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Tectonic overview of the West Gondwana margin

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Abstract

The oceanic southern margin of Gondwana, from southern South America through South Africa, West Antarctica, New Zealand (in its pre break-up position), and Victoria Land to Eastern Australia is one of the longest and longest-lived active continental margins known. It was the site of the 18,000 km Terra Australis orogen, which was initiated in Neoproterozoic times with the break-up of Rodinia, and evolved into the Mesozoic Australides. The Gondwana margin was completed, in Late Cambrian times, by closure of the Adamastor Ocean (between Brazilian and southwest African components) and the Mozambique Ocean (between East and West Gondwana), forming the Brasiliano–Pan-African mobile belts. During the Early Palaeozoic much of the southern margin was dominated by successive episodes of subduction-accretion. Eastern Australia, Northern Victoria Land and the Transantarctic Mountains were affected by one of the first of these events – the Late Cambrian Ross/Delamerian orogeny, remnants of which may be found in the Antarctic Peninsula – but also contain two accreted terranes of unknown age and origin. Similar events are recognized at the South American end of the margin, where the Cambrian Pampean orogeny occurred with dextral strike-slip along the western edge of the Río de la Plata craton, followed by an Ordovician active margin (Famatinian) associated with the collision of the Precordillera terrane. However, the central part of the margin (the Sierra de la Ventana of eastern Argentina, the Cape Fold Belt of South Africa and the Ellsworth Mountains of West Antarctica) seem to represent a passive margin during the Early Palaeozoic, with the accumulation of predominantly reworked continental sedimentary deposits (Du Toit's 'Samfrau Geosyncline'). In many of the outer areas, accretion and intense granitic/rhyolitic magmatism continued during the Late Palaeozoic, with collision of several small continental terranes, many of which are nevertheless of Gondwana origin: e.g., southern Patagonia and (possibly) 'Chilenia' in the South American–South African sectors, and the Western Province and Median Batholith terranes of New Zealand. The rhyolitic Permo–Triassic LIP of southern South America represents a Permo-Triassic switch to extensional tectonics, which continued into the early Jurassic, and was followed by the establishment of the Andean subduction margin. Elsewhere at this time the margin largely became passive, with terrane accretion continuing in New Zealand. In the Mesozoic, the Terra Australis Orogen evolved into the accretionary Australides, with episodic orogenesis in the New Zealand, West Antarctic and South American sectors in Late Triassic-Early Jurassic and mid-Cretaceous times, even as Gondwana was breaking up.

Key words: Accretionary orogen, terrane, Palaeozoic, Laurentia, Rodinia

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1. Introduction

The oceanic margin of Gondwana was of the order of 40,000 km long (Fig. 1). Its northern boundary was the source of Avalonian and Cadomian terranes in the west and Cimmerian terranes in the east (Unrug, 1997). Its southern margin has been proposed as one of the largest and longest-lived accretionary orogens on Earth (Cawood, 2005; Vaughan et al., 2005b) - the Proterozoic and Palaeozoic Terra Australis orogen (Cawood, 2005), which evolved into the Australides (Vaughan et al., 2005b) during the Palaeozoic and Mesozoic. This orogen was over 18000 kilometres long, incorporating margins against the Iapetus and palaeo-Pacific oceans (Unrug, 1997) (Fig. 1), and is comparable in scale to the Late Palaeozoic Alleghenian/Hercynian/Uralian orogen of central Pangaea (Vaughan et al., 2005b). Today, the southern margin of Gondwana can be subdivided into Australian, Victoria Land, New Zealand, West Antarctic, South African and South American sectors (Figure 1). Apart from the West Antarctic and South African sectors, these have recently been reviewed in a Geological Society Special Publication (Vaughan et al., 2005a). The present paper focuses on the Iapetus and palaeo-Pacific margin of West Gondwana (Fig. 1), i.e. the West Antarctic and South American sectors; it does not deal with the collisional margin between East and West Gondwana, nor with the Avalonian/Cadomian or Cimmerian margins (Fig. 1). However, it does touch on the New Zealand and Victoria Land sectors (including the Transantarctic Mountains) of the margin of East Gondwana, as these may have contributed detrital material and terranes to the accretionary margin of West Gondwana from Palaeozoic times onwards.

Moving clockwise along the southern margin of Gondwana, from modern-day east to west (Figure 1), starting in East Gondwana, the Phanerozoic history of the Victoria Land sector of the margin has recently been reviewed by Tessensohn and Henjes-Kunst (2005) and the New Zealand sector has had recent and comprehensive reviews by Mortimer (2004) and Wandres and Bradshaw (2005). Moving into West Gondwana, aspects of the West Antarctic sector have been reviewed in the past 10 years by Pankhurst et al. (1998b) and Vaughan and Storey (2000), but is a sector of the margin in need of an up-to-date treatment. Rapalini (2005) reviewed the southern South American sector of the margin from the latest Proterozoic to the late Palaeozoic on the basis of palaeomagnetic data, and a brief review of this sector was presented in Vaughan et al. (2005b), but an up-to-date comprehensive review of the whole South American sector is lacking. Given the pace of recent developments (e.g., Casquet et al., 2006; Pankhurst et al., 2006), and the considerable controversy over the Palaeozoic history of this sector of the margin, particularly regarding the origin of the

Precordillera or Cuyania terrane (e.g., Thomas and Astini, 2003; Finney et al., 2005), a further review is appropriate.

2. What is West Gondwana?

In simple terms West Gondwana is that part of the supercontinent represented today in South America, Arabia, Africa and West Antarctica. From a geological point of view, however, this definition is over-simplified and it reflects a subdivision based on the break-up rather than the amalgamation configuration of the supercontinent (e.g., Storey et al., 1996; Veevers, 2004). The earliest geologically-based separation of Gondwana into eastern and western parts was made by Du Toit (1937) (Fig. 2). He further separated Antarctica into eastern and western parts, as suggested by Suess (1883–1901), assigning them to East and West Gondwana, respectively (see Thomson and Vaughan (2005) for a brief discussion), but placed New Zealand in East Gondwana, off the eastern coast of Australia (Fig. 2). More recently, West Gondwana has been defined on the basis of the Archaean shields, cratons and cratonic fragments, the intervening Mesoproterozoic and Neoproterozoic mobile belts, and the outer belts of Proterozoic–Mesozoic terranes that make it up (e.g., Unrug, 1997; Pankhurst et al., 1998b; Brito Neves et al., 1999; Vaughan and Storey, 2000; Murphy et al., 2004; Tohver et al., 2006).

