The links between large igneous provinces, continental break-up and environmental change: evidence reviewed from Antarctica

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ABSTRACT: Earth history is punctuated by events during which large volumes of predominantly mafic magmas were generated and emplaced by processes that are generally accepted as being, unrelated to 'normal' sea-floor spreading and subduction processes. These events form large igneous provinces (LIPs) which are best preserved in the Mesozoic and Cenozoic where they occur as continental and ocean basin flood basalts, giant radiating dyke swarms, volcanic rifted margins, oceanic plateaus, submarine ridges, and seamount chains. The Mesozoic history of Antarctica is no exception in that a number of different igneous provinces were emplaced during the initial break-up and continued disintegration of Gondwana, leading to the isolation of Antarctica in a polar position. The link between the emplacement of the igneous rocks and continental break-up processes remains controversial. The environmental impact of large igneous province formation on the Earth System is equally debated. Large igneous province eruptions are coeval with, and may drive environmental and climatic effects including global warming, oceanic anoxia and/or increased oceanic fertilisation, calcification crises, mass extinction and release of gas hydrates.

This review explores the links between the emplacement of large igneous provinces in Antarctica, the isolation of Antarctica from other Gondwana continents, and possibly related environmental and climatic changes during the Mesozoic and Cenozoic.

KEY WORDS: climate change, Earth System, Gondwana break-up, mafic magma, supercontinent

One of the intriguing aspects of the geological evolution of Antarctica is the large volume of intracontinental igneous rocks that were emplaced during the Mesozoic and Cenozoic. This is in marked contrast to the Palaeozoic, which was almost devoid of intracontinental igneous activity and during which time Antarctica was located almost centrally within Gondwana. The emplacement of the Mesozoic igneous provinces was contemporaneous with the gradual breakup and disintegration of Gondwana, leading eventually to the isolation of Antarctica in a south polar position. What is even more notable is that Antarctica itself continued to rift after it was isolated in its south polar position, forming the West Antarctic Rift System (Behrendt *et al.* 1991), with emplacement of related igneous rocks.

The link between the emplacement of the igneous rocks in Antarctica, rifting and continental breakup processes remains enigmatic (Storey 1995; Rosenbaum *et al.* 2008). The potential link between large igneous provinces and plate tectonic processes has been considered because many of the Mesozoic provinces were located close to once active plate boundaries and continental margins. Alternatively, the magmatic pulses responsible for producing large volumes of igneous rock in relatively short periods of time have also been related to some form of internal heating (thermal anomaly) in the Earth's mantle, due either to the insulation of the Gondwana supercontinent (e.g., Gurnis 1988; Coltice *et al.* 2007), or a mantle-sourced thermal upwelling, i.e., mantle plume (Morgan 1971, 1981; Richards *et al.* 1989). Mantle plumes may either have caused the continents to rift and break up (active mantle hypothesis, Morgan 1971) or have been unroofed by chance due to plate tectonic processes causing continental break-up (passive mantle hypothesis, White & McKenzie 1989). Although the Gondwana magmatic provinces are mainly mafic in composition, large silicic provinces also exist, part of which are present in Antarctica (Pankhurst *et al.* 1998).

