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## Antarctica and supercontinent evolution: historical perspectives, recent advances and unresolved issues

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**Abstract:** The Antarctic rock record spans some 3.5 billion years of history, and has made important contributions to our understanding of how Earth's continents assemble and disperse through time. Correlations between Antarctica and other southern continents were critical to the concept of Gondwana, the Palaeozoic supercontinent used to support early arguments for continental drift, while evidence for Proterozoic connections between Antarctica and North America led to the 'SWEAT' configuration (linking SW USA to East Antarctica) for an early Neoproterozoic supercontinent known as Rodinia. Antarctica also contains relics of an older Palaeo- to Mesoproterozoic supercontinent known as Nuna, along with several Archaean fragments that belonged to one or more 'supercratons' in Neoarchaean times. It thus seems likely that Antarctica contains remnants of most if not all Earth's supercontinents, and Antarctic research continues to provide insights into their palaeogeography and geological evolution. One area of research is the latest Neoproterozoic–Mesozoic active margin of Gondwana, preserved in Antarctica as the Ross Orogen and a number of outboard terranes that now form West Antarctica. Major episodes of magmatism, deformation and metamorphism along this palaeo-Pacific margin at 590–500 Ma and 300–230 Ma can be linked to reduced convergence along the internal collisional orogens that formed Gondwana and Pangaea, respectively; indicating that accretionary systems are sensitive to changes in the global plate tectonic budget. Other research has focused on Grenville-age (*c.* 1.0 Ga) and Pan-African (*c.* 0.5 Ga) metamorphism in the East Antarctic Craton. These global-scale events record the amalgamation of Rodinia and Gondwana, respectively. Three coastal segments of Grenville-age metamorphism in the Indian Ocean sector of Antarctica are each linked to *c.* 1.0 Ga collision between older cratons but are separated by two regions of pervasive Pan-African metamorphism ascribed to Neoproterozoic ocean closure. The tectonic setting of these events is poorly constrained given the sparse exposure, deep erosion level, and likelihood that younger metamorphic events have reactivated older structures. The projection of these orogens under the ice is also controversial, but it is likely that at least one of the Pan-African orogens links up with the Shackleton Range on the palaeo-Pacific margin of the craton. Sedimentary detritus and glacial erratics at the edge of the ice sheet provide evidence for *c.* 1.0 and 0.5 Ga orogenesis in the continental interior, while geophysical data reveal prominent geological boundaries under the ice, but there are insufficient data to trace these features to exposed structures of known age. Until we can resolve the subglacial geometry and tectonic setting of *c.* 0.5 and 1.0 Ga metamorphism there will be no consensus on the configuration of Rodinia, or the size and shape of the continents that existed immediately before and after this supercontinent. Given this uncertainty it is premature to speculate on the role of Antarctica in earlier supercontinents, but it is likely that Antarctica will continue to provide important constraints when our attention shifts to these earlier events.

## Introduction

Most Earth scientists consider the continents to have been organised on Earth in two distinct ways through time: dispersed, with several large continents and intervening oceans; and coalesced, with one or perhaps two ‘supercontinents’ present (Nance *et al.* 2013). The alternation between these two states is the major control on a number of secular trends observed in the geological record (Fig. 1; Bradley 2011), which can in turn be used to establish a timescale for the supercontinent cycle. Recent work suggests that there have been three principal periods of continental amalgamation, responsible for the Pangaea (*c.* 0.3 Ga), Rodinia (*c.* 1.0 Ga), and Nuna (*c.* 1.7 Ga) supercontinents, together with a time at the close of the Archaean when Earth’s continents were assembled either into one dominant landmass (Kenorland; Williams *et al.* 1991) or into a small number of independent ‘supercratons’ (Superia, Scalvia, Vaalbara; Bleeker 2003). It is also commonplace to grant supercontinent status to Gondwana, the amalgam of present-day southern continents that formed at *c.* 0.5 Ga as a precursor to Pangaea. The influence of this continual reorganisation of Earth’s landmasses is not restricted to the continental crust, and is also believed to have affected the surface environment triggering profound changes in climatic and biological evolution (e.g. Valentine & Moores 1970; Campbell & Allen 2008; Eyles 2008). This history is also linked to Earth’s deep interior, with evidence that the supercontinent cycle is coupled with mantle convection patterns (Gurnis 1988; Li & Zhong 2009).

Relics of these former continental amalgamations are now dispersed amongst the present-day continents, and correlations between these fragments can be used to reconstruct supercontinent palaeogeography. Despite being largely concealed beneath an extensive ice sheet, Antarctica contains rocks spanning some three and a half billion years of history (Fig. 1; Elliot 1975; Tingey 1991 and other chapters in that volume; Dalziel 1992; Fitzsimons 2000a; Harley 2003; Torsvik *et al.* 2008; Boger 2011), and is likely to contain remnants of all Earth’s recognised supercontinents. The Antarctic continent is divided into two distinct geological provinces by the Transantarctic Mountains (Fig. 2). East Antarctica lies to the Indian Ocean side of these mountains and is dominated by cratonic igneous and metamorphic rocks of Archaean to Cambrian age, which are exposed sporadically along the coast and inland along the flanks of the Lambert Glacier, a topographic low in the ice sheet that overlies the late Palaeozoic to Mesozoic Lambert Graben (Fedorov *et al.* 1982; Lisker *et al.* 2003; Phillips & Läufer 2009). The Transantarctic Mountains mark the site of the Ross Orogen, a Neoproterozoic passive margin on the edge of the East Antarctic Craton that had transformed into an active convergent margin by the Cambro-Ordovician (Stump 1995; Goodge 2002). West Antarctica lies to the Pacific Ocean side of the Transantarctic Mountains and comprises several Palaeozoic to Mesozoic terranes dominated by magmatic arc and turbidite systems with a complex history of subduction, accretion, magmatism and deformation throughout the Palaeozoic and Mesozoic (Dalziel & Elliot 1982; Vaughan *et al.* 2005). As such, Antarctica has a remarkable story to tell about the evolution of our Earth, from the hottest crustal rocks yet found in an orogenic system and what they might mean for supercraton formation at 2.5 Ga, to the assembly and breakup of Gondwana in the Phanerozoic.

This Special Publication contains eight papers that deal with different aspects of Antarctica's history in supercontinent evolution, highlighting the evidence provided by petrological, geochemical and geochronological studies of sparse Antarctic outcrops of igneous, sedimentary and metamorphic rock. It builds upon other volumes published by the Geological Society of London that have focused on Antarctica and its relationships to the other southern continents, in particular the 2003 volume on "*Proterozoic East Gondwana: Supercontinent Assembly and Breakup*" (Special Publication 206 edited by M. Yoshida, B. F. Windley & S. Dasgupta), the 2005 volume on "*Terrane Processes at the Margins of Gondwana*" (Special Publication 246 edited by A. P. M. Vaughan, P. T. Leat & R. J. Pankhurst), and the 2008 volume on "*Geodynamic Evolution of East Antarctica: A Key to the East–West Gondwana Connection*" (Special Publication 308 edited by M. Satish-Kumar, Y. Motoyoshi, Y. Osanai, Y. Hiroi & K. Shiraishi). In this introductory paper we provide an historical perspective on how Antarctica has influenced models of supercontinent assembly and dispersion, and highlight a number of issues that remain unresolved.

### **Keystone of Gondwana, core of Rodinia**

Antarctica has played a pivotal role in the development of models for how the present-day continents might have been arranged in earlier configurations (Dalziel 1992). Unexpected finds of coal measures, glossopteris floras, and voluminous dolerite sills in the early 20th century by pioneering explorers of the 'golden age' (e.g. David & Priestley 1914) indicated close correlations between Palaeozoic and Mesozoic rocks of the Transantarctic Mountains and those in Australia, southern Africa and India. These findings were consistent with the concept of an ancient southern supercontinent, named Gondwanaland by Suess (1885–1909), and it was shortly after these Antarctic discoveries that continental drift was first proposed as an explanation for these and other mysterious geological correlations between the now widely separated southern continents (Wegener 1912). The leading proponents of continental drift were soon depicting Antarctica within an assembled supercontinent (Fig. 3a; Wegener 1915; Argand 1924), sandwiched between Australia, India, Africa and South America. This work culminated in the reconstructions of Du Toit (1937), who summarised a wealth of geological and palaeontological evidence for a Palaeozoic Gondwana supercontinent that began to break apart in the Jurassic and had Antarctica as its central keystone (Fig. 3b), although these correlations remained highly controversial until the plate tectonic revolution of the 1960s provided a mechanism for continental drift (Hess 1962; Dietz 1961; Vine & Matthews 1963; Wilson 1965; Isacks *et al.* 1968; Morgan 1968).

The broad framework established by Du Toit (1937) and others has largely stood the test of time, with further refinements of the Gondwana 'fit' and breakup history driven by the application of plate tectonic principles to oceanic fracture zones and seafloor magnetic anomalies, coupled with accurate mapping of continental shelves (e.g. Smith & Hallam 1970; Lawver & Scotese 1987; Reeves *et al.* 2002). As a result there is now widespread agreement on the Palaeozoic to Mesozoic

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configuration of Gondwana, although spatial and temporal correlations between the various terranes of West Antarctica remain problematic (Dalziel & Elliot 1982; Vaughan *et al.* 2005). Instead much of the debate over the last 40 years has centred on the pre-Gondwana history of the continents, and whether it is possible to identify even earlier supercontinents. It was not long after the recognition of plate tectonics on modern Earth that the Precambrian rock record was first interpreted in terms of opening and closing of ocean basins, and soon a range of geological signals were being used to infer pre-Gondwana cycles of continental assembly and breakup, including periods of orogenesis and rifting, and changes in sea level and faunal diversity (Dewey & Horsfield 1970; Valentine & Moores 1970; Bond *et al.* 1984; Worsley *et al.* 1984). While this evidence for assembly and breakup of one or more Precambrian supercontinents was convincing, it proved much more difficult to establish what the configuration of these supercontinents might have been.

Unlike Pangaea and Gondwana, which can be reconstructed by closing the present-day ocean basins, Precambrian palaeogeography must be deciphered using the continental rock record alone, through some combination of geological correlation and palaeomagnetism. Precambrian geological correlations are based on matching the age and orientation of features such as orogenic belts, passive margins, and dyke swarms. While such correlations might seem straightforward, typically any one correlation can be solved by several possible continental configurations and modern Earth tells us that similar geological settings can exist simultaneously on quite different parts of the globe. For this reason the best correlations are those that match multiple geological features, but even then the resulting configurations are qualitative at best. Conversely, palaeomagnetism can provide quantitative information on the relative and absolute geographic position and orientation of the continents, but is plagued by a relatively limited Precambrian dataset of variable reliability and uneven geographic spread.

The first suggested configuration for a Pre-Gondwana supercontinent was based primarily on palaeomagnetic data, which were used to argue for a long-lived Proterozoic supercontinent that closely resembled the Pangaea configuration, with Antarctica in its Gondwana fit (Piper 1976). It was later referred to as ‘Palaeopangaea’ (Piper 2000) and required that most Proterozoic orogens within the present-day continents were the result of intracratonic reworking rather than ocean closure at a plate margin. Much of the evidence for this proposal was, however, disputed and it never gained widespread acceptance (e.g. Van der Voo & Meert 1991). The breakthrough came in 1991 with the suggestion on geological grounds that Laurentia (ancestral North America) and Antarctica were juxtaposed in the Proterozoic along a conjugate rift margin (Moores 1991; Fig. 4). This proposal paired a Neoproterozoic passive margin along the western edge of North America with a similar length of Neoproterozoic passive margin in eastern Australia and the Transantarctic Mountains. It also linked the *c.* 1.0 Ga Grenville Orogen of eastern North America with a similar aged metamorphic belt that was believed to wrap around the Antarctic coastline from Dronning Maud Land through to Wilkes Land where it passed into the Albany–Fraser Orogen of Western Australia. The other continents were

then placed around this so-called SWEAT reconstruction (linking southwestern US to East Antarctica) to recreate a late Proterozoic supercontinent (Dalziel 1991; Hofmann 1991). This supercontinent was assumed to have assembled through ocean closure and continental collision along a global network of *c.* 1.0 Ga orogens that are a prominent feature of many present-day continents. It then rifted apart in the late Neoproterozoic, with the present-day southern continents of Antarctica, Australia, India, Africa and South America subsequently assembling into their Gondwana fit at *c.* 0.5 Ga along the so-called ‘Brasiliano’ orogens of South America and ‘Pan-African’ orogens of Africa (e.g. Hoffman 1991; Rogers *et al.* 1995; Meert & Van der Voo 1997), to be joined by North America and Eurasia at *c.* 0.3 Ga to form Pangaea.

Following an earlier suggestion of McMenamin & McMenamin (1990), the name ‘Rodinia’ was soon adopted for this early Neoproterozoic supercontinent and Antarctica was once again at the centre of supercontinent debate. The idea of an early Neoproterozoic supercontinent that linked Laurentia to a number of other continents including southern Africa, East Antarctica, India and Australia via a global-scale 1.0 Ga Grenville-age mountain belt had great appeal. It stimulated intense research on several continents, generating a large range of possible Rodinia configurations and heated discussion that has continued to the present day (e.g. Meert & Torsvik 2003; Pisarevsky *et al.* 2003; Li *et al.* 2008, 2009; Evans 2009). It has also led to growing interest in even earlier supercontinents, in particular the Palaeoproterozoic supercontinent of ‘Nuna’ (or ‘Columbia’) for which a number of preliminary configurations have been proposed (Zhao *et al.* 2002, 2004; Evans & Mitchell 2011; Zhang *et al.* 2012).