2.1 Cratonic elements

The major cratonic elements comprise the Amazonia-West Africa craton, Sao Francisco-Congo craton, Kalahari–Grunehogna craton, Río de la Plata craton, and the Arabian–Nubian shield (Tohver et al., 2006) (Fig. 3). Cordani et al. (2003) pointed out that there are smaller cratonic fragments of considerable importance in understanding the evolution of the supercontinent. These include the Central Goias massif (Fischel et al., 2001), the Luiz Alves, Río Apa, Sao Luis and Paraná cratonic fragments (e.g., Tohver et al., 2006) (Fig. 3). The Hoggar–Potiguar plate of Brito Neves et al. (1999) is another potential cratonic fragment (e.g., Liegeois et al., 2003; Ouzegane et al., 2003), although its limits are not currently delineated.

2.2 Mesoproterozoic and Neoproterozoic mobile belts

Brito Neves et al. (1999) used the term Brasiliano–Pan African collage for the Mesoproterozoic and Neoproterozoic–Cambrian mobile belts involved in the final amalgamation of West Gondwana. Tohver et al. (2006) listed 19 individual belts to this collage, illustrated in Figure 3. Brito Neves et al. (1999) summarized them as the Neoproterozoic Borborema/Trans-Saharan and Tocantins belts, and the Neoproterozoic–Cambrian Pampean and Mantiqueira belts in modern-day South America, and, in modern-day Africa, the Neoproterozoic Dahomeyide belt and the Neoproterozoic–Cambrian Damara, and Zambesi belts. Other important parts of Neoproterozoic–Cambrian West Gondwana include the Cariris-Velhos terrane (Brito Neves et al., 1999) of northern South America–East Africa and the "Grenville" Neoproterozoic rocks of the Haag Nunataks block of West Antarctica and the Falklands Plateau (e.g., Storey et al., 1994; Wareham et al., 1998).

2.3 Palaeozoic–Mesozoic terranes

Accretion of new terrane material to Gondwana was active during amalgamation (Cawood, 2005) and continued until the late stages of break-up of the supercontinent (e.g., Vaughan et al., 2002b). In the Phanerozoic, these include the Cambrian rocks of the Ellsworth–Whitmore Mountains block of West Antarctica (e.g., Curtis et al., 1999), and the Cambrian rocks of the Western Province of New Zealand (Münker and Cooper, 1995). Various Proterozoic fragments of West Gondwana also became part of the margins of the Laurentia and Baltica cratons (Skehan, 1997). Murphy et al. (2004) reviewed these and summarized them as being formed either of reworked Neoproterozoic "juvenile crust within the Panthalassa-type ocean surrounding Rodinia", the so-called Avalonian-type terranes, or of reworked West African Palaeoproterozoic crust, the so-called Cadomian-type terranes. Following amalgamation, the Gondwana margin continued to be active with addition of new oceanic material (e.g., Cawood et al., 2002) and remobilization of existing parts of the margin by strike-slip faulting (e.g., Cawood, 2005). Major episodes of terrane addition and remobilization occurred during the Gondwanan Orogeny of the Permo-Carboniferous (e.g., Cawood, 2005; Pankhurst et al., 2006) and during global orogenesis in the Triassic–Jurassic and Cretaceous (e.g., Vaughan and Livermore, 2005).

2.4 Boundary with East Gondwana

The boundary with East Gondwana consists of a meandering zone of late Neoproterozoic to earliest Cambrian orogenic and mobile belts, termed Pan-African, extending from and including the Arabian–Nubian Shield in the north to Antarctica in the south (e.g., Shackleton, 1996). Perhaps the most important of these belts is that of the East African–Antarctic orogeny (Jacobs and Thomas, 2004). Unrug (1997) shows a very broad zone of potential convergence in the northern segment, which include eastern Africa and the Arabian–Nubian Shield. The southernmost extent of this collision zone includes the Namaqua–Natal–Maud belt on the margin of the Kalahari–Grunehogna craton in southern Africa and Dronning Maud Land in East Antarctica (Jacobs et al., 2003). The essentially synchronous collision Brasiliano zone is the subject of a new survey of geological links across the present South Atlantic region (Pankhurst et al., in press).

3. The formation and dispersal of West Gondwana

Formation of the Gondwana supercontinent appears to have overlapped with the break-up of Rodinia (a possible supercontinent built around Laurentia), which occurred between 1000 and 750 million years ago (e.g. Cordani et al., 2003; Meert and Torsvik, 2003). The series of accretionary and collisional events that formed West Gondwana began 850 million years ago and were complete by the latest Cambrian (490 million years ago) (e.g., Brito Neves et al., 1999). It is overly simplistic to think of the final formation of Gondwana in terms of a collision between the East and West parts (e.g., Meert, 2001). Recent palaeomagnetic data (Tohver et al., 2006) suggest that prior to final amalgamation of Gondwana in the mid-Cambrian, the Amazon–West Africa block of West Gondwana was still a separate entity from Rodinia, and was separated from other blocks that constitute West Gondwana (Congo–São Francisco–Kalahari–Arabia–Río de la Plata). Trindade et al. (2006) provided palaeomagnetic support for this for Amazonia and proposed that amalgamation involved successive suturing along three major orogenic belts, the

Mozambique, Kuunga and Pampean–Araguaia belts through closure of the Mozambique, Adamastor and Clymene oceans. However, the associated complex collisional processes produced deformation and magmatism throughout the late Neoproterozoic and Early Cambrian in the East African–Antarctic belt and in the Brasiliano belt between the Kalahari and Amazonia cratons. Jacobs & Thomas (2004) suggest dispersal of smaller continental fragments by escape tectonics associated with a Himalayan style and scale mountain range formed in the Mozambique belt. These major orogenies, and their topographical and erosional consequences, are the most probable explanation for the widespread occurrence of detrital zircons of this age span in the subsequent sedimentary record of both East and West Gondwana margins (See also Squire et al., 2006). According to Basei et al. (2005), a narrow band of Neoproterozoic metasedimentary rocks on the Atlantic coast of South America is equivalent to the southwest African sequences formed by erosion of the Kalahari and Namaqua–Natal basement and was left behind on the Cretaceous opening of the South Atlantic Ocean, so that the suture zone resulting from closure of the Adamastor ocean now lies within southeastern Brazil and Uruguay.

