex (summarised by Sheraton *et al.*, 1987) are also predominantly from the Thala Hills region, but similar Rb-Sr ages from the Nye Mountains and a 511 Ma K-Ar biotite age from pegmatite at Doggers Nunataks in the eastern Rayner Complex (600 km east of Lützow Holmbukta) indicate a moderate Pan-African thermal overprint throughout the Rayner Complex, probably associated with pegmatite emplacement and mylonite development.

Although the western and, to a lesser extent, the eastern margins of the Cambrian mobile belt in Dronning Maud Land have been defined, it is difficult to constrain the precise location of the inferred suture between East and West Gondwana in this region (Jacobs *et al.*, 1998). Shackleton (1996) argued that it was likely to pass through, or near, the Heimefront Shear Zone at the western margin of Pan-African tectonism, whereas Grunow *et al.* (1996) and Wilson *et al.* (1997) preferred a suture passing through the Lützow Holmbukta region near the eastern limit of high-grade Pan-African tectonism, and these differences mirror, to a large extent, the considerable uncertainty in the location of the suture within the East African Orogen itself. Whatever its location on the coast of Dronning Maud Land, there is good evidence that the suture passes through the Shackleton Range (Grunow *et al.*, 1996; Wilson *et al.*, 1997; Tessensohn *et al.*, 1999) where Cambrian tectonism has juxtaposed Palæoproterozoic basement and Neoproterozoic sediments (Pankhurst *et al.*, 1983) with evidence for collisional nappe tectonics (Buggisch and Kleinschmidt, 1999) and a Neoproterozoic ophiolite complex with Pan-African metamorphic ages (Talarico *et al.*, 1999). In the past, Early Palæozoic tectonism in the Shackleton Range has been correlated with the peripheral Ross Orogen, but it is more likely that it correlates with the interior Pan-African orogens developed in response to collisional tectonics during the amalgamation of Gondwana, which would explain why the tectonic grain of the Shackleton Range is perpendicular to that of the Transantarctic Mountains.

Further evidence for the continuation of the principal suture between East and West Gondwana across Antarctica to the Shackleton Range has been provided by the palæomagnetic data of Gose *et al.* (1997), which indicate that the Kaapvaal-Zimbabwe-Grunehogna Craton and the Grenville-age mobile belt exposed immediately south of this craton in the Maud Province of Antarctica and the Namaqua-Natal Province of southern Africa, did not amalgamate with East Gondwana until the Cambrian. These data still allow a coherent East Gondwana throughout the Neoproterozoic (comprising the bulk of East Antarctica, India and Australia), but indicate that southern Africa and much of Dronning Maud Land-Coats Land were part of West Gondwana and not East Gondwana as previously believed.

Prydz Bay and the Denman Glacier region: a second Cambrian suture?

Various high-grade metamorphic and intrusive rocks crop out along the southern margin of Prydz Bay, between the Lambert Graben and the Vestfold Hills-Rauer Group (Sheraton and Collerson, 1983; Fitzsimons, 1997). These rocks were assumed to be a westward extension of late Mesoproterozoic high-grade rocks in the Rauer Group (Tingey, 1981; Kinny *et al.*, 1993) and thus part of the East Antarctic Grenville-age belt. A poorly defined Rb-Sr whole rock isochron of ~560 Ma for various paragneisses (Sheraton *et al.*, 1984) was attributed to a low- to medium-grade overprint associated with the emplacement of post-tectonic plutons like the Landing Bluff Granite, which has a Rb-Sr whole rock age of ~490 Ma (Tingey, 1981; recalculated by Sheraton *et al.*, 1984) and a U-Pb SHRIMP zircon age of ~500 Ma (L.P. Black, *unpubl. data*, quoted by Tingey, 1991).