### **From Rodinia to Gondwana**

The terms East and West Gondwana were first used to describe the Mesozoic breakup of Gondwana (e.g. Dietz & Holden 1970), which commenced with the rifting of South America and Africa (West Gondwana) away from Antarctica–Australia–India (East Gondwana), but a renewed focus on the Neoproterozoic continental reorganisation from Rodinia to Gondwana suggested that this east–west distinction was also relevant to Gondwana assembly (Rogers *et al.* 1995; Fig. 5). This built upon palaeomagnetic evidence that East and West Gondwana were independent cratonic units before they collided at *c.* 0.5 Ga along the Mozambique Belt of eastern Africa (McWilliams 1981), and was consistent with early plate tectonic interpretations of this belt as a Tibetan-style orogen (Burke & Dewey 1972). This belt is now regarded as part of the East African Orogen (Shackleton 1986, 1996; Stern 1994, 2002), a zone of late Neoproterozoic ocean closure and continental collision with well-preserved ophiolite in the north (Arabian–Nubian Shield; Johnson & Woldehaimanot 2003; Johnson *et al.* 2011) and evidence of oceanic influence at least as far south as the Vohibory unit of southwestern Madagascar (Jöns & Schenk 2008).

Not only was the East African Orogen identified as the principal collisional zone during Gondwana assembly, but it also appeared to suture two continental blocks of different geological

character. Thus while both South America and Africa are transected by multiple belts of late Neoproterozoic metamorphism (the Brasiliano and Pan-African orogens), there appeared to be no significant metamorphism within East Gondwana younger than *c.* 1.0 Ga (Fig. 5). Although there was (and still is) disagreement about whether individual Neoproterozoic metamorphic belts in western Africa and South America are ocean sutures or examples of intracratonic reworking (e.g. the Damara Orogen of southwest Africa; Kröner 1977; Porada 1979; Gray *et al.* 2008), there is some consensus that West Gondwana assembled in the late Neoproterozoic from two or more fragments (Rogers *et al.* 1995; Trompette 1997; Cordani *et al.* 2003; Tohver *et al.* 2006) that collided to close one or more oceans (e.g. the Adamastor Ocean of Hartnady *et al.* 1985; the Clymene Ocean of Trindade *et al.* 2006). Conversely, it was believed that East Gondwana was released from Rodinia as an already assembled block that collided with the composite blocks of West Gondwana along the East African Orogen to form the unified Gondwana supercontinent (Yoshida *et al.* 1992; Rogers *et al.* 1995; Unrug, 1996).

Models for a coherent East Gondwana that assembled as part of Rodinia at *c.* 1.0 Ga and survived until Mesozoic breakup of Gondwana were consistent with the traditional view of East Antarctic geology as a central Archaean to Palaeoproterozoic East Antarctic Craton wrapped by a coastal *c.* 1.0 Ga orogen (Ravich & Kamenev 1975; Grew 1982; James & Tingey 1983; Tingey 1991; Fig. 5). Indeed this *c.* 1.0 Ga orogen (the Circum East Antarctic Mobile Belt of Yoshida 1995) and its correlation with the Grenville Orogen of North America was one of the crucial pieces of evidence used to constrain the SWEAT reconstruction of Rodinia (Fig. 4; Moores, 1991). Although *c.* 0.5 Ga granitic magmatism and thermal resetting of Rb–Sr and K–Ar mineral isotope systems had been identified across much of East Antarctica, metamorphic pressure–temperature (*P–T*) conditions at this time were not believed to have exceeded greenschist facies at current erosion levels and were viewed as an intraplate response to the onset of subduction along the palaeo-Pacific margin of Gondwana (Stüwe & Sandiford 1993).

### **Antarctica divided**

The notion of a coherent East Gondwana from *c.* 1.0 to 0.2 Ga was challenged in the 1990s as U–Pb zircon geochronology coupled with structural and metamorphic mapping identified belts of *c.* 0.5 Ga granulite-facies metamorphism and deformation within East Gondwana. The first evidence came from southern India and Sri Lanka (Burton & O’Nions 1990; Baur *et al.* 1991; Choudhary *et al.* 1992; Kröner & Williams 1993; Hölzl *et al.* 1994; Miller *et al.* 1996), where detailed geochronology using a range of techniques established that peak granulite metamorphism was ‘Pan-African’ in age and that previous evidence for older ages reflected pre-metamorphic protolith material. These Pan-African granulites and similar-aged rocks in Madagascar (Paquette *et al.* 1994; Kröner *et al.* 1996) were interpreted as the eastern margin of the East African Orogen and so did not require any major changes to existing models for a coherent East Gondwana during the Neoproterozoic, but one unresolved issue

was the southward extension of the East African Orogen beyond Madagascar (Fig. 5). While some assumed that this collisional suture turned westwards along the Damara–Zambezi system making the Kalahari Craton of southern Africa part of East rather than West Gondwana (e.g. Hoffman 1991), others considered this unlikely and speculated that it might extend into Antarctica (Stern 1994; Shackleton 1996).

Evidence for the latter geometry was provided by reports of pervasive high-grade Pan-African metamorphism overprinting *c.* 1.0 Ga rocks of Dronning Maud Land (Fig. 6a), first from the Lützow–Holm Complex of eastern Dronning Maud Land (Shiraishi *et al.* 1992, 1994, 2008) and then western and central Dronning Maud Land (Moyes & Groenewald 1996; Jacobs *et al.* 1998). These results were used to argue for a continuous East African–Antarctic Orogen (Grunow *et al.* 1996; Jacobs *et al.* 2003a, *c.*; Jacobs & Thomas 2004) stretching 8,000 km from the Arabian–Nubian Shield through eastern Africa and Dronning Maud Land to the Shackleton Range on the Coats Land coast of Antarctica (path EA1 in Fig. 6b), where a nappe complex with ophiolite and *c.* 0.5 Ga eclogite was interpreted as a Pan-African suture (Talarico *et al.* 1999; Tessensohn *et al.* 1999; Kleinschmidt *et al.* 2002; Zeh *et al.* 2004; Schmädicke & Will 2006; Will *et al.* 2010). The Archaean Grunehogna Craton and *c.* 1.0 Ga rocks of the Maud Belt in far western Dronning Maud Land do not show this Pan-African overprint and have geological and palaeomagnetic links with the Kalahari Craton, suggesting they belong to the western foreland of the East African–Antarctic Orogen (Barton *et al.* 1987; Arndt *et al.* 1991; Jacobs *et al.* 2003c; Jones *et al.* 2003; Marschall *et al.* 2010). Detailed zircon geochronology indicates that the *c.* 1.0 Ga Maud Belt has a distinctive record of 1140–1130 Ma volcanism and 1090–1030 Ma granulite-facies metamorphism, and that rocks with this same history form the protoliths to Pan-African granulites across western and central Dronning Maud Land (Fig. 6b; Jacobs *et al.* 2003b, *c.*; Bisnath *et al.* 2006). Undeformed rhyolite and granophyre exposed in Coats Land, between western Dronning Maud Land and the Shackleton Range, have magmatic ages of *c.* 1110 Ma with no trace of *c.* 0.5 Ga tectonism (Gose *et al.* 1997), suggesting that they too are part of the western foreland to the Pan-African Orogen. However, palaeomagnetic and isotopic data from Coats Land support links with Laurentia at 1110 Ma rather than with the Kalahari Craton, consistent with the original SWEAT hypothesis that the Maud Belt is a 1090–1030 Ma collision zone between the Kalahari Craton and Laurentia–Antarctica (Jacobs *et al.* 2003b; Loewy *et al.* 2011).

The preservation of a Maud Belt age signature into the *c.* 0.5 Ga granulites of central Dronning Maud Land suggests that any extension of the East African suture into Antarctica is likely to lie in eastern Dronning Maud Land. The eastern foreland of this Pan-African orogen would be the *c.* 1.0 Ga Rayner Complex of Enderby, Kemp and MacRobertson lands, which has characteristic charnockite magmatism and metamorphism at 990–900 Ma and correlates with the Eastern Ghats Province of India (Black *et al.* 1987; Kelly *et al.* 2002; Dobmeier & Raith 2003; Halpin *et al.* 2005; Dasgupta *et al.* 2013). Protolith ages for the Pan-African granulites of eastern Dronning Maud Land are poorly constrained, but meta-tonalite in the southwestern Sør Rondane Mountains preserves pre-

metamorphic intrusive ages of 998–995 and 945–920 Ma (Kamei *et al.* in press). This confirms earlier suggestions of a change in protolith age between central Dronning Maud Land and the Sør Rondane Mountains (Jacobs *et al.* 2008), and allows the possibility that the Sør Rondane tonalite is part of the Rayner Complex metamorphosed at *c.* 0.6–0.5 Ga. This would place the Rayner–Maud boundary between central Dronning Maud Land and the Sør Rondane Mountains, which would therefore also be a likely site for any Pan-African oceanic suture. However, the tonalite has quite different geochemistry and is markedly more juvenile than Rayner Complex charnockites, making their direct correlation problematic.

If the East African suture does pass into Dronning Maud Land and continue to the Shackleton Range, then outcrops in western and central Dronning Maud Land and in Coats Land must have been part of West Gondwana and only amalgamated with the rest of the East Antarctic Craton at *c.* 0.5 Ga. This still allows the larger part of East Gondwana to have been untouched by pervasive Pan-African tectonism and so does not require substantial changes to models of a coherent East Gondwana throughout the Neoproterozoic. However, evidence for Pan-African metamorphism and deformation was also emerging from the Prydz Bay coast of East Antarctica, in the heart of East Gondwana (Fig. 6a), where rocks previously regarded as part of the *c.* 1.0 Ga Circum East Antarctic Mobile Belt were found to have a pervasive *c.* 0.5 Ga granulite-facies overprint (Zhao *et al.* 1992, 1993, 2003; Hensen & Zhou 1995, 1997; Carson *et al.* 1996; Fitzsimons *et al.* 1997; Kelsey *et al.* 2003, 2007). Outcrops farther west in MacRobertson Land and the northern Prince Charles Mountains belong to the *c.* 1.0 Ga Rayner Complex with only localised evidence for the 0.5 Ga event (Kinny *et al.* 1997; Boger *et al.* 2000, 2002; Carson *et al.* 2000), and so appear to mark a western limit for Pan-African tectonism. However, Pan-African metamorphism and deformation was found to extend south of Prydz Bay along the eastern edge of the Amery Ice Shelf (Liu *et al.* 2009b) and inland to the Grove Mountains (Mikhalsky *et al.* 2001; Liu *et al.* 2006, 2007) and southern Prince Charles Mountains in the Lambert Graben (Boger *et al.* 2001, 2008; Corvino *et al.* 2005, 2008; Phillips *et al.* 2009).

Most rocks in the Prydz Bay region affected by this Pan-African event preserve an earlier history of *c.* 1.0 Ga magmatism and metamorphism correlated with events in the adjacent Rayner Complex (Fig. 6b; Wang *et al.* 2008; Grew *et al.* 2012) and so provide no evidence of a suture, but relationships are more complex in northern Prydz Bay and the southern Prince Charles Mountains. The Rauer Group of northern Prydz Bay comprises Archaean orthogneiss, with *c.* 3.3 and 2.8 Ga emplacement ages, interleaved with *c.* 1.0 Ga units. These rocks show no evidence of a shared tectonothermal history until *c.* 0.5 Ga (Kinny *et al.* 1993; Harley *et al.* 1998), which is consistent with terrane assembly at that time, although juxtaposition at 1.0 Ga followed by reworking at 0.5 Ga cannot be ruled out (Harley & Kelly 2007a). The history of the adjacent late Archaean to earliest Palaeoproterozoic Vestfold Hills Block is dominated by magmatism and metamorphism at *c.* 2.5 Ga (Black *et al.* 1991; Snape *et al.* 1997) and appears unrelated to older Archaean rocks in the Rauer Group, again suggesting this region might comprise several terranes juxtaposed by later events.



Three different-aged basement associations are identified in the southern Prince Charles Mountains, each dominated by granitoid and felsic orthogneiss, along with several variably deformed and metamorphosed sedimentary sequences (Kamenev *et al.* 1993; Boger *et al.* 2001, 2006; Mikhalsky *et al.* 2006, 2010; Phillips *et al.* 2006, 2009). The youngest basement unit is exposed in the north and is an extension of the *c.* 1.0 Ga Rayner Complex, but basement outcrops farther south belong either to an Archaean association with major igneous events at *c.* 3.2 and 2.8 Ga (the Ruker Complex, but called the Tingey Complex by Phillips *et al.* 2009) or a Palaeoproterozoic association with major igneous events at *c.* 2.4 and *c.* 2.1 Ga (the Lambert Complex). While the age of the Ruker Complex correlates closely with Archaean parts of the Rauer Group, *c.* 2.1 Ga ages reported from the Lambert Complex have no known counterpart in Antarctica. Parts of the Lambert Complex record a metamorphic overprint at *c.* 1.0 Ga (Corvino *et al.* 2008) indicating that it was linked to the Rayner Complex by Grenville times, but relationships with the Ruker Complex are less clear. High-strain zones at the boundaries between all basement units show evidence for *c.* 0.5 Ga amphibolite-facies metamorphism (Corvino *et al.* 2008; Phillips *et al.* 2009) and one of the more intense areas of Pan-African reworking occurs at the eastern edge of the Prince Charles Mountains, where it juxtaposes the Lambert Complex to the north and Ruker Complex to the south. Boger *et al.* (2001) interpreted this as a major Pan-African suture zone that extends east–west across the southern Prince Mountains, consistent with a lack of evidence for *c.* 1.0 Ga metamorphism in the Ruker Complex basement. However, more recent geochronology indicates that the Ruker and Lambert complexes farther west do not have a simple outcrop pattern (Phillips *et al.* 2006; Mikhalsky *et al.* 2010), and has also identified 3.2 Ga detrital zircon grains in one of the sedimentary sequences that lost Pb at 990–900 Ma (Phillips *et al.* 2006), consistent with a Rayner overprint on Ruker material. Thus while Boger (2011) has continued to argue for a *c.* 0.5 Ga suture in the southern Prince Charles Mountains, others have proposed that these terranes assembled at *c.* 1.0 Ga and that their boundaries were reactivated at *c.* 0.5 Ga in response to collisional tectonics elsewhere (Phillips *et al.* 2009; Mikhalsky *et al.* 2010).