During and subsequent to Late Cambrian times, West Gondwana continued to accrete microcontinents and terrane fragments (e.g., Cawood, 2005; Vaughan and Livermore, 2005). The origin of some, such as the Precordillera terrane and its relationship to Laurentia and the Pampia Terrane, continues to be extremely controversial (e.g., Thomas and Astini, 2003; Finney et al., 2005).

4. The oceanic margin of West Gondwana

4.1 South America

In the southern South American sector of the margin, the accretionary orogen model has to take into account widely held ideas of collisional accretion of individual terranes of pre-existing continental crust (Fig. 4). Many of these terranes were first proposed and named by Ramos (1988) and, although many are accepted in general, the essential details of their delineation, composition, and the timing of their accretion to Gondwana continue to be controversial.

The best known of these is the Precordillera terrane (Astini et al., 1995), often equated with and referred to as Cuyania (Ramos, 1988; 2004). This has an outcrop area at least 300 km from north-to-south and less than 100 km in width where the geology is dominated by Cambrian to Middle Ordovician limestones, succeeded unconformably by Silurian–Devonian clastic sediments that pass upwards into typical Gondwana sequence lacustrine deposits and red beds of Carboniferous to Triassic age. Alonso et al. (2008) present structural and sedimentological evidence for the passive margin nature of this sequence. The most significant feature of the limestones is a change from a Cambrian brachiopod and trilobite fauna of Laurentian affinity to a Middle to Late Ordovician Gondwana fauna (Benedetto, 1998; Astini et al., 2004). For many, this supports the idea that the Precordillera terrane was derived from Laurentia, but approached Gondwana during the Early Ordovician, followed by accretion during a Middle Ordovician collision. This idea is supported by a wide range of evidence, e.g., an Early-to-Middle magmatic arc including both I- and S-type granites developed on the marginal continental crust of Gondwana – the Famatinian arc (Pankhurst et al., 1998a; Pankhurst et al., 2000). Other aspects compatible with this scenario are contemporaneous bentonite ash bands in the Precordillera limestones (Huff et al., 1998; Fanning et al., 2004), and palaeomagnetic data (Rapalini, 2005). Middle Ordovician metamorphism has been found in rocks east of the Precordillera (Casquet et al., 2001; Vujovich et al., 2004) and equated with the collision stage, and Castro de Machuca et al. (2008) ascribe an Early Silurian age to major post-collisional shear zones. This is also the interpretation given in Chernicoff et al. (2007) who have studied detrital zircon in a Late Ordovician–Devonian sedimentary sequence which they regard as deposited in a post-collisional foreland basin. However, others (e.g., Aceñolaza et al., 2002) have proposed an alternative origin for the Precordillera terrane in another part of West Gondwana, with Ordovician emplacement by massive strike-slip movement along the margin. Attempts to resolve these opposing hypotheses for the origin source of the Precordillera terrane continue without final agreement, largely based on the patterns of detrital zircon provenance ages determined by U–Pb geochronology (Thomas and Astini, 2003; Finney et al., 2005).

Another aspect of the Precordillera terrane hypothesis is the nature and origin of its underlying crustal basement. Unfortunately, this is not unambiguously exposed. There is indirect indication for it consisting of a high-grade metamorphic complex of ‘Grenvillian’ age through the occurrence of ~1000 Ma amphibolite xenoliths brought up in a Miocene dacite through the easternmost limestone outcrops (Kay et al., 1996). High-grade rocks of 1200–1000 Ma have since been discovered throughout the Western Sierras Pampeanas sequences to the east of the Precordillera (McDonough et al., 1993; Varela et al., 1996; Pankhurst and Rapela, 1998; Casquet et al., 2001; 2005; 2006). Ordovician limestones are associated with high-grade granite gneiss of ‘Grenville’ age as far south as Ponon Trehue (Fig. 4, Heredia, 2002; Cingolani et al.,

2005) and ‘Grenville’-age tonalites at Las Matras (Sato et al., 2000). Initially these occurrences were mostly considered to be representative of the middle crustal basement of the Precordillera terrane, consistent with a Laurentian origin, but more recently (e.g., Galindo et al., 2004; Casquet et al., 2006) it has been suggested that the ‘Grenville’-age rocks of the Western Sierras Pampeanas could be regarded as autochthonous Gondwana basement during the Ordovician, and Casquet et al. (2006; 2007) have interpreted some at least as equivalent to the Arequipa-Antofalla block, normally regarded as unambiguously autochthonous. The true nature of the Precordillera basement thus remains questionable.