This traditional model of high-grade Grenville-age tectonism, followed by magmatism and a low- to medium-grade Cambrian thermal overprint, was first challenged in the Prydz Bay region by Pb-Pb zircon evaporation ages of 560–540 Ma for the syn-tectonic Progress Granite (Zhao *et al.*, 1992), which were subsequently refined to 515 Ma by SHRIMP U-Pb zircon analysis (Carson *et al.*, 1996). These ages imply that at least the later stages of high-grade ductile deformation in southern Prydz Bay are Pan-African in age, as do garnet-whole rock Sm-Nd ages of 517–467 Ma for paragneiss and leucogneiss samples (Hensen and Zhou, 1995). SHRIMP U-Pb ages of 535–530 Ma for zircon and monazite in partial melt bodies (Fitzsimons *et al.*, 1997) confirmed that all high-grade structures and mineral assemblages in the paragneiss developed at 550–500 Ma. Older zircons within the paragneiss, ranging from 1200–700 Ma, are probably detrital grains (Zhao *et al.*, 1995), although they have also been used as evidence for Grenville-age metamorphism of the paragneiss before reworking at 550–500 Ma (Zhang *et al.*, 1996). In contrast, orthogneiss units interleaved with the paragneiss locally preserve 960–920 Ma U-Pb zircon ages (Zhao *et al.*, 1995) and 990–900 Ma garnet-whole rock Sm-Nd ages (Hensen and Zhou, 1995), although high-grade fabrics in these rocks are still likely to reflect Cambrian tectonism. The extent of Cambrian tectonism in the Rauer Group is controversial (Dirks and Wilson, 1995; Harley and Fitzsimons, 1995; Hensen and Zhou, 1997; Harley *et al.*, 1998). Two distinct terranes have been identified in the Rauer Group on the basis of protolith age (3.3–2.8 Ga and 1060–1000 Ma: Kinny *et al.*, 1993). U-Pb zircon systematics are partially reset at 550–490 Ma in both terranes, which is consistent with their juxtaposition during Cambrian tectonism (Hensen and Zhou, 1997), but it is not clear whether high-grade mineral assemblages and fabrics reflect Cambrian or earlier events. It is also possible that the Vestfold Hills Block was juxtaposed with the Rauer Group at this time.

The western margin of high-grade pervasive Cambrian tectonism in Prydz Bay is broadly defined by the Lambert Glacier-Amery Ice Shelf system, which follows the underlying Lambert Graben (Fig. 3; Wellman and Tingey, 1976; Fedorov *et al.*, 1982a). Granulite metamorphism and deformation to the east of this regional structure reflect pervasive Cambrian tectonism, with rare relics of reworked Grenville-aged crust, whereas high-grade fabrics and minerals in the northern Prince Charles Mountains, to the west of the Lambert Graben, reflect tectonism at 1000–950 Ma (Kinny *et al.*, 1997; Boger *et al.*, 1999). Although they preserve no U-Pb evidence for pervasive Pan-African reworking, gneisses at the eastern edge of the northern Prince Charles Mountains, immediately adjacent to the Lambert Graben, are intruded by 550–500 Ma biotite granite and pegmatite (Manton *et al.*, 1992), and show an increased Pan-African influence in Sm-Nd garnet-whole rock data (Hensen *et al.*, 1997) with a metamorphic overprint attributed to the Pan-African event (Scrimgeour and Hand, 1997). Rb-Sr biotite data yield ages of 550–450 Ma for much of the Prince Charles Mountains (Tingey, 1991; Hensen *et al.*, 1997) indicating that the Pan African event had a significant thermal influence in the region even though pervasive fabric and mineral assemblages reflect Grenville-age tectonism; and, as with the Rayner Complex, the Cambrian overprint is spatially and temporally associated with pegmatite emplacement and amphibolite- to greenschist-facies mylonite zones. The eastern boundary of Cambrian tectonism is less easy to define due to a lack of basement outcrop for about 1000 km east of the Rauer Group-Vestfold Hills region, but it is possible that Cambrian tectonism extends all of this distance to outcrops at Mirny Station and Denman Glacier, which, although not as well studied as Prydz Bay, preserve evidence of Pan-African activity.