Unlike the Dronning Maud Land granulites, which are along strike from the *c.* 0.5 Ga East African Orogen in Gondwana reconstructions, supercontinent configurations provide few constraints on the setting of Pan-African metamorphism in Prydz Bay. Extensions of the Prydz Belt away from Antarctica project beneath the sedimentary basins of northern India, and the next basement outcrop along the Antarctic coastline occurs *c.* 700 km to the east at Mirny Station. Limited age data from this area provide evidence for a major tectonic boundary beneath the Denman Glacier, about 200 km east of Mirny. Archaean orthogneiss west of Denman Glacier was metamorphosed at *c.* 0.5 Ga and intruded by *c.* 0.5 Ga charnockite and syenite, but bears no evidence of metamorphism at *c.* 1.0 Ga. Conversely, rocks in the Bunger Hills and Windmill Islands of Wilkes Land, east of Denman Glacier, underwent high-grade metamorphism at 1330–1280 and 1200–1130 Ma with only a partial isotopic overprint at *c.* 0.5 Ga that decreases in intensity eastwards (Black *et al.* 1992; Sheraton *et al.* 1992, 1995; Post *et al.* 1997). This boundary is correlated with the Darling Fault of Western Australia (Fig.

6a), which lies adjacent to the Denman Glacier region in Gondwana reconstructions. The southern section of the Darling Fault separates the Albany-Fraser Orogen in the east, with metamorphic events at 1345–1260 Ma and 1215–1140 Ma, from the Pinjarra Orogen in the west, which records a variably developed *c.* 0.5 Ga metamorphic overprint on 1090–1060 and 800–650 Ma magmatic and metamorphic rocks (Sheraton *et al.* 1995; Harris 1995; Clark *et al.* 2000; Fitzsimons 2003; Kirkland *et al.* 2011).

In the absence of any outcrop between them, *c.* 0.5 Ga magmatism and metamorphism in the Prydz Bay and Denman Glacier regions are assumed to represent the western and eastern margins of a single Pan-African orogenic belt (Fitzsimons 2000*a, b*, 2003; Boger *et al.* 2001, Boger 2011), although its tectonic setting remains enigmatic. There is no evidence for Neoproterozoic oceanic crust or arc magmatism, although it is impossible to rule out their presence under the ice or in those parts of India now subducted under the Himalaya or hidden beneath the Indo-Gangetic Plain, and glacial erratics discovered in the Grove Mountains with 545 Ma high-pressure mafic granulite assemblages do provide some support for Pan-African collisional orogenesis in the Prydz Bay area (Liu *et al.* 2009*a*). There is geological evidence for sinistral displacement of crustal blocks along the southern segment of the Darling Fault at *c.* 0.5 Ga (Harris 1994), with comparable lateral movements inferred for its Antarctic counterpart in the Denman Glacier region, although arguments for *c.* 0.5 Ga terrane assembly farther west in the Rauer Group and southern Prince Charles Mountains remain inconclusive given the possibility that amalgamation occurred at *c.* 1.0 Ga. While the magnitudes of Pan-African displacement in the Prydz–Denman region are poorly constrained and need not have been linked to ocean closure, indirect evidence for significant relative movement is provided by palaeomagnetic data from the 770–750 Ma Malani Igneous Suite of northwest India (Fig. 6a). These data suggest that India was *c.* 45° of latitude north of its Gondwana fit with Australia at 750 Ma (Torsvik *et al.* 2001; Gregory *et al.* 2009), which requires *c.* 5,000 km of Neoproterozoic movement between India and Australia. The Prydz–Denman region is the most likely candidate for displacements of this magnitude, although another possible site is the Eastern Ghats Belt of India, where like Antarctica there is increasing evidence for Pan-African 0.5 Ma tectonism within what was previously regarded as a *c.* 1.0 Ga metamorphic belt. This has led to controversial proposals that the Eastern Ghats and equivalent Rayner Complex of Antarctica collided with the Dharwar and Bastar cratons of India at *c.* 0.5 Ga (Dobmeier *et al.* 2006; Biswal *et al.* 2007; Simmat & Raith 2008), but most workers still argue for assembly at *c.* 1.0 Ga followed by intracratonic reworking at *c.* 0.5 Ga (e.g. Dasgupta *et al.* 2013).

Thus it appears that two major zones of Pan-African magmatism, metamorphism and deformation intersect the East Antarctic coastline, splitting the *c.* 1.0 Ga Circum East Antarctica Mobile Belt into three segments (Wilkes Land, Rayner Complex, Maud Belt; Fig. 6b). While each segment has broadly comparable metamorphic ages, there are consistent differences in the precise timing of the major events with peak metamorphism at 1200–1130 Ma in Wilkes Land, 990–900 Ma in the Rayner Complex, and 1090–1030 Ma in the Maud Belt. Fitzsimons (2000*b*) proposed that each

segment might be a distinct orogenic belt juxtaposed during Gondwana assembly, although the geometry and tectonic setting of Pan-African displacements are poorly constrained.

### **Joining the dots**

Although there was some resistance to the concept of three separate Antarctic blocks in the Neoproterozoic, given that differences in the timing of *c.* 1.0 Ga metamorphism could reflect temporal variations along a single orogen (Yoshida *et al.* 2003; Yoshida 2007), it has been adopted in many palaeogeographic models for Neoproterozoic Earth and the preceding Rodinia supercontinent (e.g. Collins & Pisarevsky 2005; Li *et al.* 2008). However, such models require extrapolation of the Pan-African orogens under the Antarctic ice sheet to define the size and shape of inferred Australo-Antarctic, Indo-Antarctic and African-Antarctic blocks that assembled at *c.* 0.5 Ga to form East Gondwana. Boger *et al.* (2001), Fitzsimons (2003), Boger & Miller (2004) and Boger (2011) have used the geological evidence available from the sparse Antarctic outcrop to speculate on potential pathways for these orogens under the ice (Fig. 6b).

The only direct evidence for a Pan-African orogenic belt at the Pacific margin of Antarctica is in the Shackleton Range at the African end of the Transantarctic Mountains. While these *c.* 0.5 Ga thrust sheets of eclogite and ophiolite are usually interpreted as the Pacific termination of the East African–Antarctic Orogen that formed through ocean closure and collision of African cratons with those in India and Antarctica (path EA1 in Fig. 6b; Grunow *et al.* 1996; Kleinschmidt *et al.* 2002; Jacobs *et al.* 2003*a, c*; Jacobs & Thomas 2004), they could also be an extension of the Prydz–Denman orogenic belt. Two possible paths have been proposed for a Pan-African orogen linking the Prydz–Denman region to the Shackleton Range. Boger *et al.* (2001), Boger & Miller (2004) and Boger (2011) suggested it might pass through the inferred suture between the Ruker and Lambert complexes in the southern Prince Charles Mountains (path PD1 in Fig. 6b), although others have argued that this suture formed at *c.* 1.0 rather than 0.5 Ga (Phillips *et al.* 2009; Mikhalsky *et al.* 2010). Fitzsimons (2003) suggested an alternative path (path PD2 in Fig. 6b) that passes under the ice between the southern Prince Charles Mountains and the Gamburtsev Subglacial Mountains, an enigmatic and unexposed mountain range *c.* 500 km south of the Prince Charles Mountains (Figs 2 & 6). The tectonic framework for these inferred orogenic belts remains unclear, with Fitzsimons (2000*b*, 2003) noting that the proposed displacements could result either from ocean closure and continental collision or from continent-scale transcurrent tectonics. However, Boger (2011) has argued specifically for ocean subduction leading to continental collision, which would be consistent with the Shackleton Range ophiolite and eclogite. If the Prydz–Denman Orogen does extend to the Shackleton Range, this raises the question of what happens to the southern extension of the East African–Antarctic Orogen. Boger & Miller (2004) depicted the Prydz–Denman Orogen truncating the East African–Antarctic Orogen under the ice in Dronning Maud Land, and Boger (2011) proposed a similar model but with an additional earlier Pan-African suture between western Dronning Maud Land and the *c.* 1.110 Ga Coats

Land Block (path EA2 in Fig. 6b). This latter suggestion followed Kleinschmidt & Boger (2009), who proposed this geometry to explain why the Coats Land magmatic rocks have no record of the 1090–1030 Ma granulite metamorphism seen in western Dronning Maud Land. However, this proposal remains rather speculative given the lack of evidence for *c.* 0.5 Ga events in either the Coats Land Block or westernmost Dronning Maud Land, and juxtaposition of these two blocks by *c.* 1.0 Ga is perhaps more likely (Jacobs *et al.* 2003b; Loewy *et al.* 2011).

Another possibility is that the Prydz–Denman Orogen intersected the Palaeo-pacific margin of Antarctica somewhere south of the Shackleton Range, and constraints on possible locations are provided by basement units exposed along the cratonic edge of the Ross Orogen, namely the Terre Adélie Craton, the Miller Range of the central Transantarctic Mountains, and the Read Mountains of the southern Shackleton Range (Fig. 6a). Coastal outcrops of the Terre Adélie Craton are dominated by metamorphism at *c.* 2.5 and 1.7 Ga (Peucat *et al.* 1999; Duclaux *et al.* 2008). These rocks are clear correlatives of the formerly contiguous Gawler Craton of Australia and this composite Antarctic–Australian crustal block has been named the Mawson Continent (Oliver & Fanning 1997). Metamorphism at *c.* 1.7 Ga is also a feature of the Miller Range (Goodge *et al.* 2001) and the Read Mountains (Will *et al.* 2009), although contrasting *P–T* conditions (Fig. 1) have led to different tectonic models for the two locations. The preservation of *c.* 1.7 Ga eclogite in the Miller Range is consistent with orogenic thickening during continental collision (Peacock & Goodge 1995), whereas similar-aged low-pressure amphibolite and granulite metamorphism in the Read Mountains is thought to reflect accretionary orogenesis at an active margin (Will *et al.* 2010). Despite these differences, both metamorphic events have been correlated with the 1.7 Ga ‘Kimban’ orogeny of the Gawler Craton, and if correct this implies that the Palaeoproterozoic Mawson Continent extended for more than 4,000 km along the palaeo-Pacific margin of Gondwana from South Australia to the Pan-African suture in the Shackleton Range. However, there are extensive outcrop gaps between Terre Adélie and the Miller Range (> 1,000 km), and between the Miller Range and Read Mountains (> 1,000 km), and although satellite magnetic data suggest that the Mawson Continent extends for *c.* 800 km into Antarctica from the Terre Adélie coastline (Finn *et al.* 2006; Goodge & Finn 2010) there is no conclusive evidence for geological continuity beyond this. If there is a major geological break between Terre Adélie and the Shackleton Range, then one possibility would be in the central Transantarctic Mountains (Fitzsimons 2003) where there is a change in the geochemistry of Ross-age granites (Borg *et al.* 1990) and in lower Palaeozoic stratigraphy (Rowell & Rees 1989). Although this boundary is typically drawn parallel to the Ross Orogen and interpreted either as a feature inherited from the passive margin rift geometry (Goodge *et al.* 2004) or a result of terrane accretion at the active margin (Borg *et al.* 1990), Fitzsimons (2003) speculated that it might reflect an extension of the Prydz–Denman orogen (path PD3 in Fig. 6b).

Further constraints on the presence and age of orogenic belts within the East Antarctic Craton are provided by detrital zircons eroded from the Antarctic interior and deposited at the continental

margins (e.g. Goodge & Fanning 2010; Veevers & Saeed 2011, 2013). These zircons include significant U–Pb age populations at 1.3–0.9 Ga and 0.7–0.5 Ga, which are taken as evidence for magmatism and metamorphism of this age within the centre of the Antarctic craton. Although there have been attempts to couple regional variations in the U–Pb age and Hf isotope composition of these zircons with glacial drainage patterns to identify discrete basement provinces (e.g. Veevers *et al.* 2008, Veevers & Saeed 2011, 2013), these spatial constraints are qualitative at best. The detrital zircon data also provide few constraints on the tectonic setting of magmatism or metamorphism and in particular cannot easily distinguish collisional metamorphism at an oceanic suture zone from intracratonic reworking at an older terrane boundary, although Hf data could identify any major component of juvenile crust such as an oceanic arc. A similar but more powerful approach is to study glacial clasts in moraines, which have been eroded from the subglacial bedrock and have the potential to link zircon age data with specific igneous and metamorphic regimes based on host clast petrology and geochemistry. An excellent example of this approach is provided by the work of Goodge *et al.* (2008, 2010) who have described glacial clasts collected from the craton side of the central Transantarctic Mountains. These clasts include samples of felsic orthogneiss with *c.* 1.1 Ga magmatic zircon ages that are consistent with the presence of a Grenville-age orogen under the continental ice sheet. Goodge *et al.* (2010) argued that *c.* 0.5 Ga zircon overgrowths in these rocks reflect craton margin events in the Ross Orogen, in which case the samples must have originated relatively close to their collection site, although the possibility that *c.* 0.5 Ga metamorphism might reflect Pan-African reworking of Grenville rocks in the continental interior would allow a more distal source. U–Pb and Hf data from detritus and glacial erratics have also characterised several pre-Grenville zircon populations that can be correlated with basement rocks in Laurentia or the Mawson Continent, including a distinctive *c.* 1.45 Ga granitoid clast that closely matches an A-type granite suite in Laurentia and provides strong support for the SWEAT connection between Antarctica and North America (Goodge *et al.* 2008).