The Eastern Sierras Pampeanas constitute another putative continental terrane accretion event (the Pampia terrane of Ramos, 1988, see Fig. 4). This is a belt of migmatitic gneisses, low-grade metasediments, granites and metabasites which underwent orogenic deformation, metamorphism and anatexis in Early-to-Middle Cambrian times (Rapela et al., 1998a; Rapela et al., 1998b; Rapela et al., 2002), although Guereschi and Martino (2008) suggest that an even older migmatization event may also have occurred. Their Early Palaeozoic history is thus incompatible with the Palaeoproterozoic Río de la Plata craton to the east and the passive margin limestones of the Precordillera sequence to the west, suggesting an exotic terrane. The predominant Nd model age signature of these rocks is a Mesoproterozoic one (as is that of the Famatinian rocks to the west). For this reason, Rapela et al. (1998b) followed previous authors in thinking that the metasedimentary component must have been derived from such a source to the east as a foreland sequence above an eastward dipping subduction zone; however, no Mesoproterozoic source is exposed. They suggested that the terrane was not allochthonous but had previously been rifted-off from a similar position on the Gondwana margin in Neoproterozoic times, and was similar to the Arequipa–Antofalla blocks of northern Chile and Peru. Simpson et al. (2003) and Schwartz and Gromet (2004) proposed subduction of a spreading ridge in Middle Cambrian times as an alternative to collision of a continental block. As a recent development based on detrital zircon U–Pb and whole-rock Sm–Nd data, Escayola et al. (2007) have proposed a radical model in which subduction towards the west occurred in Neoproterozoic times, with sediments being deposited in a back-arc basin from both the Grenville-age Western Sierras Pampeanas and the arc itself rather than from the Río de la Plata craton to the east. The high-grade metamorphism of the Pampean belt followed Early Cambrian closure of the back-arc basin. This could explain the metabasites (as basin floor remnants) but there is no evidence for the arc itself. The problem of the Pampean orogeny is ripe for new data to resolve these and possibly other alternatives, and Rapela et al. (in press) present new evidence on the extent of the craton, the origin of the Pampean belt metasedimentary rocks and the Cambrian tectonic events leading to their juxtaposition.

The latest collisional event proposed by Ramos (1988) for the central part of this sector in that of the hypothetical Chilenia terrane (Fig. 4). This is supposed to have occurred in Devonian time, and was principally invoked in order to explain granite magmatism of this age that occurs both within the Pampean belt and to the south. A major unit in the former category is the Achala batholith in the southern Sierras de Córdoba. This consists of evolved S-type granites (some with high U contents), of generally post-orogenic characteristics (Lira and Kirschbaum, 1990). Geuna et al. (2007) present palaeomagnetic data that support rapid cooling soon after crystallization.

Finally, moving south to Patagonia, we arrive at a situation that has been a long-lived puzzle. The source of the problem is the ?Cambrian to Permian Gondwanide sedimentary sequence that forms a Late Permian fold and thrust belt in the Sierra de la Ventana (*aka* Sierras Australes) of southernmost Buenos Aires province, Argentina (Fig. 4). As emphasized by du Toit (1937), this has an obvious continuation in the Cape Fold Belt of South Africa and the Ellsworth Mountains sequence of West Antarctica – all of these must have been joined together as a single stratigraphical and tectonic system during the Late Palaeozoic evolution of Gondwana.

Ramos (1984; 1986) proposed that an allochthonous (exotic) Patagonian terrane collided with cratonic South America (supercontinental Gondwana) along the Río Colorado zone (Fig. 4) in Carboniferous times. This was thought to have resulted from southwest-dipping subduction beneath the North Patagonian Massif. Devonian–Carboniferous penetrative deformation, southward-verging folds and southward-directed thrusting of supracrustal rocks of the northeastern North Patagonian Massif was described by Chernicoff and Caminos (1996) and elaborated in a detailed structural study by von Gosen (2003), who argued for Permian rather than Carboniferous crustal shortening, and possibly a northeastward-directed accretionary process.

A major revision of the original collision model for Patagonia has been proposed by Pankhurst et al. (2006). They claim that the majority of rocks in the North Patagonian Massif are autochthonous to Gondwana. The basement to the immediate south of the Sierra de la Ventana itself includes Late Neoproterozoic and Cambrian granites and volcanic rocks of a similar age to those of the Pampean orogeny, albeit in a different tectonic setting, and the northeastern part of the North Patagonian Massif has Ordovician granite magmatism and metamorphism equivalent to the Famatinian orogeny. There is no evidence of a Grenville-age belt similar to the Western Sierras Pampeanas, but this could possibly be hidden beneath the deep Mesozoic and younger sediments of the Río Colorado basin. Thus any collision must have occurred to the south of this massif with its deformed Cambro-Ordovician cover. The discovery of Early Carboniferous subduction-related magmatism followed by mid-Carboniferous S-type granites in a belt that runs southeastwards from the western margin of the North Patagonian Massif led to the proposal that this was essentially the zone of collision, and that the distinctive crustal complexes of the Deseado Massif to the south represents part of the colliding terrane (Pankhurst et al., 2006). The pre-Jurassic geology of the Deseado Massif is very poorly exposed, but it includes Late Neoproterozoic sedimentation, Cambrian plutonism, and both Silurian and Devonian granite magmatism (Pankhurst et al., 2003).

Another prominent feature of the Palaeozoic geology of southern South America is the enormously voluminous and extensive eruption of Permian and Triassic rhyolitic rocks and the emplacement of associated granites (ca 290–220 Ma) – the Choiyoi complex (Kay et al., 1989; Mpodozis and Kay, 1990). These are so far most closely controlled in terms of their chronology in Patagonia, where they have a wide range ages and isotopic characteristics. Initiation in Early Permian times was ascribed by Pankhurst et al. (2006) to post-collisional break-off of the down-going slab, perhaps with delamination of the crust beneath the North Patagonian Massif, leading to large-scale access of heat to the middle crust. It was suggested that this could have lead to promulgation of the slab break-off towards the north along the Gondwana margin, where the magmatism of the Permo-Triassic Choiyoi Group may be more closely related to east-directed subduction than to collision.

Some of the youngest rocks in this sector of West Gondwana are the accretionary complexes forming the farthest outboard part of the margin (e.g., Vaughan and Storey, 2000; Hervé and Fanning, 2003; Mortimer, 2004; Glen, 2005). These largely formed after Gondwana was assembled and are semi-continuous from southern South America to eastern Australia, ranging in age from Carboniferous to Cretaceous. Detrital zircon studies show that he material within these complexes are of Gondwanan origin (Hervé et al., 2003; Augustsson et al., 2006). Sepúlveda et al. (2008) show that a relatively recent example, the Madre de Dios terrane (Fig. 4), contains evidence of a Late Carboniferous–Early Permian mid-ocean ridge origin. The terrane was accreted to the Gondwana margin during deformation in Late Triassic-Early Jurassic times, called the Chonide orogeny (Hervé et al., 2003; Sepúlveda et al., 2008) in Patagonia, but which was part of a global event (Vaughan and Livermore, 2005).