A large charnockite pluton of probable Cambrian age (K-Ar and Rb-Sr data: Ravich *et al.*, 1968; McQueen *et al.*, 1972) occurs in the vicinity of Mirny Station (250 km west of Denman Glacier), and a syenite pluton immediately west of Denman Glacier has yielded 516 Ma U-Pb zircon ages (Black *et al.*, 1992b). These plutons intrude various orthogneiss lithologies including tonalitic gneiss, which has a U-Pb zircon emplacement age of 3.0 Ga and evidence for further zircon growth during high-grade tectonism at 2.9 Ga, followed by partial resetting of the U-Pb system during magmatism at 600–500 Ma (Black *et al.*, 1992b). Structural relationships in these rocks are poorly known, and it is unclear whether the Cambrian thermal event was associated with deformation. Pan-African events are also recorded by partial resetting of Rb-Sr and K-Ar isotope systems (but not U-Pb zircon) and the emplacement of 500 Ma alkali basalt and trachybasalt dykes in gneisses of the Bunger Hills, east of Denman Glacier (Sheraton *et al.*, 1990). However, unlike the west side of Denman Glacier, this overprint was imposed upon rocks with widespread evidence of high-grade late Mesoproterozoic tectonism. U-Pb zircon dating of rocks immediately east of Denman Glacier has identified orthogneiss protoliths with 2.6 Ga and 1700–1500 Ma magmatic ages, which were deformed and metamorphosed at 1190 Ma under granulite-facies conditions, and then intruded by 1170–1150 Ma gabbroic to granitic plutons and 1140 Ma dolerite dykes (Sheraton *et al.*, 1992). A lack of evidence for these Mesoproterozoic events west of Denman Glacier implies that the two rock masses on either side of the glacier were juxtaposed sometime after 1140 Ma, perhaps during the Cambrian event (Sheraton *et al.*, 1992, 1995). It is possible that the youngest generations of mylonite and brittle fracture in the Bunger Hills were developed at this time (Sheraton *et al.*, 1993; Wilson, 1997), but more work is needed to constrain the timing of these structures.

Indirect evidence for the likely importance of Pan-African deformation in this area is provided by Gondwana reconstructions that place Denman Glacier adjacent to the 780–500 Ma Leeuwin Block at the southern end of the Darling Mobile Belt of Western Australia. This belt preserves evidence of magmatism (Wilde and Murphy, 1990; Nelson, 1996) and intense deformation during sinistral transcurrent shearing (Harris, 1994; Beeson *et al.*, 1995), and it has been suggested that the Darling Mobile Belt, Denman Glacier region and Prydz Bay outcrops are part of a single Pan-African mobile belt extending across 1000 km of the Antarctic coastline (Carson *et al.*, 1996; Hensen and Zhou,1997). The intensity of the Cambrian event decreases significantly to the east, and late Mesoproterozoic gneisses in the Windmill Islands preserve 1130–1050 Ma K-Ar biotite ages with no Pan-African overprint (Webb *et al.*, 1964).

Whereas the Cambrian mobile belt in Dronning Maud Land can be spatially related to the East African Orogen, and is thus assumed to mark a site of ocean closure and continental collision (Shackleton, 1996; Dalziel, 1997; Wilson *et al.*, 1997; Jacobs *et al.*, 1998), the regional tectonic setting of Cambrian deformation and metamorphism in Prydz Bay remains uncertain given that most of the contiguous rocks in Gondwana reconstructions are obscured by the Antarctic ice sheet or by extensive sediments that blanket much of eastern India. Cambrian tectonism in Prydz Bay was characterised by an extreme thermal gradient (850°C at depths of 25 km), high degrees of partial melting, pervasive ductile deformation and significant vertical movement of the crust including 10 km of exhumation after peak metamorphism, which have been interpreted in terms of crustal thickening during compression and burial of sediments to depths of 25 km followed by extensional exhumation as the orogen collapsed (Carson *et al.*, 1995, 1997; Dirks and Wilson, 1995; Fitzsimons, 1996, 1997). These features have, in turn, been ascribed to continental collision at a convergent plate margin (Fitzsimons, 1996, 1997; Carson *et al.*, 1997), although it must be emphasised that there is no conclusive evidence that Pan-African tectonism in Prydz Bay involved ocean closure. There is no record of convergent margin magmatism preceding the inferred collision and no exposed ophiolites, high pressure blueschists nor eclogites indicative of subduction. The observed relationships could reflect closure of a failed rift without an intervening ocean (Kriegsman, 1995) or intracontinental tectonism in response to collision in the East African Orogen (Wilson *et al.*, 1997). Evidence in support of collision and/or transcurrent tectonics includes the apparent juxtaposition of different terranes during the Pan-African event both in Prydz Bay and the Denman Glacier region, although more work is needed to correlate isotopic data with specific structural features.