This paper will review the connections between the emplacement of the large igneous provinces in Antarctica formed during the Mesozoic and Cenozoic and the relationship of these to the break-up of Gondwana. A central question is whether these huge manifestations of basic magmatism were associated with notable positive thermal anomalies in the subcontinental upper asthenospheric mantle (e.g., Richards *et al.* 1989; White & McKenzie 1989; Johnston & Thorkelson 2000; Thompson & Gibson 2000; Coltice *et al.* 2007) or whether they formed by decompression melting related to plate tectonic processes (e.g., King & Anderson 1995; Anderson 2000, 2005; Elkins-Tanton 2005; Foulger 2007). For this reason, petrogenetic models for the formation of the igneous provinces are reviewed. The paper will also consider the impact of the formation of the igneous provinces on the Earth System in general. Large igneous province eruptions are implicated in environmental and climatic changes including global warming, oceanic anoxia and/or increased oceanic fertilisation, calcification crises, mass extinction and potentially the release of gas hydrates (Hesselbo *et al.* 2000; Wignall 2001; Wignall *et al.* 2005). Although the volume of igneous rocks emplaced during the Mesozoic and Cenozoic evolution of Antarctica may not, in some cases, strictly be of sufficient volume for them to be classified as large igneous
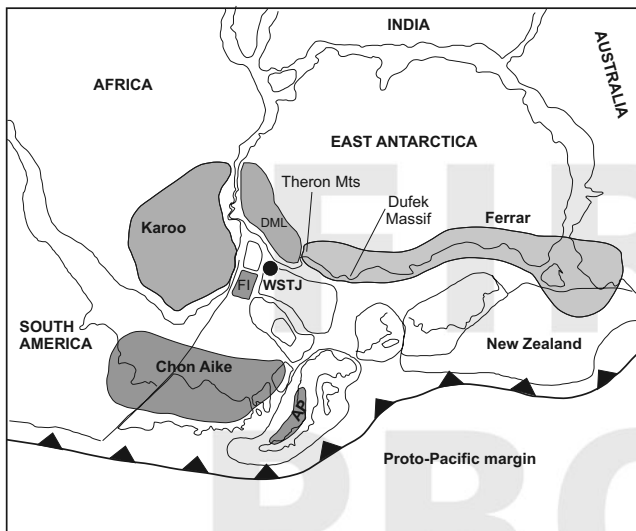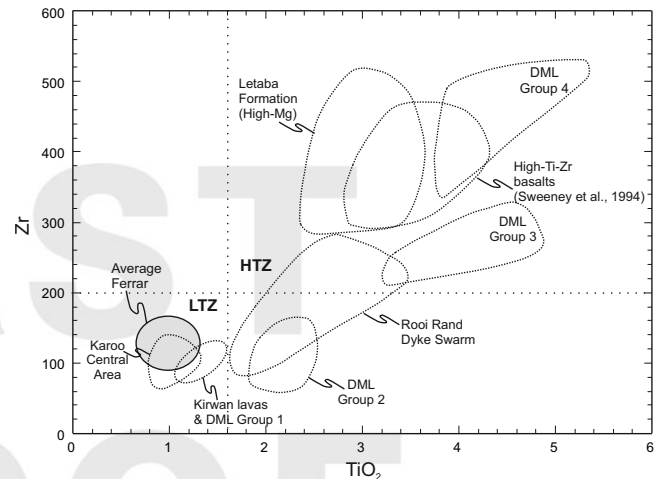
Figure 1 Middle Jurassic Gondwana reconstruction showing three large igneous provinces, Ferrar, Karoo and Chon Aike (after Storey & Kyle 1997), and the location of the Weddell Sea Triple Junction (WSTJ) after Elliot & Fleming 2000. Abbreviations: AP = ▊▊; DML = Dronning Maud Land; FI = Falkland Islands.

Figure 2 Variation in Zr vs TiO_2 for dyke and lava compositions from the Karoo (Kirwan lavas, Karoo central area, Rooi Rand dyke swarm, Letaba Formation, Lebombo high Ti–Zr basalts) and Dronning Maud Land provinces (DML groups 1–4) and average Ferrar compositions. Data sources in Riley *et al.* (2006). Abbreviations: HTZ = high Ti zone; LTZ = low Ti zone.

provinces (LIPs), nevertheless they are included here as they are clearly related to Gondwana rifting and subsequent breakup. We first present details of the Antarctic igneous provinces, including their petrogenesis, and then consider their links to continental break up processes. Central to the debate concerning the origin of any large igneous province is establishing whether a mantle plume source existed and determining whether the role of the plume was restricted to conductive heat transfer to the lithosphere, or whether uncontaminated plume-derived magmas were erupted at the surface or intruded at upper crustal levels.

# 1. Antarctic intracontinental igneous provinces

1.1. Ferrar magmatic province

The Middle Jurassic ($180 \cdot 3 \pm 2 \cdot 2$ Ma; Heimann *et al.* 1994) Ferrar magmatic province in Antarctica is predominantly a mafic sill complex, but includes flood basalts (Elliot *et al.* 1999), phreatomagmatic volcanic rocks (Elliot & Hanson 2001), mafic dykes (Fleming *et al.* 1992; Leat *et al.* 2000) and layered mafic intrusions (Storey & Kyle 1997). It has a linear outcrop and extends 3500 km from the Theron Mountains of Antarctica to southeast Australia (Fig. 1) (Elliot & Fleming 2004). Its linear outcrop pattern is unusual among LIPs, but the extent to which the elongate outcrop is a function of ice-cover limiting the outcrop is uncertain (Leat 2008) and there is geophysical evidence indicating a greater extent of Ferrar province rocks under the East Antarctic Ice Sheet (Ferraccioli *et al.* 2001). Its main outcrops are in Antarctica (Kyle 1980; Kyle *et al.* 1981), but it also occurs in southeast Australia, (Hergt *et al.* 1989a) New Zealand (Mortimer *et al.* 1995), and South Africa (Riley *et al.* 2006). The total volume of lava and intrusions in the Ferrar Province is estimated to be around 200,000 km³, allowing 60,000 km³ for the Dufek–Forrestal intrusions, 125,000 km³ for sills, lavas and dykes in Antarctica, and 15,000 km³ for sills in Tasmania (Hergt *et al.* 1989a; Elliot & Fleming 2000). This is a considerable reduction from early estimates of 500,000 km³ (e.g. Kyle *et al.* 1981), following a reinterpretation of the extent of the Dufek and Forrestal intrusions based on aeromagnetic surveys (Ferris *et al.* 1998).