4.2 South Africa

The Cape Fold Belt of South Africa (e.g., Johnston, 2000) (including the Falkland Islands block (Mitchell et al., 1986; Storey et al., 1999)), together with the Sierra de la Ventana of eastern Argentina (e.g., Rapela et al., 2003) and the Ellsworth Mountains of West Antarctica (e.g., Curtis, 2001), forms the central part of the margin of West Gondwana. The basement consists of the 2000-1000 Ma metamorphic volcano-sedimentary rocks of the Namaqua-Natal belt (e.g., Dewey et al., 2006; Eglington, 2006; McCourt et al., 2006), which was deformed during late Neoproterozoic to early Palaeozoic Gondwana amalgamation (e.g., Jacobs et al., 2003). The Phanerozoic continental margin sedimentary succession is represented by the 6–10 km thick, siliciclastic Cape Supergroup (Broquet, 1992; Barnett et al., 1997) and subsequent glacial, marine and terrestrial-fluvial successions of the Karoo Supergroup, which includes the Dwyka, Ecca, Beaufort and Stormberg lithostratigraphic units (Catuneanu et al., 2005). The sedimentary succession ranges in age from Neoproterozoic to mid-Jurassic, terminated by basin-wide basaltic volcanism of the Karoo Igneous Province (e.g., Duncan et al., 1997). This sector of the margin appears to represent a passive margin during the Early Palaeozoic (Shone and Booth, 2005), with the accumulation of predominantly reworked continental sedimentary deposits (the 'Samfrau Geosyncline' (Du Toit, 1937)). It was deformed by the Gondwanide Orogeny in the Late Permian-Early Triassic (e.g., Johnston, 2000). This major fold belt is often modelled as an intraplate orogen representing far-field-deformation related to distant subduction (e.g., Johnston, 2000), although Dalziel et al. (2000) suggested that flattening of the subduction zone could have been driven by interaction with mantle plume that was subsequently responsible for continental break-up. However, a recent re-evaluation by Pankhurst et al. (2006), using data from the South American, Sierra de la Ventana section of the fold belt, supports a possible collisional origin.

4.3 West Antarctica

West Antarctica was originally split into four (Dalziel and Elliot, 1982), or five (Storey et al., 1988), tectonic blocks. The innermost of these is the Ellsworth-Whitmore mountains block, which has sedimentological affinities to the Cape Fold Belt of South Africa (Curtis et al., 1999; Curtis, 2001). It preserves a passive margin volcano-sedimentary succession that ranges from the Cambrian to the Permo-Triassic and may have been derived from the Natal embayment (Randall and Mac Niocaill, 2004).

Recent reassessments of the large-scale structure of West Antarctica suggests that the remaining blocks of West Antarctica can be subdivided into at least three main terrane belts that appear to be continuous from the New Zealand sector of East Gondwana to the Antarctic Peninsula (Pankhurst et al., 1998b; Vaughan and Storey, 2000). The innermost and oldest of these is termed the Ross province in West Antarctica and called the Eastern Domain in the Antarctic Peninsula (Vaughan and Storey, 2000). The Hf-isotope composition of inherited zircons in Late Palaeozoic–Mesozoic granites, migmatites and paragneisses from the Antarctic Peninsula show that they are derived from Mesoproterozoic sources and have been taken to suggest that this domain is underlain by crust of that age (e.g., Flowerdew et al., 2006). The oldest rocks of this Palaeozoic ocean-marginal domain are the Ordovician turbidite sequences of the Swanson Formation of Marie Byrd Land (Pankhurst et al., 1998b). These have no equivalents elsewhere in West Antarctica although turbidites of similar age are seen in the Robertson Bay terrane of Victoria Land in East Gondwana (Stump, 1995). These are intruded by the Ford Granodiorite in Marie Byrd Land, which are equivalent in age to the older granitoids from Target Hill in the northern Antarctic Peninsula (Millar et al., 2002). A suite of granitoids emplaced between 340 and 320 million years ago (Pankhurst et al., 1998b) are widely developed in Marie Byrd Land and are also seen at Target Hill in the northern Antarctic Peninsula (Millar et al., 2002). Although not developed in Marie Byrd Land, the Eastern Domain in the Antarctic Peninsula contains a sequence of Middle Jurassic Gondwana break-up rhyolite volcanic rocks, the Ellsworth Land Volcanic Group (Hunter et al., 2006b), and an Early Jurassic to Cretaceous (Willan and Hunter, 2005; Hunter et al., 2006a) sequence of deep and shallow marine clastic sedimentary rocks called the Latady Group (Laudon et al., 1983; Hunter and Cantrill, 2006). The latest event seen in this domain is the mid-Cretaceous emplacement of arc plutons of the voluminous Lassiter Coast Intrusive Suite (e.g., Flowerdew et al., 2005).

Outboard of the Ross Province/Eastern Domain is a series of magmatic arc terranes termed the Amundsen Province in Marie Byrd Land (Pankhurst et al., 1998b) and the Central Domain in the Antarctic Peninsula (Vaughan and Storey, 2000). The Amundsen Province and Central Domain are largely magmatic and show many similarities in compositional types and in timing of magmatic emplacement (Vaughan and Storey, 2000). Plutonism appears to have peaked in three discrete episodes in the Late Triassic, mid-Jurassic, and Late Jurassic to Early Cretaceous (Leat et al., 1995; Vaughan and Storey, 2000). Recent geophysical data from the Antarctic Peninsula suggest that the Central Domain is composite and made up of smaller terranes (Ferraccioli et al., 2006). So far, a mafic eastern Central Domain and a granitic western Central Domain have been identified (Ferraccioli et al., 2006). Major deformational episodes affected the Central Domain in Late Triassic-early Jurassic and mid-Cretaceous times (Vaughan et al., 2002a; Vaughan et al., 2002b; Vaughan and Livermore, 2005).