DISCUSSION

New data indicate that the East Antarctic Shield underwent significant Cambrian tectonism and that the simple thermal overprint model for the Pan-African event in East Antarctica is not valid (Krynauw, 1996). Cambrian mobile belts overprint and truncate regions of Grenville-age tectonism, and it is important to determine whether these mobile belts developed by closure of major ocean basins (in which case East Gondwana did not amalgamate until the Cambrian) or involved significant lateral offset of the Grenville-age rocks that they truncate (in which case the present-day alignment of these Grenville-age rocks cannot be used to reconstruct the Rodinia Supercontinent). These two questions are likely to be related, given that opening and closure of major ocean basins will typically juxtapose terranes that were previously some distance apart, although it should be noted that it is possible to create large offsets without an intervening ocean by intracontinental transcurrent tectonics. The possibility of opening and closing an ocean without offset (closure orthogonal to original rifting) is perhaps less likely.

Late Mesoproterozoic tectonism: one belt or three distinct segments?

One of the major arguments in support of the Rodinia configuration is that it links Grenville-age belts in the Baltic and North America with a contemporaneous belt that skirts around the coast of East Antarctica (Dalziel, 1991; Moores, 1991). It is now apparent that the Grenville-age belt in East Antarctica actually comprises at least three broad 1300–900 Ma crustal segments, separated by two Pan-African mobile belts. These three segments are the Maud Province of Coats Land-Dronning Maud Land, the Rayner Complex-northern Prince Charles Mountains of Enderby, Kemp and Mac.Robertson Lands, and the Bunger Hills-Windmill Islands of Wilkes Land. In all three cases, there is evidence of inheritance from Meso- to Palæoproterozoic protoliths with little or no Archæan component (inherited zircons and Sm-Nd model ages span a typical range of 2.5–1.6 Ga). The three segments also have a similar Mesoproterozoic to early Neoproterozoic evolution, with a history of convergent margin magmatism, followed by granite plutonism and high-grade tectonism, most likely in response to a collision event, but the precise timing of these events is markedly different in each segment.

The Maud Province records a history of felsic volcanism and plutonism at 1140–1130 Ma, followed by a major episode of granitic plutonism and granulite-facies metamorphism at 1100–1080 Ma and a final phase of felsic magmatism and amphibolite metamorphism at 1060–1040 Ma (Arndt *et al.*, 1991). Similar histories are preserved in the Namaqua-Natal Province of South Africa (e.g. Thomas *et al.*, 1994, 1996; Cornell *et al.*, 1996; Jacobs *et al.*, 1997a), which was contiguous with the Maud Province before Gondwana break-up. In all cases, high-grade metamorphism was at 1100–1080 Ma in response to collision of the Kaapvaal-Zimbabwe-Grunehogna Craton with an unexposed continental fragment in the interior of Dronning Maud Land shortly before 1100 Ma, magmatism and deformation were complete by 1000 Ma, and K-Ar isotope diffusion had closed in micas by 960 Ma (Jacobs *et al.*, 1995). A dominant episode of magmatism and metamorphism at 1100–1080 Ma is also preserved in central Dronning Maud Land, even though this area was intensely reworked by Pan African tectonism (Jacobs *et al.*, 1998), implying that these rocks are part of the Maud Province.