Geophysical data should provide the best constraints on the location of Antarctic orogenic belts under the ice, but there is an uneven coverage of data across the continent and much of it is relatively low resolution. Prominent geophysical boundaries have been identified in Dronning Maud Land, Lake Vostok and the Gamburtsev Subglacial Mountains, but there is no information on the age of these structures and none of them can be confidently matched with exposed geology. The Forster magnetic anomaly occurs inland of the coastal outcrops of Dronning Maud Land (Riedel *et al.* 2013) and might be an extension of the South Orvin Shear Zone exposed in central Dronning Maud Land (Jacobs 1999). Although it has been interpreted as a major tectonic boundary or suture within the East African–Antarctic orogen, it is located too far north to link with the inferred Pan-African suture in the Shackleton Range, a conclusion supported by the expanded magnetic data set of Mieth & Jokat (in press). Studinger *et al.* (2003) presented magnetic, gravity and seismic evidence for a major crustal boundary trending north–south underneath Lake Vostok, near the centre of the East Antarctic ice sheet (Fig. 2), which is assumed to be a collisional suture of broadly ‘Proterozoic’ age. This survey provided

no data to constrain the boundary beyond the immediate vicinity of the subglacial lake, although the inferred boundary does lie along one of three possible paths suggested by Fitzsimons (2003) for the Antarctic extension of the Pinjarra Orogen (path PD3 in Fig. 6b). This proposed path also corresponds with the eastern branch of the East Antarctic Rift System (Figs 2 & 6; Ferraccioli *et al.* 2011), a prominent subglacial topographic feature that has a western branch in the Lambert Graben and is likely to follow older geological boundaries. Although Fitzsimons (2003) favoured a Pan-African age for this structure, there is evidence for metamorphism and magmatism at 1090–1060 Ma, 800–650 Ma and 550–500 Ma in the Pinjarra Orogen of Western Australia (Fig. 6b), and Boger (2011) suggested that this orogen might split into separate Pan-African and Grenville-age segments under the Antarctic ice sheet, in which case the Lake Vostok boundary might correspond to the older *c.* 1.0 Ga belt with or without a younger overprint at *c.* 0.5 Ga. Detrital zircon and monazite in a siltstone clast recovered from a Lake Vostok borehole yielded ages between 1.8 and 0.6 Ga (Leitchenkov *et al.* 2007) consistent with Grenville and Pan-African tectonism in the region. Another major crustal structure has been inferred from ENE–WSW trending magnetic anomalies along the northern edge of the Gamburtsev Subglacial Mountains (Ferraccioli *et al.* 2011). This boundary is interpreted as a suture between the Archaean Ruker Complex and a concealed ‘Gamburtsev Province’, and is assumed by Ferraccioli *et al.* (2011) to be *c.* 1.0 Ga in age, partly because its trend is similar to that of Grenville-age structures in the Prince Charles Mountains. There are, however, no reliable age constraints and this structure could also be Pan-African in age, in which case it might correspond to path PD2 in Fig. 6b. Unfortunately there are currently no detailed geophysical data for regions to the east or west of the Gamburtsev Subglacial Mountains, frustrating attempts to link this inferred suture with coastal outcrops.

### **New constraints on Africa–Antarctica connections**

A recent reassessment of the Damara–Zambezi Orogen and its intersection with the East African Orogen in Mozambique has questioned some of the widely accepted correlations made between Antarctica and Africa. This was prompted by mounting evidence for a Pan-African suture along the Damara–Zambezi Orogen, including data demonstrating that previously correlated units on either side of the orogen are of quite different age (De Waele *et al.* 2003) and the identification of basaltic rocks with MORB chemistry that were subjected to eclogite metamorphism at *c.* 0.6 Ga (John & Schenk 2003). These rocks preserve cool geothermal gradients of *c.* 8 °C/km, consistent with a long-lived subduction zone, and imply that an ocean closed along the Damara–Zambezi Orogen sometime before collisional metamorphism at *c.* 0.5 Ga. The east–west structural trend of the Zambezi Orogen continues eastwards through Mozambique as the Lurio Belt, which appears to truncate the East African Orogen and pass into the thrust sheets of Sri Lanka (e.g. Bingen *et al.* 2009). If so, this would make the Dronning Maud Land granulites of Antarctica part of the east–west Damara–Zambezi Orogen rather than a north–south East African–Antarctic Orogen, and make it unlikely that ophiolite

and eclogite in the Shackleton Range represent the extension of the East African Orogen. These cross-cutting relationships suggest that there should be an age difference between the two Pan-African orogens, which might explain a bimodal distribution of Pan-African age data first described by Clifford (1967), who distinguished an early ‘Katangan’ event (680–580 Ma) from a younger ‘Damaran’ event (550–500 Ma). Meert (2003) suggested that the older ages occurred predominantly north of Mozambique and reflected collision along the East African Orogen, while the younger event was recorded farther south in the Damara–Zambezi Orogen, which he named the Kuunga Orogen and took to represent the final amalgamation of Gondwana. These spatial and temporal relationships remain hotly debated, however, with others arguing that both periods of metamorphism occur in the East African Orogen, perhaps reflecting an earlier event linked to arc magmatism before terminal ocean closure and collision (e.g. Appel *et al.* 1998) or early collision followed by later extension and orogenic collapse (e.g. de Wit *et al.* 2001). According to this latter model, east–west trending structures in the Lurio Belt would reflect collapse of the East African Orogen at 550 Ma rather than a second suture zone (Ueda *et al.* 2012), and the status of the Dronning Maud Land granulites will remain unclear until this issue is resolved. One intriguing possibility is that the Damara–Zambezi suture continues through the Lurio Belt and Sri Lanka, and connects with Pan-African tectonism in the Eastern Ghats Belt, lending support to arguments that the boundary between the Eastern Ghats and cratonic India is a major Pan-African suture zone.

### **The Gondwana margin**

Following Gondwana assembly at *c.* 0.5 Ga, the focus of Antarctic tectonic activity moved to the palaeo-Pacific margin, which evolved from a passive to an active continental margin. This change is recorded by the Ross Orogen along the edge of the East Antarctic Craton and a number of outboard terranes including those in present-day West Antarctica and New Zealand (Fig. 6a), which preserve a history of episodic magmatism, coupled with multiple stages of contractional and extensional deformation. These rocks form part of an extensive Neoproterozoic to Mesozoic accretionary orogen that extended along the palaeo-Pacific margin of Australia, Antarctica and South America, collectively referred to as the Australides by Vaughan *et al.* (2005), and split into the Neoproterozoic–Palaeozoic Terra Australis Orogen and Mesozoic Gondwanides Orogen by Cawood (2005).

Latest Neoproterozoic to Ordovician subduction under the Ross Orogen was associated with the emplacement of an extensive 590–480 Ma magmatic arc (the Granite Harbour Intrusives), together with deformation, metamorphism, and deposition of syn-orogenic sedimentary sequences (Borg & DePaolo 1991; Stump 1995; Encarnación & Grunow 1996; Rocchi *et al.* 1998; Cox *et al.* 2000; Allibone & Wysoczanski 2002; Goodge *et al.* 2002, 2004, 2012; Myrow *et al.* 2002; Goodge 2002, 2007; Cooper *et al.* 2011). This event was accompanied by accretion of the Bowers and Robertson Bay terranes to the craton margin along the Lanterman Range of northern Victoria Land by the latest Cambrian or earliest Ordovician (Tessensohn & Henjes-Kunst 2005; Federico *et al.* 2006). Other

outboard terranes with a record of Palaeozoic to Mesozoic tectonism are exposed in West Antarctica, which has been subdivided into five discrete blocks that moved relative to one another and to the craton during Gondwana breakup (Fig. 2; Haag Nunataks, Ellsworth–Whitmore Mountains, Antarctic Peninsula, Thurston Island and Marie Byrd Land; Dalziel & Elliot 1982; Storey *et al.* 1988). Detailed geological and geochronological correlations have now established the broad geometry of these terranes prior to breakup (Fig. 6a). The Haag Nunataks comprise Mesoproterozoic gneissic units (Millar & Pankhurst 1987) interpreted as a displaced fragment of the Dronning Maud Land basement (Grantham *et al.* 1997) and the Ellsworth–Whitmore Mountains block is a rotated section of the passive margin (Curtis 2001), but the other blocks define three broad belts of Palaeozoic to Mesozoic subduction-related terranes that can be correlated from the Antarctic Peninsula through to New Zealand (Fig. 6; Vaughan & Pankhurst 2008).

An inner belt of terranes comprising early Palaeozoic Gondwana-derived sedimentary sequences and Devonian (*c.* 400–350 Ma) and Carboniferous (*c.* 340–320 Ma) subduction-related granitoids is referred to as the Ross Province in Marie Byrd Land (Pankhurst *et al.* 1988; Mukasa & Dalziel 2000; Siddoway & Fanning 2009) and the Eastern Domain in the Antarctic Peninsula (Vaughan & Storey 2000). These rocks are correlated with the Robertson Bay Terrane of northern Victoria Land, the Western Province of New Zealand, and the Lachlan, Thomson and New England orogens of eastern Australia (Bradshaw *et al.* 1983; Muir *et al.* 1996; Ireland *et al.* 1998; Tulloch *et al.* 2009), and all form part of the Terra Australis Orogen. This Palaeozoic accretionary orogen records alternating episodes of extension and contraction linked to periods of subduction zone advance and retreat (Collins 2002) and terminated with the 300–230 Ma Gondwanides Orogeny (Cawood 2005). This episode of widespread deformation and metamorphism is recorded to varying degrees by rocks along the entire length of the orogen from eastern Australia to the Andean margin of South America, and was first recognised by Du Toit (1937) as the Samfrau Geosyncline (Fig. 3b).

Gondwanide orogenesis in the Antarctic sector was linked to a stepping out of the subduction zone and the development of a belt of 320–110 Ma magmatic arc rocks outboard of the Palaeozoic arc (Fig. 6b). This Mesozoic arc complex, which also locally contains evidence of much earlier 450–420 Ma magmatism, is referred to as the Amundsen Province in Marie Byrd Land (Pankhurst *et al.* 1988; Mukasa & Dalziel 2000) and the Central Domain in the Antarctic Peninsula (Vaughan & Storey 2000), and is correlated with magmatic rocks in Thurston Island and the Median Tectonic Zone of New Zealand. The outermost belt of terranes is a Mesozoic subduction-accretion complex developed between the magmatic arc and the subduction zone, and is exposed as the Western Domain of the Antarctic Peninsula and the Eastern Province of New Zealand (Fig. 6b; Vaughan & Storey 2000). Further evidence for the Late Palaeozoic to Mesozoic active margin in West Antarctica is preserved on the craton by the Devonian to Lower Jurassic sandstone-dominated Beacon Supergroup of the Transantarctic Mountains, which was in part derived from detritus shed by the evolving magmatic arc (Elliot & Fanning 2008; Goodge & Fanning 2010). As with the Palaeozoic subduction complex, the



Mesozoic rocks record periods of episodic deformation, including the *c.* 200 Ma Peninsula Orogeny and *c.* 110 Ma Palmer Land Event of the Antarctic Peninsula (Vaughan *et al.* 2005). This latter event has been correlated with the final juxtaposition of Central and Eastern domains of the Antarctic Peninsula (Vaughan *et al.* 2002), and was synchronous with the assembly of the Amundsen and Ross provinces of Marie Byrd Land into their present-day positions (DiVenere *et al.* 1995).

Antarctica had already begun to undergo extension in response to Gondwana breakup by the time of these final accretion events (Veevers 2004, 2012). Early stages of extension commenced immediately after the Gondwanide Orogeny, and were marked by *c.* 180 Ma mafic magmatism of the Ferrar Province, which overlies and intrudes the Beacon Supergroup in the Transantarctic Mountains (Fleming *et al.* 1997; Elliot & Fleming 2004). Significant extension in the Weddell Sea area began at *c.* 170 Ma, as Africa and South America started to split from Antarctica, leading to rotation of the Ellsworth–Whitmore and Falklands–Malvinas blocks (Dalziel & Grunow 1992; König & Jokat 2006) and the formation of oceanic crust within the Weddell Sea by *c.* 150 Ma. Oceanic crust had formed between India and Antarctica by 130 Ma, and between Australia and Antarctica by 90 Ma, possibly propagating eastwards with full separation at 50 Ma (Veevers 2004, 2012; Direen 2011). Rifting was also widespread in West Antarctica at *c.* 100 Ma, resulting in extension, A-type magmatism and metamorphism in Marie Byrd Land. This was linked to development of the West Antarctic Rift System (Mukasa & Dalziel 2000; Siddoway 2008) and the separation of New Zealand and other blocks away from West Antarctica (Mortimer 2004), leaving Antarctica in more-or-less its present-day configuration.