The outermost of the West Antarctic terrane belts is termed the Western Domain in the Antarctic Peninsula (Vaughan and Storey, 2000). It has no equivalent in Marie Byrd Land although similar accretionary complex terranes are developed in New Zealand and in southern South America (Vaughan and Storey, 2000). Accretionary complex rocks range in age from Late Carboniferous (Kelly et al., 2001) to Late Cretaceous (Vaughan and Storey, 2000). The Western Domain in the Antarctic Peninsula was affected by deformation in the Late Triassic-early Jurassic and in the mid-Cretaceous (Vaughan and Livermore, 2005).

5. Adjacent parts of the oceanic margin of East Gondwana

5.1 New Zealand

The New Zealand sector of the eastern Gondwana margin (e.g. Mortimer, 2004; Wandres and Bradshaw, 2005) is made up of a collage of terranes, composed of basement rocks ranging in age from early Cambrian to late Early Cretaceous. These can be grouped into three provinces, the Western Province, the Median Province, and the Eastern Province (Coombs et al., 1976; Bishop et al., 1985; Bradshaw, 1989). The Western Province is made up of two terranes that formed the Palaeozoic margin of East Gondwana and largely consist of lower Palaeozoic metasedimentary rocks cut by series of Devonian, Carboniferous and Early Cretaceous granite plutons (e.g., Cooper, 1989; Muir et al., 1996; Waight et al., 1998). In addition there are some minor volcanic and metamorphic rocks of Cambrian age (e.g., Münker and Crawford, 2000). The Median Province is largely magmatic and consists of suites of Carboniferous to

Early Cretaceous subduction-related arc plutons with subordinate volcanic and sedimentary rocks (e.g., Muir et al., 1998; Mortimer et al., 1999). The Eastern Province (e.g., Mortimer, 2004; Wandres and Bradshaw, 2005) consists of arc, fore-arc and accretionary complex rocks that formed and accumulated during Permian to Cretaceous plate convergence and subduction. These have been subdivided into up to 13 terranes, several of which are grouped into a Torlesse Superterrane (Campbell, 2000). As pointed out by Wandres and Bradshaw (2005) the bulk of New Zealand continental crust is submerged by the sea. Adams (2008) examines the terrane evidence from this hidden area by studying Rb-Sr metamorphic and U-Pb detrital zircon ages from the emergent island parts of the submerged continental crust, called "Zealandia". The data show that the Campbell Plateau segment of Zealandia has clear affinities with the Western Province/Ross Province and the Median Province/Amundsen Province, with little evidence for extension of the Eastern Province.

5.2 Victoria Land and the Transantarctic Mountains

Although strictly part of East Gondwana, the Transantarctic Mountains are important because they both acted as a source for sediments deposited in West Gondwana, particularly in West Antarctica (e.g., Flowerdew et al., 2006), and were themselves a sedimentary sink for sediments derived from West Gondwana in Late Palaeozoic and Early Mesozoic times (e.g., Elliot and Fanning, 2007). At their most northerly extent, in Northern Victoria Land, the Transantarctic Mountains are composed of Cambrian and Ordovician terranes amalgamated during the Ross Orogeny (recently reviewed by Tessensohn and Henjes-Kunst, 2005). The main part of the Transantarctic Mountains is underlain by Neoproterozoic, and possibly older (e.g., Fanning et al., 1996; Fitzsimons, 2003), basement, intruded by granitoid plutons of the Ross Orogeny (Stump, 1995). This is unconformably overlain by the quartzose sandstones of the Devonian Taylor Group (Isbell, 1999). The Taylor Group was deformed by the end-Palaeozoic Gondwanan orogeny (Cawood, 2005) and is in turn unconformably overlain by the Permo-Triassic glacial, marine, terrestrial and fluvial sedimentary rocks of the Victoria Group (Collinson et al., 1994). This upper sedimentary sequence was intruded in the Lower Jurassic by sills and dikes of Ferrar Dolerite (e.g., Hergt et al., 1991) with co-magmatic overlying basaltic pyroclastic rocks (e.g., Elliot and Hanson, 2001) and Kirkpatrick Basalt flood lavas (e.g., Elliot et al., 1999).

6. Concluding remarks

The longevity and extent of the Gondwana margin has ensured that it has remained the subject of intense study for over seventy years. It was one of the birthplaces of terrane theory (e.g., Vaughan et al., 2005b) and it continues to be a proving ground for theories of supercontinental amalgamation (e.g., Cawood, 2005) and break-up (e.g., Rapela et al., 2005; Veevers, 2005; Willan and Hunter, 2005).

An interesting question is the one of translation of terranes along the Gondwana margin. Cawood et al.(2002) have shown evidence for translations of thousands of kilometres along the Gondwana margin from the Permian to the Cretaceous, and this idea has been inherent in some treatments of the older Palaeozoic tectonics. Structural evidence suggests that large scale strike-slip faults exist (e.g. Vaughan and Storey, 2000). Some support for large-scale translation can be derived from zircon data although the only way that these movements can be confirmed or quantified is by multidisciplinary studies that include palaeomagnetic analysis and interpretation.

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Figure Captions

Figure 1: Gondwana reconstruction after Unrug (1997) showing major terrane belts on the margins of the supercontinent: NZ: New Zealand; TAM: Transantarctic Mountains. Boundary zone between East and West Gondwana after Unrug (1997) shown as overlay: ANS: Arabian–Nubian Shield; N–N–M: Namaqua–Natal–Maud belt.

Figure 2: Gondwana reconstruction after Du Toit (1937), showing earliest subdivision of the supercontinent into eastern and western parts.