As a result of detailed $^{40}Ar/^{39}Ar$ and U–Pb geochronology, the synchronicity of the Ferrar and Karoo province in southern Africa has long been recognised (e.g. Encarnación *et al.* 1996; Pálfy & Smith 2000; Riley & Knight 2001), although the peak (based on a compilation of age dates) of Karoo magmatism at 183 ± 2 Ma is 3 Myr older than the Ferrar peak of $180 \cdot 3 \pm 2 \cdot 2$ Ma. Although closely spaced in time, the rocks of the Ferrar and the Karoo volcanic provinces are markedly different in their geochemistry. The basalts of the Ferrar province are entirely of low-Ti–Zr type and are typically high SiO_2 compared to the once neighbouring Karoo province (Fig. 2). Other key features of the Ferrar Province are Sr and Nd isotope ratios, with Ferrar basalts having initial $(^{87}Sr/^{86}Sr)_{180}$ ratios in the range 0.708–0.711, and εNd_{180} values in the range -2 to -8 (Fig. 3). These isotopic characteristics of the erupted rocks of the Ferrar province, coupled with the high SiO_2 (50–52 wt%) and high concentrations of the large ion lithophile elements, have led several workers (e.g. Antonini *et al.* 1999) to suggest that processes involving contamination of the magmas by continental crust was important, whilst other workers (e.g. Kyle 1980; Hergt 2000) maintain that the continental crust was not involved in the petrogenesis of Ferrar magmas. Molzahn *et al.* (1996) suggested that their 'mantle-like' Os isotope ratios and their radiogenic $^{87}Sr/^{86}Sr$ are characteristics of their mantle source.