While this complex sequence of Palaeozoic to Mesozoic events along the active margin of Gondwana was initially viewed in isolation from events elsewhere, it has been increasingly recognised that major episodes of magmatism, deformation and metamorphism along an accretionary orogen can be linked to processes operating on a supercontinent scale. Thus the onset of subduction along the craton margin at 590–550 Ma is now widely regarded as a response to the reduction of convergence along the internal collisional orogens of Gondwana, reflecting a need for subduction to commence elsewhere to maintain a balance between divergent and convergent plate boundaries (Grunow *et al.* 1996; Goodge 1997; Boger & Miller 2004; Cawood & Buchan 2007). More specifically, a major pulse of deformation within the Ross Orogen at *c.* 515 Ma, synchronous with magmatism and deformation in the equivalent Delamerian Orogen of Australia (Foden *et al.* 2006), has been correlated with a major plate reorganisation and increased subduction rates following the final suturing of the Pan-African collisional belts (Boger & Miller 2004; Paulsen *et al.* 2007). Similarly the 300–230 Ma Gondwanide deformation was synchronous with final stages of Pangaea assembly, consistent with increased convergence rates at the active margin in compensation for reduced convergence across the Appalachian, Variscan and Ural collisional orogens (Cawood & Buchan 2007). It has also been noted that periods of Mesozoic deformation and terrane accretion in the Antarctic Peninsula and Marie Byrd Land at *c.* 200 Ma and 110 Ma were synchronous with other deformation events worldwide, leading to

suggestions that they were a response to mantle ‘superplume’ events linked to the progressive breakup of Pangaea (Vaughan 1995; Vaughan & Livermore 2005).

### **Antarctica and Supercontinent Evolution**

The above discussion has focused largely on the assembly and subsequent evolution of the Gondwana supercontinent, and considered pre-Gondwana rock units primarily for the constraints they provide on the locations of Neoproterozoic orogens. However, Antarctica also contains a valuable record of Mesoproterozoic, Palaeoproterozoic and Archaean events that will need to be incorporated into any comprehensive models for Rodinia, Nuna and earlier supercontinental assemblies.

For Rodinia, an important goal is the correlation of Antarctic Grenville-age belts with similar-aged orogens elsewhere. The original SWEAT hypothesis connected the Grenville Orogen proper of North America to the Maud Belt (Moores 1991; Li *et al.* 2008; Loewy *et al.* 2011) but others have linked it with Wilkes Land outcrops via the Albany–Fraser Orogen (Karlstrom *et al.* 1999; Pisarevsky *et al.* 2003) while some Rodinia configurations have no Grenville links between Antarctica and Laurentia at all (Evans 2009). A fourth possibility, consistent with the Grenville-age glacial clasts described by Goodge *et al.* (2010) from the central Transantarctic Mountains, is that the Laurentian Grenville links up with Grenville-age rocks in the Pinjarra Orogen of Western Australia via a subglacial orogen that follows the eastern branch of the East Antarctic Rift System (PD3 in Fig. 6b).

Attention switches to the Mawson Continent for reconstructions of Nuna – which is believed to have assembled by the collision of multiple continental blocks along a series of Palaeoproterozoic orogens, with the final stages of assembly at 1.9–1.8 Ga (Zhao *et al.* 2004; Reddy & Evans 2009; Evans & Mitchell 2011). Important questions in Antarctica include whether the Mawson Continent extends as far as the Miller and Shackleton ranges, and if so whether there is a continuous 1.7 Ga orogen between these outcrops and the Gawler Craton of South Australia (Payne *et al.* 2009). This 1.7 Ga belt passes between the Mawson Continent and Laurentia in most Nuna reconstructions (Zhao *et al.* 2002, 2004; Evans & Mitchell 2011; Zhang *et al.* 2012), challenging arguments that Nuna had already assembled by 1.8 Ga (e.g. Zhang *et al.* 2012). If this belt does reflect juxtaposition of Laurentia and the Mawson Continent at 1730–1720 Ma (e.g. Betts *et al.* 2008; Payne *et al.* 2009; Boger 2011), then this means a relatively late assembly for this part of Nuna. Another possibility is that *c.* 1.7 Ga metamorphism in the Miller Range (and perhaps the Shackleton Range) is unrelated to Kimban events in South Australia, and is instead linked to events at the active margin of Laurentia which should have extended into the Mawson Continent somewhere close to the Miller Range according to the correlations of Goodge *et al.* (2008).

A number of studies have attempted to categorise and correlate Earth’s Archaean cratons (e.g. Bleeker 2003; Pehrsson *et al.* 2013). Although the notion of a single Neoarchaean supercontinent has been rejected, making Nuna the first true ‘true’ supercontinent, it does seem likely that most if not all of Earth’s Archaean continental crust was assembled into three or four ‘supercratons’ at *c.* 2.5 Ga.

Antarctica contains several isolated blocks of Archean crust that appear to have little in common with one another (Harley & Kelly 2007b) but which can generally be correlated with larger cratons in formerly adjacent continents. The Grunehogna Craton in western Dronning Maud Land has links with the Archean of southernmost Africa and is inferred to have been part of the Vaalbara Supercraton (Cheney 1996; Bleeker 2003), while the Napier Complex and Vestfold Hills are generally correlated with the Dharwar and Singhbhum cratons of India (e.g. Veevers 2012). Bleeker (2003) argued that the Dharwar Craton (and Napier Complex) were part of a 'Sclavia' supercraton, while Pehrsson *et al.* (2013) allocated both the Dharwar and Singhbhum cratons, along with Neoproterozoic rocks of the Mawson Continent, to a variant of Sclavia they name Nunavutia. However, there are as yet no established correlations for the relatively poorly exposed and geologically isolated Ruker Complex. The Neoproterozoic supercratons are generally believed to be the earliest examples of stable aggregated continental crust, given a more-vigorous mantle and smaller plates on the early Earth (Pollack 1997), and our understanding of the continents before this time is compromised by a very sparse rock record. However, Antarctica is one of the few places to provide evidence of this early history through one of Earth's oldest known rocks, the 3.8–3.9 Ga protolith to the Mount Sones Orthogneiss in the Napier Complex (Black *et al.* 1986; Harley & Kelly 2007b).

Given that the Precambrian of Antarctica occurs almost exclusively as metamorphic rocks of varying grade, this prolonged history of continental assembly and breakup is best illustrated in terms of metamorphic age and peak geothermal gradient. This approach has been adopted on the global scale by Brown (2006, 2007), who compiled age and  $P$ – $T$  information from over two hundred metamorphic belts to test for secular trends in metamorphism. He divided the belts according to peak thermal gradient into three groups (Fig. 1): high-pressure to ultrahigh-pressure (HP–UHP) belts, eclogite to high-pressure granulite (E–HPG) belts, and granulite to ultrahigh temperature (G–UHT) belts. Brown (2006) observed that whilst HP–UHP metamorphism is only recorded since the latest Neoproterozoic, E–HPG and G–UHT metamorphic belts have been forming on Earth since at least the mid- to late Archean. The restriction of HP–UHP metamorphism to younger ages has been proposed to reflect a change in the thermal regime of subduction to 'cold' subduction, in which a strong mantle lithosphere facilitates focused downward and upward flow of material in subduction channels (Brown 2007; Gerya *et al.* 2008; Sizova *et al.* 2010). The only example of HP–UHP metamorphism in East Antarctica is that reported from the Lanterman Range of Northern Victoria Land (Palmeri *et al.* 2007). Like other HP–UHP areas it is no older than Ediacaran to Cambrian, and can be linked to subduction-accretion along an active ocean-continent margin.

Brown (2006, 2007) proposed that the two thermal regimes represented by E–HPG and G–UHT metamorphic belts represent the hallmark of plate tectonics involving subduction, in existence since at least the late Archean. In this duality E–HPG metamorphism reflects subduction-to-collision orogeny in which 'warm' crustal material chokes the subduction zone at moderate depths, whereas G–UHT belts are attributed to the closure and thickening of continental backarcs, characterised by

abundant accreted juvenile crust. Both Brown (2006, 2007) and workers using zircon isotopic systems to trace the growth of continental crust (Hawkesworth & Kemp 2006; Kemp *et al.* 2006) have linked the formation and preservation of these metamorphic belts with the assembly of past supercontinents.

Figure 1 compares the global metamorphic data set of Brown (2006, 2007) and the metamorphic data set based solely on East Antarctic belts with the ages of supercontinent assembly episodes discussed above. Whilst E-HPG belts are scarce in Antarctica, those that have been identified have ages that can be correlated with the final assembly of Gondwana at 550–500 Ma or, as discussed in detail above, the final assembly of Nuna at *c.* 1.7 Ga. Exposed Antarctic G-UHT metamorphic belts, on the other hand, have ages that strongly correlate with the assembly of Gondwana at 0.6–0.5 Ga and of Rodinia at 1.2–0.9 Ga. In some cases both events are recorded in the same belt or region (e.g. Prydz Belt), where the younger event appears to be dominated by reworking of older deep crust with no evidence of juvenile magmatism. While apparently inconsistent with G-UHT metamorphism forming by inversion of a continental backarc, it is possible that associated juvenile rocks are concealed by the ice sheet or that G-UHT metamorphism was linked to formation of a long-lived orogenic plateau at some distance from the plate boundary (e.g. Clark *et al.* 2011). No Grenville-age E-HPG metamorphism has yet been identified in Antarctica, but given evidence for E-HPG events in other 1.2–0.9 Ga belts (e.g. Carlson *et al.* 2007) this might reflect poor exposure rather than a breakdown in the metamorphic duality proposed by Brown (2006). Finally, Antarctica preserves a number of Archaean G-UHT belts that, as noted above, may provide information on the nature and extent of Neoarchaean supercratons. Most notable amongst these belts is the Napier Complex, a globally significant UHT belt that preserves extreme metamorphic conditions reflected in its  $dT/dz$  gradient of *c.* 40 °C/km at 2.6–2.5 Ga (Fig. 1). The metamorphic age of the Napier Complex lies within the range of time attributed to the assembly of ‘Kenorland’ or of Scavia, but as it is comprised mainly of much older protoliths instead of juvenile 2.6–2.5 Ga crust, unlike the Vestfold Hills, its relationship to supercraton or supercontinent assembly remain enigmatic.

### **Current research themes**

The present volume arises from a thematic session on "Antarctica and Supercontinent Evolution" at the 12th International Symposium on Antarctic Earth Sciences, held in Edinburgh in July 2011. This theme considered not only the formation of supercontinents from the Antarctic perspective, with a focus on Rodinia and Gondwana, but also on how supercontinents evolve and eventually fragment, perhaps with the involvement of mantle plumes giving rise to flood basalts and large igneous provinces such as the Ferrar Province. The theme attracted some 46 oral and poster presentations, of which eight have been developed into papers contributing to this volume. The collected papers present new research results from three regions (see Fig. 6b): the Lambert Graben—Prydz Bay area and eastern Dronning Maud Land, both critical to understanding *c.* 1.0 and 0.5 Ga metamorphism in the

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East Antarctic Craton, and the Pacific-facing margin of Antarctica that records the Palaeozoic to Mesozoic evolution of the Gondwanan active margin.

#### *Lambert Graben—Prydz Bay*

Four papers in this volume are concerned with India–Australia–Antarctica connections in the Lambert Graben—Prydz Bay sector of East Antarctica, and the potential placement of a Neoproterozoic suture in this region.

**Mikhalsky *et al.*** (2013) present a synthesis of the geochemistry, ages and initial Nd-isotopic signatures of Rayner Complex gneisses in the northern and central Prince Charles Mountains, Amery Ice Shelf and Prydz Bay coastline, and report new data for the eastern edge of the Amery Ice Shelf. The Rayner Complex of the northern Prince Charles Mountains comprises high-grade gneiss of the Beaver Terrane, with 1070–1020 Ma and older protoliths metamorphosed during the 990–900 Ma Rayner Structural Episode, and the Fisher Terrane with a distinctive *c.* 1.3 Ga metavolcanic sequence and a significant component of juvenile Mesoproterozoic crust. Similar relationships in the Amery Ice Shelf and western Prydz Bay region imply that these outcrops are part of the Rayner Complex even though they have been reworked by Pan-African events, as suggested previously by Wang *et al.* (2008) and Grew *et al.* (2012), and indicate that any Pan-African suture must lie to the east of the Prydz Bay outcrops. More controversially, *c.* 1.6–1.2 Ga protolith ages are correlated with events in the Albany-Fraser Orogen of Western Australia and Wilkes Province of Antarctica. Similar correlations have been noted by Halpin *et al.* (2012), and are used by Mikhalsky *et al.* (2013) to support ‘old’ models of a continuous *c.* 1.0 Ga metamorphic belt suturing Australia, Antarctica and India at *c.* 1.0 Ga. These suggestions challenge palaeomagnetic evidence for wide separation of India and Australia at 750 Ma (Torsvik *et al.* 2001; Gregory *et al.* 2009) unless an alternative Neoproterozoic suture can be identified within India, and will no doubt stimulate more geochronological and Nd–Hf isotopic characterisation of protoliths in the *c.* 1.0 Ga orogens of East Gondwana.