Figure 3: Reconstruction of West Gondwana after Tohver et al.(2006) showing cratonic and Brasiliano–Panafrican elements. Cratons shown in light grey: Am, Amazonia; ANS, Arabian–Nubian Shield, C, Congo; GM, Goias Massif; K-G, Kalahari–Grunehogna; LA, Luis Alves, P, Paraná, RA, Río Apa, SF, São Francisco; SL, São Lius; WA, West Africa. Brasiliano–Panafrican belts (ringed): Ac, Araçuaí; Ag, Araguaia; Bo, Borborema; Br, Brasilía; Da, Damara; DF, Dom Feliciano; Dh/O, Dahomeides/Oubangides; G, Gariep; H, Hoggar; Ka, Kaoko; K/Z, Katangan/Zambezi; LA, Lufilian Arc; M, Mozambique; P, Paraguai; R/M, Ribeira/Mantequeira; Ro, Rockelides; Ta, Tanzania; Tu, Tucavaca; WC, West Congo.

Figure 4: Schematic representation of the tectonic elements of the margin of West Gondwana, extensively modified after Rapalini (2005) and references therein, using further information from Pankhurst et al. (2006) and personal communications from C.W. Rapela and C. Casquet. Amazonia, Río Apa, Río de la Plata (and in some schemes, Arequipa and Antofalla) are the cratonic blocks of Palaeoproterozoic to Neoproterozoic age. The Pampean belt (which encompasses the Eastern Sierras Pampeanas Pampia terrane of Ramos (1988), is shown as continuous with the Araguaia belt of Brazil, following Trindade et al. (2006), and the approximate form of the Patagonian plate is from Pankhurst et al. (2006). The known extent of Grenville-age belts of Sunsas (S) and the Western Sierras Pampeanas (W) is indicated, although the latter also occurs beneath the Argentine Precordillera (Cy), as either stratigraphical or tectonic basement. The Ordovician Famatinian orogenic belt (F) overprints the earlier complexes, including those of the Antofalla block, where Lucassen et al.

(2000) recognise Pampean metamorphism and magmatism as reflecting an accretionary orogeny.