The linear outcrop pattern of the Ferrar magmatic province, sub-parallel to the proto-Pacific margin of Gondwana (Fig. 1), has led some workers (e.g. Hergt *et al.* 1991) to attribute the chemistry of the Ferrar magmas to enrichment of their mantle source material by subduction-derived fluids. For the most part, the outcrop pattern follows the subduction related Cambro–Ordovician Ross Orogen and is sub-parallel to the active Mesozoic continental margin, although geophysical data (Ferraccioli *et al.* 2001) provides evidence for Ferrar magmatic rocks more than 500 km from the margin, beneath the Wilkes Subglacial Basin (Fig. 4), making a subduction-related origin less likely. Cox (1988), however, attributed the linear outcrop pattern to a similar-shaped heat source that he referred to as a "hot line". Elliot *et al.* (1999) and Storey & Kyle (1997) suggested the Ferrar magmas originated from a single magmatic centre and that the present-day outcrop is the result of long distance magma transport from this point source in sills or
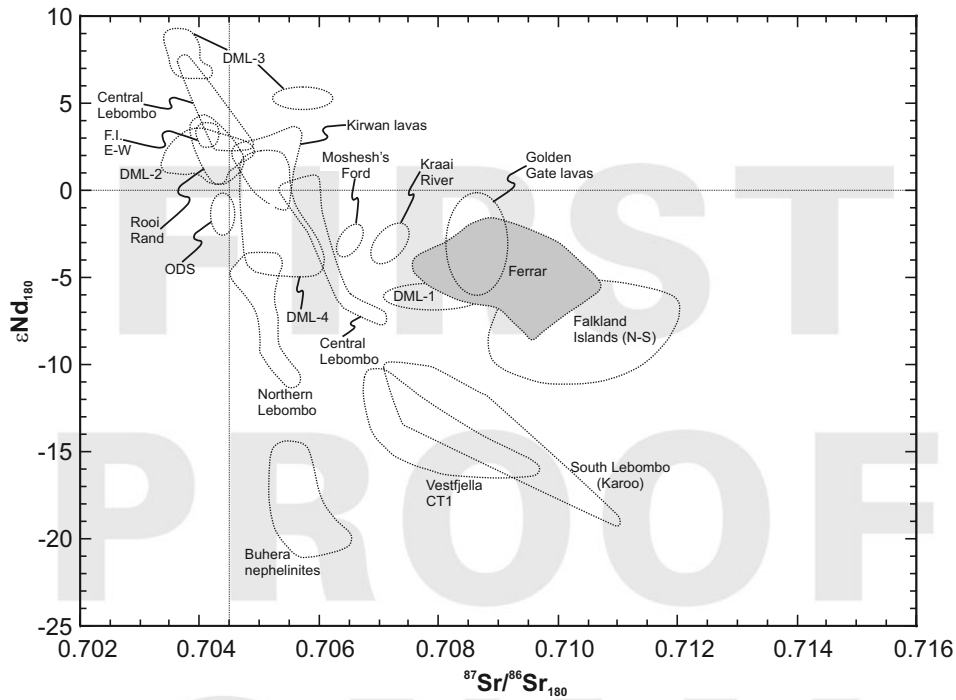
Figure 3 Initial δNd and $_{87}Sr/_{86}Sr$ for intrusive rocks and lavas from the Karoo and Ferrar magmatic provinces. All data sources are available in Riley *et al.* 2006. All data are normalised to an initial value at 180 Ma. Abbreviations: F.I. = Falkland Islands; ODS = Okavango dyke swarm.
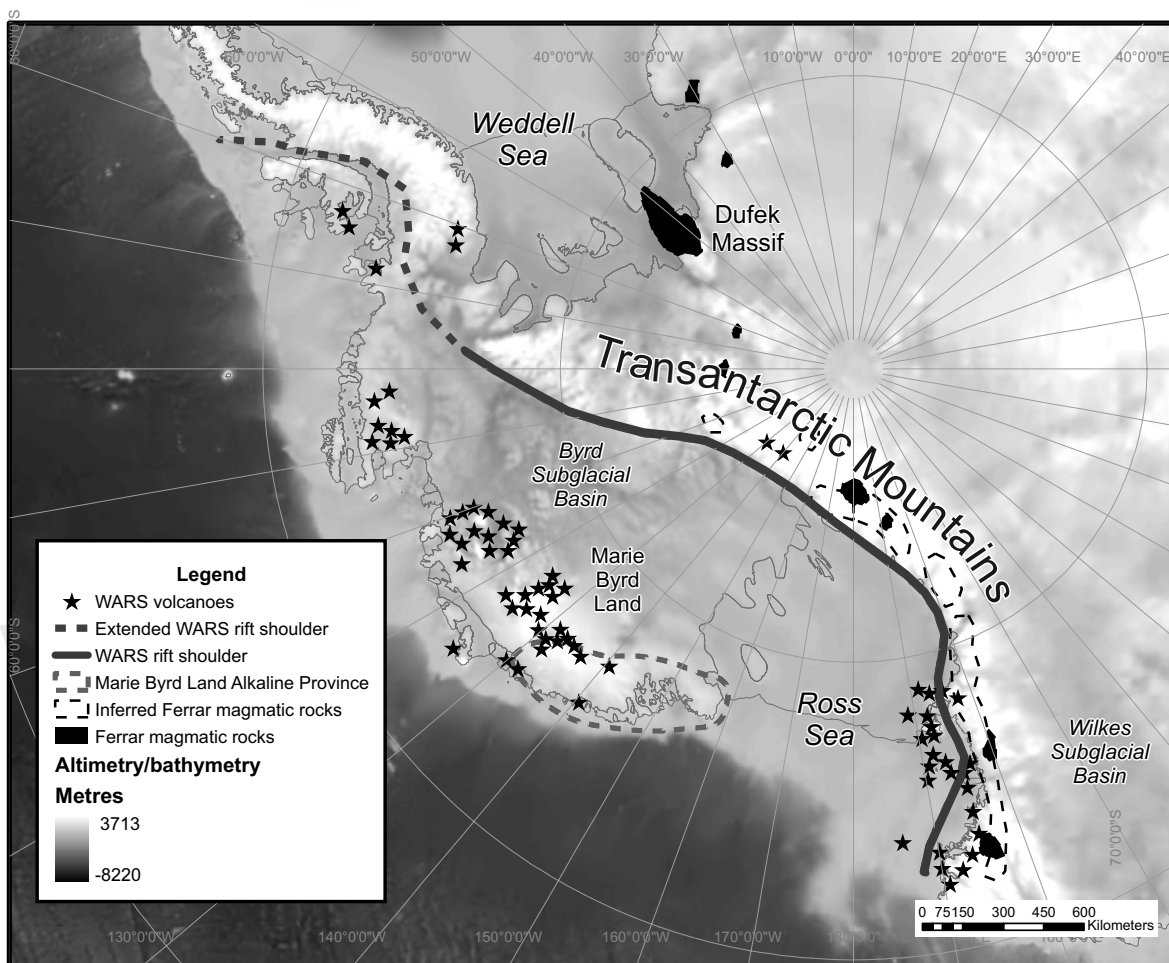
Figure 4 Antarctic map showing the Transantarctic Mountains as the rift shoulder of the West Antarctic Rift System (WARS), the related Cenozoic alkaline magmatic province (WARS volcanoes), the outline of the Middle Jurassic Ferrar magmatic province and the outline of the mid Cretaceous alkaline magmatism in Marie Byrd Land.