**Flowerdew *et al.*** (2013a) also consider the basement constitution and age-isotope signatures of the Prydz Bay—Lambert Graben sector, but from an entirely different perspective and approach. They use the Pb isotopic compositions of feldspar from orthogneiss units in coastal outcrops (Prydz Belt, Rauer Group, Vestfold Hills, Napier Complex) and inland outcrops (Beaver and Fisher Terranes of the Rayner Complex, Lambert Complex, Ruker Complex) to fingerprint the major terranes in this region and evaluate potential links with India and elsewhere. These data suggest that coastal Archaean terranes in this sector of Antarctica (Napier Complex and Vestfold Hills) share isotopic characteristics with the eastern Dharwar Craton, consistent with an Indian origin, but that the inland Ruker Complex has a distinctive unradiogenic Pb isotope composition unlike any nearby Archaean terranes other than the Rauer Group. This questions previous correlations between the Ruker Complex and Yilgarn Craton (Mikhalsky *et al.* 2010), but supports arguments that Archaean rocks of the Ruker Complex

(and perhaps the Rauer Group) form part of a unique craton largely concealed by the ice sheet (Boger 2011). The Pb data also indicate that the Ruker and Lambert complexes of the southern Prince Charles Mountains have quite distinct isotopic compositions, supporting arguments that the boundary between them is a fundamental crustal structure (Boger *et al.* 2001). They also confirm that the Lambert and Ruker complexes are interleaved with a complex outcrop pattern, but do not provide any constraints on whether they were juxtaposed at *c.* 1.0 or *c.* 0.5 Ga. While not identical, Pb isotopes indicate that the Beaver Terrane and Prydz Belt share similar protoliths, and moreover that these overlap with Pb-isotope signatures of the Eastern Ghats Belt in India supporting previous correlations made using other techniques. These compositions are quite distinct, however, from those in the Maud Belt, consistent with these two *c.* 1.0 Ga metamorphic belts being unrelated. This paper illustrates the potential of Pb isotopes to make important correlations between basement terranes, and also provides a valuable Pb-isotopic database that will allow future studies to link detrital feldspars to their source terrane, which has already proven useful for understanding concealed bedrock and glacial flow patterns in other parts of Antarctica (e.g. Flowerdew *et al.* 2012, 2013b).

In the third paper of this set, **Grew *et al.*** (2013) focus on unusual outcrops of boron- and phosphate-rich paragneiss from the Larsemann Hills of Prydz Bay, which have important implications for the Proterozoic geological setting of Prydz Bay given that boron mineralisation is typically linked spatially to a plate margin. The borosilicate minerals tourmaline, prismaticine and grandierite, together with apatite and several other rare phosphate minerals, are developed over a range of stratigraphic levels in granulite-facies metapelite, metaquartzite, metapsammite and other rock compositions in the Larsemann Hills. This paper uses a synthesis of existing geochemical data, together with new whole-rock major, trace element and rare earth element (REE) data, to constrain models for the origin of boron enrichment in the sedimentary precursors to the paragneiss. Comparisons are drawn with older borosilicate rocks of the Willyama Complex at Broken Hill, Australia, and the cases for non-marine evaporite and mud volcano origins are discussed in depth. With some caveats, the authors attribute boron and phosphorus enrichment to pre-metamorphic hydrothermal alteration in a rifted basin located inboard of a continental arc. The age of the sedimentary sequence, and by extension the age of boron mineralisation and associated magmatic arc, is controversial. Kelsey *et al.* (2008) argued for deposition at *c.* 0.6 Ga, between the two regional metamorphic events at *c.* 1.0 and 0.5 Ga, but Wang *et al.* (2008) and Grew *et al.* (2012) argued for deposition at 1.1–1.0 Ga, followed by metamorphism at *c.* 1.0 Ga and *c.* 0.5 Ga. The preference in this paper is that deposition occurred inboard of the ‘Rayner’ active margin of an Indian continent just prior to collision and metamorphism at 1.0–0.9 Ga.

**Liu *et al.*** (2013) review and synthesise geochronological and metamorphic *P–T* data from the Prydz Bay and Prince Charles Mountains regions with an emphasis on *c.* 1.0 and 0.5 Ga tectonothermal events. They highlight evidence for discrete periods of metamorphism within the earlier event at 1000–970 Ma and 930–900 Ma. Evidence for both events is preserved across the region, including the Rayner Complex where there is limited evidence for the *c.* 0.5 Ga event, and

western Prydz Bay where there is a significant *c.* 0.5 Ga granulite-facies overprint. This is consistent with these all being part of a single *c.* 1.0 Ga orogenic province that correlates closely with the Eastern Ghats Belt of India. The authors also report unpublished evidence for high-grade 1.0–0.9 Ga metamorphism in the southwestern Vestfold Hills, lending support to arguments that terranes in this area were assembled at *c.* 1.0 Ga rather than *c.* 0.5 Ga, and consistent with Pb isotope evidence that the Vestfold Hills have an Indian origin (Flowerdew *et al.* 2013a). *P–T* data are used to suggest that the 1000–970 Ma event was associated with medium- to low-pressure granulite metamorphism, while the 930–900 Ma event was of medium- to high-pressure character, consistent with a switch from an active continental margin to a collisional orogen. The consistency in *c.* 1.0 Ga protolith age across the region indicates that any Pan-African suture associated with the *c.* 0.5 Ga overprint must lie south-east of the Prydz Bay—Lambert Graben region, but in contrast to Mikhalsky *et al.* (2013) these authors argue that a Pan-African suture is present under the ice. They suggest that the 545 Ma high-pressure mafic granulites found as glacial erratics in the Grove Mountains are sourced from this suture zone (Liu *et al.* 2009a). These rocks have no record of the *c.* 1.0 Ga event and preserve *P–T* conditions typically associated with metamorphism during continental collision (O’Brien & Rötzler 2003; Brown 2006).

#### *Eastern Dronning Maud Land*

Two papers in this volume are concerned with the Pan-African granulites of eastern Dronning Maud Land, which are critical for understanding the links between *c.* 0.5 Ga metamorphism in Antarctica, Africa and Sri Lanka, and the evolution of the East African–Antarctic Orogen.

**Adachi *et al.*** (2013) characterise contrasting *P–T* conditions and *P–T*–time paths for three metamorphic domains in the Sør Rondane Mountains. They identify two domains that record peak granulite metamorphism, one with a retrograde history of near-isothermal decompression and the other dominated by isobaric cooling, both of which are affected by younger hydration. The third domain has prograde amphibolite-facies assemblages correlated with the hydration event in the other domains. Although correlations are not straightforward, existing geochronological data for Sør Rondane (Asami *et al.* 2005; Shiraishi *et al.* 2008) suggest that granulite-facies metamorphism occurred at 640–600 Ma while amphibolite metamorphism and hydration occurred significantly later at 570–520 Ma. These results are consistent with peak metamorphic ages of 660–620 Ma from the Schirmacher Hills of central Dronning Maud Land (e.g. Mikhalsky *et al.* 1997; Baba *et al.* 2010), but contrast with evidence for peak metamorphism at 550–500 Ma farther east in the Lützow–Holm Complex (Fraser *et al.* 2000; Shiraishi *et al.* 2008) and farther west in central and western Dronning Maud Land (Jacobs *et al.* 2003a; Board *et al.* 2005; Bisnath *et al.* 2006). It follows that Dronning Maud Land preserves evidence of the ‘Katangan’ and ‘Damaran’ events distinguished in Africa by Clifford (1967), and that spatial relationships between these two event are not as simple as envisaged by Meert (2003) in his arguments for a younger Kuunga Orogen cross-cutting an older East African Orogen. Grantham *et al.* (2008) argued that outcrops in central and eastern Dronning Maud Land preserving 650 Ma

metamorphism might be part of an ‘East African’ thrust sheet transported *c.* 500 km southwards during 550 Ma collision along the Kuunga Orogen, but Adachi *et al.* (2013) contend that thrusting in this area was associated with the 640–600 Ma event, while 570–520 Ma metamorphism may have been associated with voluminous magmatism rather than with any ‘terminal’ collision. The meaning of these two metamorphic events in Africa, Madagascar, Sri Lanka and Dronning Maud Land is critical to models of Pan-African orogenesis, but it seems that more work is needed to conclusively link the age data to specific tectonothermal events.

Another key feature of Pan-African events in eastern Dronning Maud Land is the sporadic occurrence of ultrahigh temperature (UHT) metamorphic rocks, which is best documented at Rundvågshetta in the Lützow–Holm Complex (Motoyoshi & Ishikawa 1997; Fraser *et al.* 2000; Kawasaki *et al.* 2011). UHT metamorphism seems to be characteristic of *c.* 0.5 Ga tectonism in several parts of Gondwana (Harley 2003; Fig. 1) and has been linked more generally to periods of supercontinent assembly (Brown 2006, 2007), but it is difficult to establish its lateral extent beyond isolated outcrops of distinctive high Mg–Al gneisses that develop diagnostic sapphirine and osumilite-bearing assemblages. Kawasaki *et al.* (2013) present a novel approach to documenting UHT over larger geographic areas using complex ilmenite–rutile Fe–Mg–Ti intergrowths present in ordinary-looking garnet–sillimanite gneiss. They document the textural and chemical features of these intergrowths and interpret them as pseudomorphs after the high-*T* mineral armalcolite. This forensic petrographic investigation is coupled with high-*T* experiments conducted at 1 atmosphere pressure, which constrain the minimum temperature of armalcolite stability to be *c.* 1290°C at 10 kbar. This is much higher temperature than other peak *T* estimates of 970–1050 °C for these rocks, but can be explained by ferric iron extending armalcolite stability to lower temperature in the Lützow–Holm Complex. The key conclusion of this study is that it is crucial to look in detail not only at silicate mineral assemblages to infer peak-*T* conditions of granulites but also the oxide mineralogy, which is likely to preserve diagnostic evidence for UHT conditions in a wider range of bulk compositions.

#### *Pacific Margin of Antarctica*

The crustal architecture and sequence of crustal differentiation episodes along the palaeo-Pacific active of Gondwana are considered in two papers that utilise very different approaches and materials to address the issues.

Accretionary orogens are major sites for the creation, reworking and consumption of continental crust (Cawood *et al.* 2009), and the palaeo-Pacific margin of Gondwana is an ideal location to study these processes. Recent studies of the Australian sector of this accretionary orogen using combined Hf–O isotope analysis of zircon from arc rocks have shown that significant crustal growth through juvenile magma addition is most pronounced in periods of extension associated with subduction zone retreat, while contractional periods are dominated by reworking of older crust (Kemp *et al.* 2009). Yakymchuk *et al.* (2013) extend this approach to the Ross Province of Marie Byrd Land,



and in particular to two generations of granite in the migmatitic Fosdick Complex. These granites are believed to reflect partial melting during two separate high-grade metamorphic events, a Devonian–Carboniferous event linked to thickening of the continental margin immediately after the major phase of arc magmatism at *c.* 370 Ma, and a Cretaceous event linked to moderate thickening and then extension during development of the West Antarctic Rift at 115–100 Ma. Hf–O data confirm field and petrological arguments that both granite generations were derived by mixing of partial melts derived from host metasedimentary and Devonian arc rocks, although the Cretaceous granite requires an additional juvenile component. Comparisons with data from granites in the Western Province of New Zealand, eastern Australia, and the Antarctic Peninsula reveal arc parallel and arc normal variations in the extent of juvenile crustal additions and in temporal patterns of magma generation, indicating a spatial petrogenetic complexity in the orogen.

Rather than study magmatic arc material directly, **Elsner *et al.*** (2013) use detrital zircons from a Triassic to Early Jurassic section of the uppermost Beacon Supergroup in northern Victoria Land to document contemporaneous magmatism. This detritus is likely to come from a wide area and so be more representative of the geology than the relatively poorly exposed arc rocks. The youngest detrital grains in each sample decrease in age from *c.* 220 Ma at the base of the section to *c.* 190 Ma at the top, consistent with erosion of an active arc. The proportion of zircon from this youngest 240–190 Ma population increases up section, as does the abundance of volcanic rock clasts, suggesting increased elevation and erosion of the Triassic–Jurassic arc with time. There are also minor components of Permian (*c.* 270–250 Ma) and Devonian–Carboniferous (410–320 Ma) zircon, also assumed to derive from arc complexes along the palaeo-Pacific margin of Gondwana. These observations are consistent with the outboard arc terranes being a topographic high in the early Mesozoic, while a minor component of 550–470 Ma zircon that decreases in abundance up-section is taken as evidence that the inboard Ross Orogen was progressively concealed by sedimentation at this time. More challenging are major populations of Pan-African (700–500 Ma) and Grenville-age (1200–800 Ma) zircons, which occur in most samples. Similar populations have been identified in other studies of the Beacon Supergroup (Elliot & Fanning 2008; Goodge & Fanning 2010), and they might represent second-cycle reworking of outboard sedimentary sequences or direct erosion of the inboard craton, although the absence of a Palaeoproterozoic (Mawson Continent) component is problematic. Interestingly there is evidence for 700–500 Ma reworking of 1200–800 Ma zircon grains, suggesting a spatial association of these two events in the source region. Following Sircombe (1999), Elsner *et al.* (2013) consider the possibility of a concealed block with Grenville and Pan-African tectonism inboard of the Ross Orogen and inland of coastal exposures of the Mawson Continent in Terre Adélie. Another possibility is the suggestion of Fitzsimons (2003) that the Pinjarra Orogen, with evidence of Grenville and Pan-African tectonism, might extend across Antarctica from the Denman Glacier region to the central Transantarctic Mountains (Path PD3 in Fig. 6b). Although the absence of conclusive outcrop or geophysical evidence makes these proposals speculative, the abundance of Grenville and Pan-African

detritus along the palaeo-Pacific margin of Australia and Antarctica remains a problem that otherwise requires sediment transport distances of up to 4,000 km (e.g. Squire *et al.* 2006).