The Rayner Complex records a history of felsic magmatism at 1500–1400 Ma, followed by granite and charnockite emplacement at 990–920 Ma, synchronous with granulite-facies metamorphism and pervasive deformation (Black *et al.*, 1987; Young and Black, 1991; Shiraishi *et al.*, 1997). A similar history is preserved in the northern Prince Charles Mountains, where volcanism at 1310–1270 Ma was followed by granite and charnockite emplacement during granulite-facies metamorphism and deformation at 1020–940 Ma and mylonite and pseudotachylite development at about 900 Ma (Beliatsky *et al.*, 1994; Kinny *et al.*, 1997; Boger *et al.*, 1999). This is consistent with the age of granulite-facies metamorphism in the Eastern Ghats Belt of India (960–940 Ma: Shaw *et al.*, 1997; Mezger and Cosca, 1999). In all cases, high-grade metamorphism and synchronous felsic magmatism is confined to the 1020–940 Ma time period, and this is commonly ascribed to 1000 Ma collision of the Napier Complex and related cratons in India with the Archæan craton exposed in the southern Prince Charles Mountains. Similar ages are preserved by nearby gneisses reworked by Pan-African tectonism. Shiraishi *et al.* (1994, 1997) reported 1020–910 Ma ages from the reworked western edge of the Rayner Complex and Lützow Holmbukta, whereas Hensen and Zhou (1995) and Zhao *et al.* (1995) reported 990–900 Ma ages from orthogneisses in the Cambrian mobile belt of Prydz Bay, immediately east of the Prince Charles Mountains. Mesoproterozoic orthogneiss in the Rauer Group preserves slightly older ages (1060–1000 Ma: Kinny *et al.*, 1993), and more work is needed to characterise Grenville-age events in this region. Another characteristic feature of the Rayner Province (and Sri Lanka) is enigmatic isotopic evidence for 700–800 Ma magmatism and metamorphism (Black *et al.*, 1987; Hölzl *et al.*, 1994; Hensen *et al.*, 1997; Shiraishi *et al.*, 1997), which again requires further study.

The Bunger Hills preserve a history of felsic orthogneiss emplacement at 1700–1500 Ma, followed by granulite-facies metamorphism at 1190 Ma, the intrusion of gabbroic to granitic rocks at 1170–1150 Ma and the emplacement of dolerite dykes and shear zone development at 1140 Ma (Sheraton *et al.*, 1990, 1992). The Windmill Islands preserve a history of amphibolite-facies metamorphism and deformation at 1340–1310 Ma, followed by a granulite-facies overprint at 1210–1180 Ma, and the emplacement of post-tectonic granites and charnockites at 1170–1130 Ma and late aplite dykes at 1135 Ma (Paul *et al.*, 1995; Post *et al.*, 1997). These two regions have similar histories, and both are consistent with the evolution of the Albany-Fraser Orogen of Western Australia, which records evidence for granite emplacement and high-grade metamorphism at 1300 Ma, followed by further magmatism and high-grade metamorphism at 1190–1130 Ma (Nelson *et al.*, 1995; Clark *et al.*, 2000). These events are interpreted in terms of protracted collision between the Yilgarn Craton of Western Australia and the Mawson Continent, commencing at 1300 Ma.

Metamorphism, deformation and magmatism clearly occurred at different times in the three major Grenville-age segments of East Antarctica, reflecting different times of continental collision (1100 Ma, 1000 Ma and 1300–1200 Ma). Although these age differences do not preclude the segments being part of a single collisional orogen between a central Antarctic craton and various marginal cratons, the consistency of ages within any one segment and the presence of Cambrian mobile belts between them suggests that three separate Grenville-age terranes are exposed in Antarctica, referred to here as the Maud, Rayner and Wilkes Provinces, and it follows that the present alignment of these terranes around the East Antarctic coastline is an artifact of Gondwana assembly at 600–500 Ma, rather than an original feature of Rodinia.

Pan-African tectonism and Gondwana amalgamation

Two high-grade Cambrian mobile belts have been identified in East Antarctica and are referred to as the Lützow Holm Belt and the Prydz Belt in the following discussion. Tectonism was, more-or-less, synchronous in the two belts with zircon growth during granulite metamorphism at 550–515 Ma, and both belts overprint late Mesoproterozoic to early Neoproterozoic Grenville-age magmatic and metamorphic rocks. The Lützow Holm Belt separates the Grenville-age Maud and Rayner Provinces and is the southernmost segment of the East African Orogen, a broad region of Pan-African tectonism passing through eastern Africa, Madagascar, southern India and Sri Lanka, into Dronning Maud Land and the Shackleton Range. Evidence for ocean closure is well documented in the East African Orogen (Stern, 1994), and this is supported in the Lützow Holm Belt by the occurrence of ophiolite material in the Shackleton Range and palæomagnetic data consistent with a large separation between the Maud Province and the rest of East Gondwana in the early Neoproterozoic (discussed earlier in the text).