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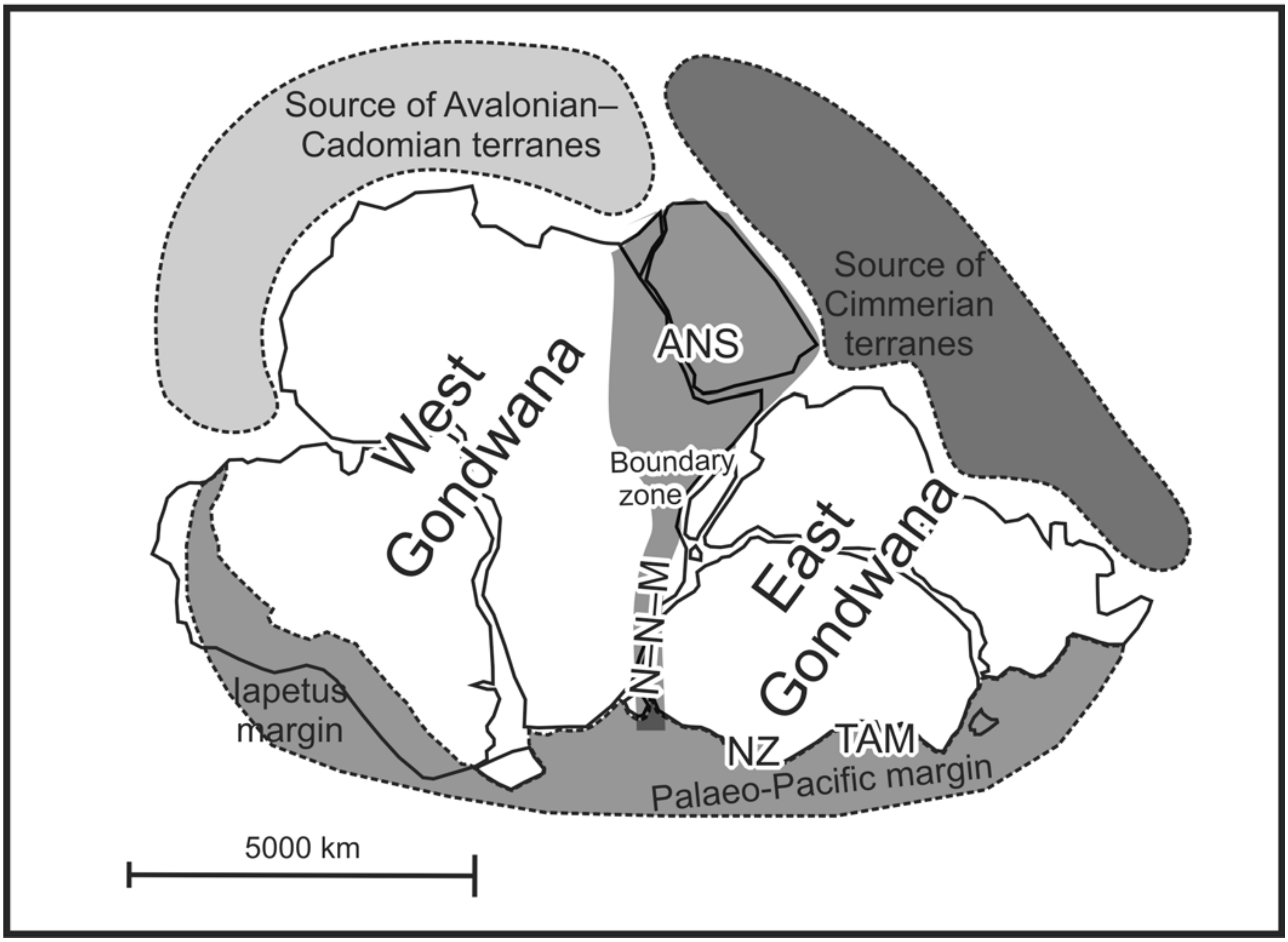
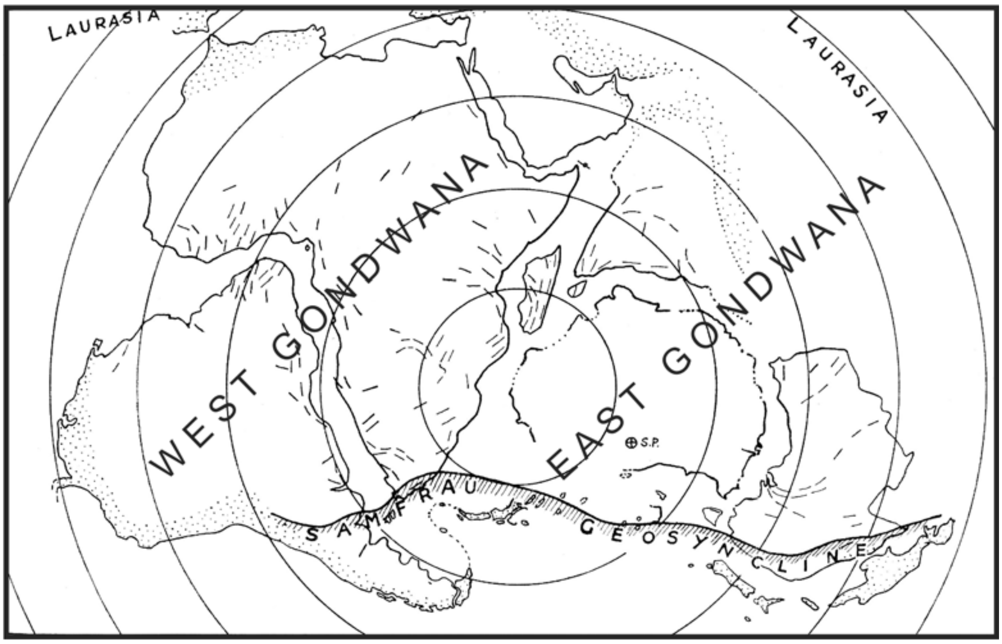
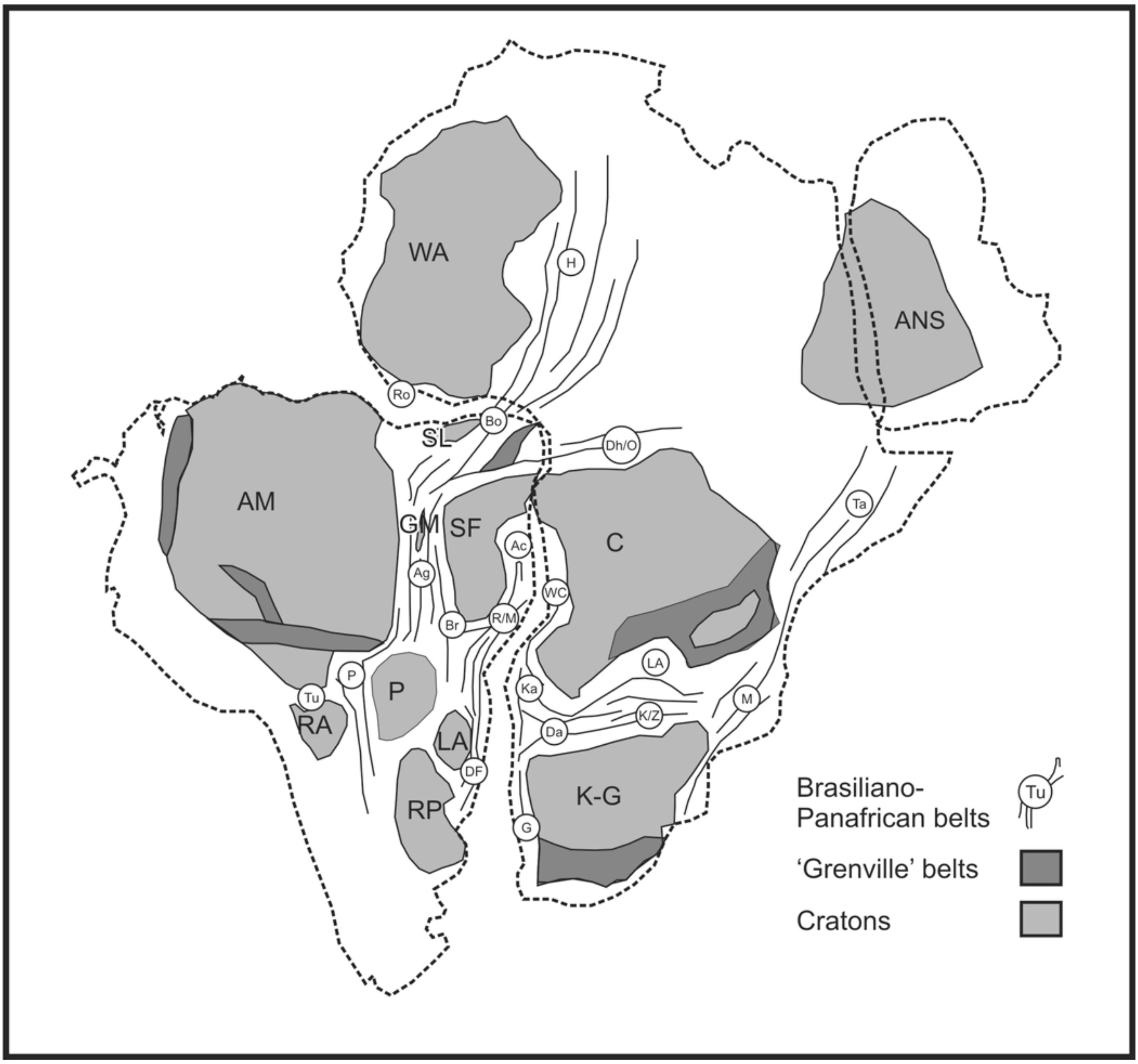
Vaughan & Pankhurst Figure 1



Vaughan & Pankhurst Figure 2



Vaughan & Pankhurst Figure 3



Vaughan & Pankhurst Fig. 4