### **Concluding remarks**

Although a broad framework for the Phanerozoic palaeogeography and tectonics of Gondwana and Pangaea was established some time ago, Antarctica continues to reveal new information on the details of this history, most notably the configuration and evolution of the accretionary orogen at its Pacific margin. New data from this margin show that accretionary systems are particularly sensitive to changes in the global plate tectonic budget, and undergo cycles of extensional and contractional deformation and episodic crustal growth in response to supercontinent assembly and breakup. Precambrian supercontinent history is less well understood, with no clear consensus on the configuration of the Rodinia supercontinent or the Neoproterozoic transformation of Rodinia to Gondwana, and our poor knowledge of the ice-covered East Antarctic Craton is a major contributor to this uncertainty.

All available geological and geophysical data point to the presence of Grenville and Pan-African orogens extending under the Antarctic ice sheet, which record events associated with the assembly of the Rodinia and Gondwana supercontinents respectively, but the exact paths of these orogens under the ice remain poorly constrained. Our knowledge will improve as future geophysical campaigns increase data coverage across the continent, although distinguishing between Pan-African and Grenville-age events remains difficult – prominent structures identified from geophysics could reflect either event, and in fact are likely to record both events if relationships seen in coastal outcrops are typical. All exposed Grenville-age belts in Antarctica have evidence for Pan-African reworking at least locally, while all Pan-African belts contain Grenville-age relics (Fig. 6b), and similar relationships are reported from Australia, India, Africa, and South America. This problem has plagued our understanding of Proterozoic Gondwana since the 1960s, and even in areas of good outcrop and comprehensive geochronology it can be difficult to isolate the geological and tectonic significance of each event, and establish whether a given tectonic episode reflects collision at a plate margin or intracratonic reworking of an older structure. Careful geochronology linked to detailed field and petrographic observations remains the only way to link ages to meaningful geological events, and such studies are needed to resolve the details of the Grenville and Pan-African events and establish the significance of age variations within them, such as Katangan and Damaran ages within the Pan-African. However, constraining the tectonic setting of these orogenic events will not be straightforward given that suture zones in deeply eroded Precambrian orogens will often be ‘cryptic’ and lack the evidence used to identify sutures in younger mountain belts (Dewey & Burke 1973). Palaeomagnetic data will provide the most valuable constraints on Precambrian plate movements and palaeogeography, although finding rocks of suitable age that will provide high-quality Precambrian palaeomagnetic poles is not easy, particularly in Antarctica. Until we can resolve the spatial

configuration and tectonic meaning of *c.* 0.5 and 1.0 Ga events, it is perhaps premature to speculate on the role of Antarctica in earlier supercontinents, but as our attention shifts to these earlier events it seems likely that Antarctica will continue to provide new solutions and raise new problems.

The collected papers in this volume only cover selected parts of the continent and hence address but a few of the many issues involved in Antarctica's role in supercontinent formation and evolution. Nevertheless, they provide an invaluable resource to complement the burgeoning literature on Antarctica in Gondwana, Rodinia and beyond, and serve to illustrate the diversity of approaches and perspectives that can be brought to bear on unravelling continental evolution.

As editors we thank the many reviewers who gave their time to constructively review and provide suggestions on each of the papers in this volume, and have thereby ensured that this collection is both topical and original. This introductory paper was improved by careful reviews by Steve Boger and John Goodge. We also acknowledge the Geological Society publication team for their support and work to bring this volume to fruition.

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**Fig. 1.** Compilation of major metamorphic belts of the world in terms of their apparent thermal gradient ( $dT/dz$ ) at peak metamorphic conditions and age, modified from Brown (2006, 2007). Thermal gradients are divided into three groups: (1) HP-UHP: high-pressure and ultrahigh-pressure metamorphic belts characteristic of modern oceanic subduction zones, marked by grey circles, with larger blue circle for the East Antarctic example in the Lanterman Range, northern Victoria Land (Palmeri *et al.* 2007); (2) E-HPG: eclogite and high-pressure granulites characteristic of continental subduction in collisional orogens, marked by grey squares, with three larger green squares for East Antarctic examples from the Miller Range of the central Transantarctic Mountains (Peacock & Goodge 1995), the Shackleton Range (Schmädicke & Will 2006), and the Grove Mountains (Lui *et al.* 2009a); (3) G-UHT: granulite and ultrahigh-temperature metamorphic belts characteristic of back-arc regions and long-lived orogenic plateaus, marked by grey diamonds, with larger orange diamonds for the many granulites and UHT areas in East Antarctica (Harley 2003). Vertical grey time bands are indicative of the four main phases of supercontinent formation, from Gondwana and Rodinia back to Nuna and Kenorland. This diagram illustrates that global metamorphic events appear to correlate with times of supercontinent assembly, and that Antarctica preserves examples from all of these time periods.

**Fig 2.** Bedrock topography of Antarctica (blues below sea level, yellows and reds above sea level) based on Bedmap2 data (Fretwell *et al.* 2013). The solid black line joining the Ross and Weddell seas divides East and West Antarctica. Prominent features of East Antarctica include the Transantarctic Mountains (TAM), Gamburtsev Subglacial Mountains (GSM), Vostok Subglacial Highlands (VSH), Dronning Maud Land mountains (DML), Prince Charles Mountains (PCM), Lambert Graben (LG), Amery Ice Shelf (AIS), Prydz Bay (PB), Lützow-Holm Bay (LHB), Lake Vostok (LV), Aurora Subglacial Basin (AB) and Wilkes Subglacial Basin (WB). Black dashed lines denote the East Antarctic Rift System (Ferraccioli *et al.* 2011). Also shown is the South Pole (SP) with ticks to indicate  $0^\circ$ ,  $90^\circ\text{E}$ ,  $180^\circ$  and  $90^\circ\text{W}$  lines of longitude, and the five principal blocks of West Antarctica: the Antarctic Peninsula (AP), the Ellsworth–Whitmore Mountains Block (EWM), Haag Nunataks (HN), Marie Byrd Land (MBL), and the Thurston Island Block (TIB).

**Fig. 3.** Early attempts at reconstructing the Phanerozoic supercontinents. (a) Pangaea reconstruction of Wegener (1915) for the Late Carboniferous (lines of latitude and longitude are for the present-day

relative to a fixed position of Africa). The fit of the southern continents is broadly similar to the modern concept of Gondwana, although India is rotated *c.* 90° anticlockwise relative to more recent reconstructions. **(b)** Late Palaeozoic Gondwana reconstruction of Du Toit (1937) with India in its currently accepted orientation (lines of latitude are for the Late Palaeozoic but the South Pole (SP) is marked in its present-day Antarctic position). Modern configurations would show South America, Africa and Madagascar in a more northerly position relative to India and Antarctica (e.g. Fig. 5), but otherwise this fit is very close to that accepted today.

**Fig. 4.** The ‘SWEAT’ reconstruction of Moores (1991) for Rodinia, the early Neoproterozoic supercontinent. This reconstruction juxtaposes Neoproterozoic passive margins in eastern Australia and the Transantarctic Mountains with western North America, and also links the Grenville Orogen of eastern North America with similar-aged metamorphic belts in East Gondwana (Circum East Antarctic Mobile Belt, Eastern Ghats Belt, Albany Fraser Orogen). Baltica is shown on the ‘other’ side of this *c.* 1.0 Ga orogen, and subsequent reconstructions added the South American and African cratons next to Baltica so that Rodinia comprised all major continental blocks (e.g. Hoffman 1991; Li *et al.* 2008). AF, Albany Fraser Orogen; B?, Baltic Shield; DML, Dronning Maud Land; DV, Death Valley (California); EL, Enderby Land; G, Gawler Craton; GSM, Gamburtsev Subglacial Mountains; K, Krylen Mountains; KG, King George V Land; LH, Lützow-Holm Complex; M, Montana; MR, Miller Range; P, Pensacola Mountains; PC, Prince Charles Mountains; R, Racklan Orogen; SK, Shackleton Range; SP, South Pole; SR, Sør Rondane Mountains; TA, Terre Adélie; U, Uinta Mountains; W, Wohlthat Mountains; WL, Wilkes Land.

**Fig. 5.** Pan-African (*c.* 0.5 Ga) and Grenville-age (*c.* 1.0 Ga) belts in Gondwana after Hoffman (1991) with present-day African north oriented to the top of the diagram. By the early 1990s a number of high-grade metamorphic belts of Pan-African age had been identified in West Gondwana (Africa, South America) while there appeared to be little pervasive metamorphism at *c.* 0.5 Ga in East Gondwana (Antarctica, Australia, India). This was taken as evidence for two-stage assembly of Gondwana: East Gondwana formed at *c.* 1.0 Ga in the Rodinia supercontinent and then collided with several West Gondwanan blocks at *c.* 0.5 Ga. A major Pan-African suture (the East African Orogen along the site of the former Mozambique Ocean) was inferred to pass from juvenile Neoproterozoic arc rocks and ophiolite of the Arabian–Nubian Shield (1) into the Mozambique Belt (2), and then pass either into the Damara–Zambezi Orogen (3a: Hoffman 1991) or Antarctica (3b: Shackleton 1996). Evidence against both proposals (no reports of pervasive 0.5 Ga metamorphism in Antarctica and apparent correlations across the Damara–Zambezi Orogen precluding wide separation) was to be challenged by improved geochronology. Two principal sutures were identified within West Gondwana: one along the Gariep and Kaoko belts of southwest Africa and Dom Feliciano and Brasilia belts of South America (4; site of the Adamastor Ocean; Hartnady *et al.* 1985) and one along the Pampean, Paraguay and Araguaia belts of South America (5; site of the Clymene Ocean; Trindade *et al.* 2006). Extrapolation of these belts into northern Africa is hindered by a poor understanding of the Saharan Metacraton (Abdelsalam *et al.* 2002) but potential extensions include the Tuareg Shield (6; Black *et al.* 1994) and Oubanguides Belt (7; Pin & Poidevin 1987). Pre-Grenvillian cratons: AMZ, Amazon; CG, Congo; EAN, East Antarctic; IN, Indian; KH, Kalahari; NA, North Australian; RP, Río de la Plata; SA, South Australian; WA, West Australian; WAF, West African. Grenville-age orogenic belts: af, Albany–Fraser; cea, Circum East Antarctic; eg, Eastern Ghats; ir, Irumide; kb, Kibaran; md, Madagascar; nn, Namaqua–Natal; rs, Rondônia–Sunsas.

**Fig. 6.** Current understanding of the basement geology of Antarctica and adjacent areas of Gondwana taken from multiple sources cited in the text (with present-day African north oriented to top of the diagram). Unlike Fig. 5, this map shows two regions of pervasive Pan-African metamorphism within East Antarctica, one contiguous with Pan-African granulites in southeastern Africa, southern India and

Sri Lanka, and the other an extension of the Pinjarra Orogen of Western Australia. Evidence for pervasive *c.* 0.5 Ga deformation and metamorphism is limited to southern sections of the Pinjarra Orogen. Outcrops in the northern Pinjarra Orogen comprise *c.* 1.1 Ga granulites cut locally by *c.* 0.5 Ga mylonite, referred to here as the Northampton Complex and marked as Grenville-age although these rocks might have been displaced by Neoproterozoic transcurrent movement (Fitzsimons 2003). Approximate locations of Gondwana margin terranes from Veevers (2012). **(a)** Areas of no outcrop in Antarctica left blank apart from outline of the Gamburtsev Subglacial Mountains (GSM), Vostok Subglacial Highlands (VSH) and East Antarctic Rift System (dotted lines after Ferraccioli *et al.*, 2011). Also highlighted is the Malani Igneous Suite, which provides palaeomagnetic evidence for a wide separation (and probable Neoproterozoic ocean basin) between northwest India and Western Australia at 750 Ma (Torsvik *et al.* 2001; Gregory *et al.* 2009). AF, Albany–Fraser Orogen; AM, Amundsen Province (Marie Byrd Land); AP, Antarctic Peninsula; BH, Bungar Hills; BK, Bundelkhand Craton; BS, Bastar Craton; CB, Coompana Block; CD, central Dronning Maud Land; CG, Congo Craton; CH, Chatham Rise; CITZ, Central Indian Tectonic Zone; CK, Choma–Kalomo Block; CL, Coats Land; CM, Campbell Plateau; CP, Cape Fold Belt; CPR, Capricorn Orogen; DG, Denman Glacier; DM, Damara Orogen; DO, Delamerian Orogen; DW, Dharwar Craton; EG, Eastern Ghats Belt; EWM, Ellsworth–Whitmore Mountains Block; FM, Falkland–Malvinas Plateau; G, Grunehogna Craton; GM, Grove Mountains; GSM, Gamburtsev Subglacial Mountains; GW, Gawler Craton; IR, Irumide Orogen; KH, Kalahari Craton; KB, Kibaran Orogen; LB, Lurio Belt; LF, Lufilian Arc; LH, Lützow–Holm Complex; LC, Lachlan Orogen; MD, Madagascar; MR, Miller Range; MY, Mirny; MZ, Mozambique Orogen; N, Napier Complex; NA, North Australian Craton; NE, New England Orogen; NH, Northampton Complex; NN, Namaqua–Natal Orogen; NPC, northern Prince Charles Mountains; NV, northern Victoria Land terranes (Bowers and Robertson Bay terranes); NZ, New Zealand; PAT, Patagonia; PB, Prydz Bay; PJ, Pinjarra Orogen; PL, Pilbara Craton; PM, Petermann Orogen; PT, Paterson Orogen; RG, Rauer Group; RO, Ross Orogen; RS, Ross Province (Marie Byrd Land); RY, Rayner Complex; SG, Southern Granulite Terrane; SI, Singhbhum Craton; SK, Shackleton Range; SP, present-day South Pole (with ticks indicating 0°, 90E°, 180° and 90°W lines of longitude); SPC, southern Prince Charles Mountains; SR, Sør Rondane Mountains; STR, South Tasman Rise; T, Tasmania; TA, Terre Adélie; TH, Thomson Orogen; TIB, Thurston Island Block; TZ, Tanzania Craton; VH, Vestfold Hills; VSH, Vostok Subglacial Highlands; WD, western Dronning Maud Land; WI, Windmill Islands; YG, Yilgarn Craton; ZM, Zambezi Orogen. **(b)** Same basement geology as map (a) showing possible subglacial extensions of the East African Orogen (EA1 and EA2) and the Pan-African orogenesis in Prydz Bay and Denman Glacier (PD1, PD2 and PD3). Areas of Grenville-age material within the Pan-African orogens are highlighted, where possible with an indication of the Grenville orogen that they have been sourced from (based on geochronological similarity and geographic proximity). Reworked Grenville in western and central Dronning Maud Land appears to correspond with the Maud Belt in westernmost Dronning Maud Land, while examples in the Prydz Bay region match the Rayner Complex. Likewise, Grenville-age protoliths within the southern Pinjarra Orogen and Denman Glacier region appear to have been derived from rocks similar to the Northampton Complex. Age data on reworked Grenville-age rocks from Sør Rondane and Sri Lanka are more difficult to fingerprint, but are critical to understanding this complex region at the junction of the East African and Damara–Zambezi orogens. Also shown are approximate locations of the Mesozoic magmatic arc and accretion-subduction complex (from Veevers 2012). Boxes mark the localities considered by other papers in this volume (1, Mikhalsky *et al.*; 2, Flowerdew *et al.*; 3, Grew *et al.*; 4, Liu *et al.*; 5, Adachi *et al.*; 6, Kawasaki *et al.*; 7, Yakymchuk *et al.*; 8, Elsner *et al.*).