Further evidence for ocean closure along the Lützow Holm Belt is provided by the different ages of Grenville-age tectonism in the Maud and Rayner Provinces, on either side of the inferred suture. These age differences can be used to constrain the position of the suture zone within the broad region of Pan-African tectonism. Cambrian orthogneiss outcrops in central Dronning Maud Land preserve protolith ages consistent with the Maud Province (Jacobs *et al.*, 1998), indicating that they lie to the west of the suture. Similar constraints further east are less clear, since most protolith ages from Lützow Holmbukta are from detrital zircon grains rather than *in situ* magmatic grains, but Shiraishi *et al.* (1994) do report an age range of 920–1030 Ma, which is consistent with erosion of a Rayner Province source. More data are needed, preferably from meta-igneous lithologies, but available data imply that the suture lies between central Dronning Maud Land and Lützow Holmbukta, or passes through Lützow Holmbukta given that sediments with a Rayner isotopic signature could lie within the suture zone itself. Several workers have postulated a suture within the Lützow Holm Complex, based largely on the occurrence of adjacent low and intermediate pressure metamorphic terranes (with a polarity implying subduction beneath the Maud Province), and high-grade ultramafic rocks interpreted as ophiolite material (Hiroi *et al.*, 1991; Shiraishi *et al.*, 1987).

The identification of a Cambrian suture in Dronning Maud Land has required changes to established models for Gondwana assembly and the configuration of Rodinia (Gose *et al.*, 1997; Dalziel, 1997), essentially transferring the Maud and Grunehogna Provinces from East to West Gondwana. Far greater changes might be required if significant Pan-African displacements have occurred in Prydz Bay and the Denman Glacier region, at the heart of East Gondwana. The juxtaposition of several unrelated terranes in this region during Cambrian tectonism is consistent with collisional and/or transcurrent tectonics, as proposed in two recent models for Cambrian tectonics in East Gondwana. Wilson *et al.* (1997) proposed a tectonic escape model in which Cambrian tectonism in the Indian Ocean sector of Antarctica reflects transcurrent movement along intracontinental shear zones (with local transpression or transtension) in response to collision in the East African Orogen. Alternatively, Meert and van der Voo (1997) suggested that Gondwana assembled in two stages, with Australia–Antarctica colliding with India to form the 'Kuunga Orogen' sometime after India collided with West Gondwana along the East African Orogen. This model was an attempt to reconcile an apparent bimodal distribution of age data from Pan-African mobile belts with tectonism before 650 Ma in the East African Orogen and at 600–500 Ma in India, Sri Lanka and East Antarctica. Data now suggest that the climax of tectonic activity in both the Lützow Holm and Prydz Belts was at 530 Ma, but the possibility of two near-simultaneous collisions cannot be discounted, and would mean that East Antarctica comprises three major crustal fragments that did not combine until the Cambrian. The timing of collision coincides with the onset of subduction-related magmatism along the Ross Orogen (Encarnación and Grunow, 1996), which is consistent with the suggestion of Grunow *et al.* (1996) that subduction in the Ross Orogen was triggered by a need to compensate for the end of subduction in the Pan-African collisional orogens. Neither Wilson *et al.* (1997) nor Meert and van der Voo (1997) correlated their speculative regional structures with actual geological trends or lineaments in East Antarctica, but Kriegsman (1995) proposed that Cambrian tectonism extended westwards from Prydz Bay to meet the East African Orogen at a triple point centred on Sri Lanka. He suggested that this mobile belt passed through the Rayner Complex, where east-west retrograde mylonite zones of assumed Cambrian age have been reported (Clarke, 1988), but a southwards extension of the Cambrian mobile belt from Prydz Bay into the continental interior would seem more likely given that the degree of Cambrian reworking decreases markedly to the west of the Lambert Graben.

The Lambert Graben extends inland for at least 700 km (Fig. 3; Fedorov *et al.*, 1982a) and is the present-day location of the largest glacier system in the world. It has been an active tectonic zone since at least the

Mesoproterozoic (Mikhalsky *et al.*, 1992), and although its present morphology reflects rifting during Mesozoic break-up of Gondwana (Fedorov *et al.*, 1982a), it is not unreasonable that this Mesozoic line of weakness was also a major feature during the Cambrian. This would be analogous to the Darling Fault at the western edge of the Yilgarn Craton of Western Australia, which was the eastern margin of the Mesozoic rift zone between India and Australia (Veevers, 1984), but whose location and orientation were inherited from much older structures, including the Cambrian Darling Mobile Belt (Harris, 1994). Continuation of the Prydz Belt parallel to the Lambert Graben leads to the southern Prince Charles Mountains (Tingey, 1982, 1991), where a variety of protoliths are separated by tectonic contacts and exhibit large variations in metamorphic grade consistent with the existence of multiple crustal terranes. Reliable geochronological data are sparse, but there is good evidence for Archæan basement and Cambrian granites, with intermediate Rb-Sr whole rock ages for other rock types, and 550–450 Ma Rb-Sr biotite ages. Reconnaissance data are consistent with Cambrian folding and metamorphism to greenschist grade or higher, and it is likely that the southern Prince Charles Mountains are a continuation of the Prydz Belt. Although there are no constraints on the further continuation of this belt under the ice sheet, it is perhaps not coincidental that the Gamburtsev Subglacial Mountains are a further 500 km to the south (Fig. 3). This prominent sub-glacial feature (Bentley, 1991) would have elevations of over 3000 m after removal of the ice sheet, and gravity data indicate local crustal thicknesses greater than 65 km (Groushinsky and Sazhina, 1982). The age of the rocks in this concealed mountain range is unknown, but the possibility that their location is in part controlled by a Cambrian tectonic boundary cannot be discounted.

All the available data argue for continuation of the Prydz Belt into the Antarctic interior, where it will ultimately intersect the Ross Orogen or the Lützow Holm Belt. It is not clear whether this belt was dominated by transcurrent or collisional tectonics, but it was a major crustal discontinuity active in the latest Neoproterozoic to Cambrian. The possibility that it marks a closed ocean basin allows a reinterpretation of the palæomagnetic data presented by Gose *et al.* (1997). Gose *et al.* (1997) assumed that the discrepancy between their data from the Maud Province and the Laurentia data used as a reference for East Gondwana at 1000 Ma reflects closure of the Mozambique Ocean along the Lützow Holm Belt, but the data can be explained by ocean closure at any suture or sutures between the Maud Province and the Palæopacific margin of East Antarctica. A suture running from Prydz Bay across the continent could account for all or part of the required Neoproterozoic separation. It is likely that the Lützow Holm Belt is the main suture, given that ocean closure is well documented for the East African Orogen, but a lack of reliable palæomagnetic poles for India and East Antarctica makes it is impossible to rule out a second Neoproterozoic Ocean between the Mawson Continent and a crustal fragment comprising India, the Napier Complex and the Rayner Province.

CONCLUSIONS

Two Pan-African mobile belts cut across the East Antarctic Shield, the Lützow Holm and Prydz Belts, and these rework, truncate and offset three Grenville-age crustal segments: the Maud, Rayner and Wilkes Provinces. These three segments were previously assumed to form one single orogen around the coastline, but now appear to represent distinct fragments juxtaposed in the Cambrian. The Lützow Holm Belt is a continuation of the East African Orogen and developed during closure of the Mozambique Ocean. It is unclear whether the Prydz Belt involved ocean closure or regional-scale transcurrent tectonics, but it does juxtapose numerous terranes with different geological histories, and it seems likely that the East Antarctic Shield was a collage rather than a keystone during the amalgamation of Gondwana. Increasing evidence that East Gondwana underwent significant reorganisation during the Cambrian will also require changes to current models for the configuration of Rodinia, which assume that East Gondwana stabilised during the late Mesoproterozoic. It is still not known if the centre of the East Antarctic Shield is a single Palæoproterozoic craton, as commonly assumed, or whether it is cut by Grenville-age or Pan-African mobile belts, which would require revision of the boundaries of the Mawson Continent. This uncertainty means that the various terranes exposed on the coast can be joined up in any number of ways, and it follows that current models for Proterozoic tectonics in East Antarctica, and for global tectonics given the crucial location of Antarctica in proposed supercontinents, will remain poorly constrained until some understanding of the continental structure beneath the ice cap is achieved.

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