Figure 2 (Harley, Fitzsimons & Zhao)

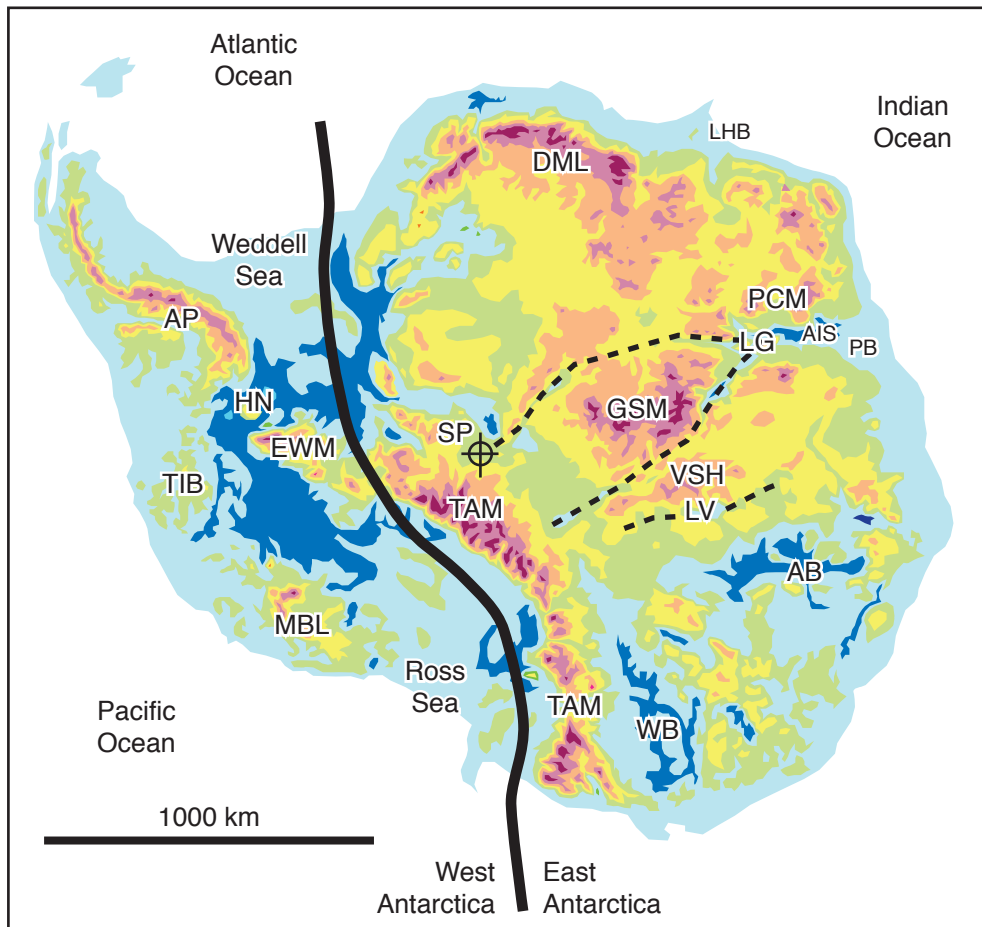


Figure 3 (Harley, Fitzsimons & Zhao)

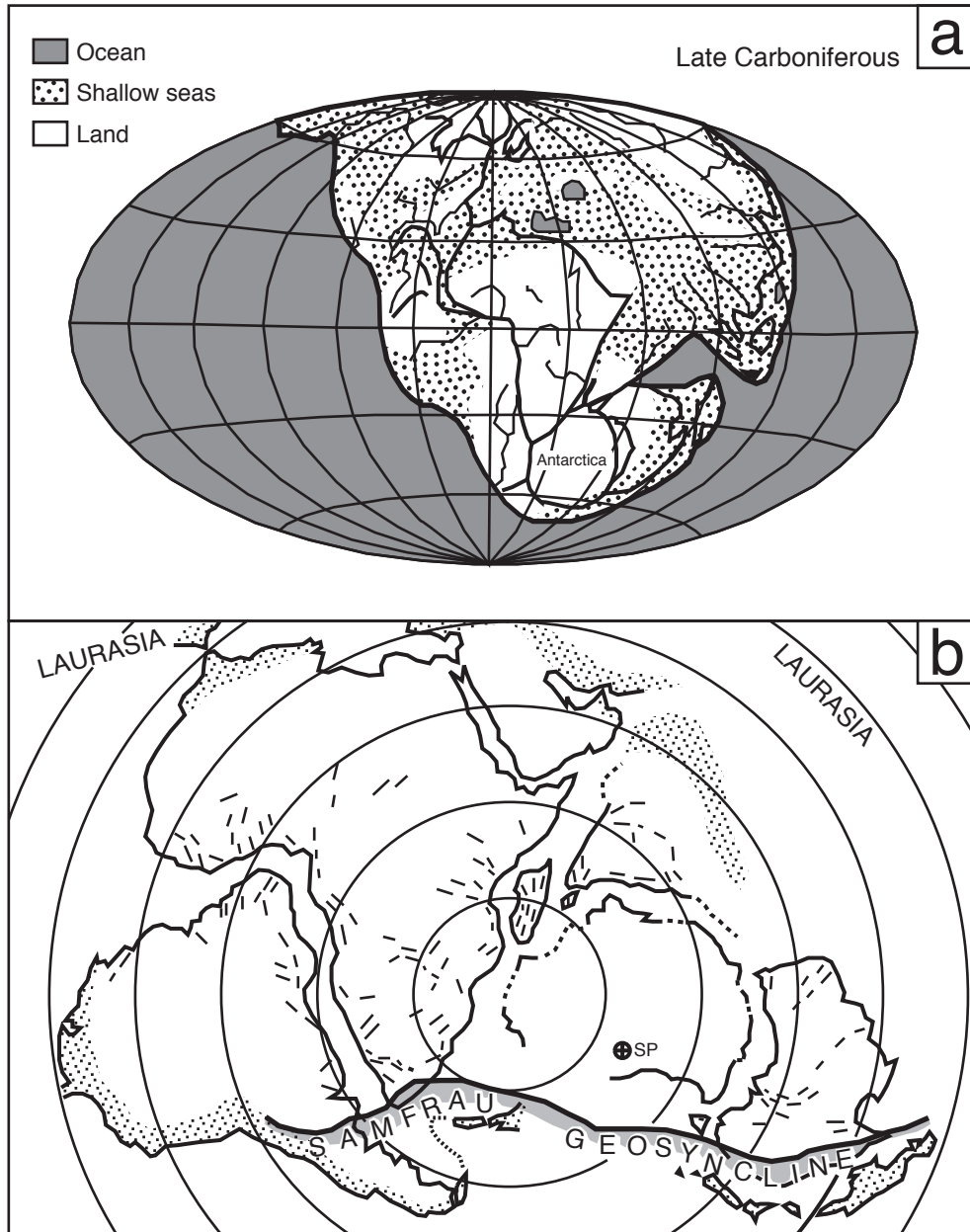




Figure 4 (Harley, Fitzsimons & Zhao)

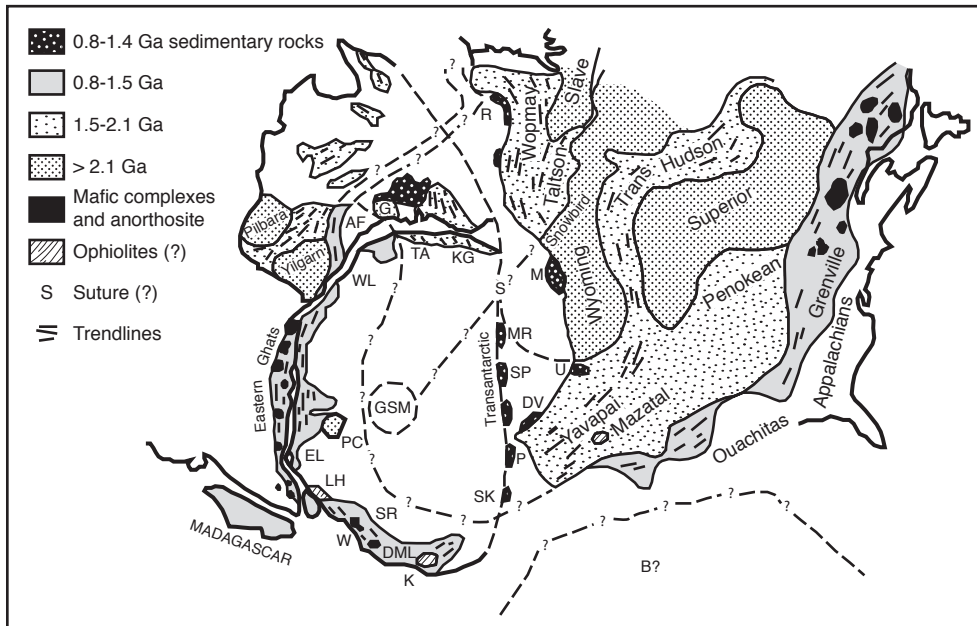


Figure 5 (Harley, Fitzsimons & Zhao)

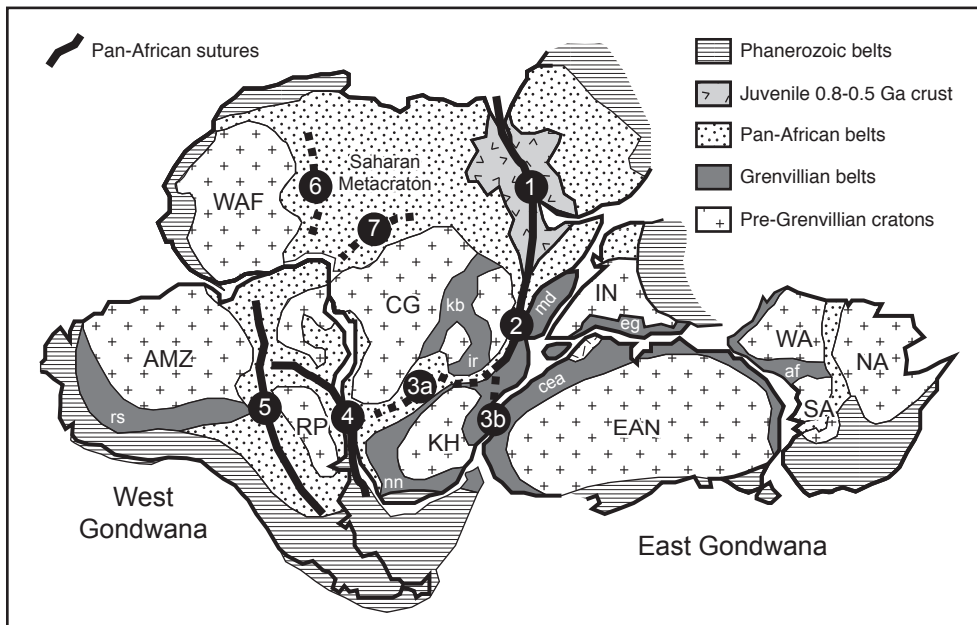


Figure 6 (Harley, Fitzsimons & Zhao)