dykes. Elliot & Fleming (2004) suggested that magma transport was ultimately controlled by an active rift system initiated in the Early Jurassic, and that the point source for the magmas was a thermal anomaly (mantle plume) at the Weddell Sea triple junction (Fig. 1) (Elliot & Fleming 2000), which was also adjudged to be responsible for the Karoo low-Ti basalts of southern Africa.

1.2. Dronning Maud Land province

Magmatic rocks of the geochemically distinct Karoo magmatic province of Southern Africa are found in the once neighbouring western Dronning Maud Land sector of Antarctica (Fig. 1). Although for the most part geographically separate, Brewer *et al.* (1992) identified both Karoo- and Ferrar-like rocks in the Theron Mountains of Coats Land, Antarctica (Fig. 1). In western Dronning Maud Land, Karoo magmatic activity appears to have been less intense. Flood basalt lava sequences are thinner (<1 km thickness; Luttinen & Furnes 2000) than their southern African equivalents, which are at least 1600 m in Lesotho (Marsh & Eales 1984). Mafic dyke suites are also on a much smaller scale, with widths typically <2 m (Riley *et al.* 2005). The geochemistry of the Karoo igneous rocks has been interpreted to indicate derivation from an enriched lithospheric mantle source (e.g. Erlank 1984) with or without crustal contamination. Others have proposed that the Karoo magmas were partial melts of a mantle plume source that were subsequently contaminated by lithospheric mantle components (Cox 1992; Ellam *et al.* 1992; Sweeney *et al.* 1994).

The presence of ferropicrite and picrite dykes, together with other geochemical and isotopic evidence, indicates that the magmas comprising many of the Dronning Maud Land dykes were formed at depth (at least garnet lherzolite stability) as a result of anomalously high temperatures (>1500°C), indicative of mantle plume derivation (Riley *et al.* 2005). Although ferropicrites may not represent a volumetrically significant magma type, the ocean island basalt (OIB)-like geochemistry and the inferred high temperatures of the ferropicritic primary melts (e.g. Gibson *et al.* 2000; Heinonen & Luttinen 2008, 2010) strongly suggest a plume source for the Karoo LIP (cf. Riley *et al.* 2005), and contribute to the debate on the nature of hotspots and the existence of mantle plumes and their significance as sources of LIP magmatism (e.g. Foulger *et al.* 2005). Strongly depleted magma types are also a key component of the early Karoo intrusive (Riley *et al.* 2005; Heinonen *et al.* 2010). Such mid-ocean ridge basalt (MORB)-like compositions ($^{87}Sr/^{86}Sr$: 0.7035, εNd: −8; Fig. 3) have been recognised from several other LIPs (e.g. Siberian Traps, Wooden *et al.* 1993; Etendeka Province, Gibson *et al.* 2000) and are considered to be a key component of mantle plumes (e.g. Kerr *et al.* 1995). Heinonen *et al.* (2010) suggest their findings are more concordant with a model (Coltice *et al.* 2009) that suggests the generation of the Karoo magmas in an extensive melting episode caused by internal heating of the upper mantle beneath the Gondwana supercontinent. On the other hand, anisotropy of magnetic susceptibility measurements indicates the presence of a regional scale radial stress system in western Dronning Maud Land, supporting a mantle plume origin for the Karoo large igneous province (Curtis *et al.* 2008) and Heron & Lowman (2011) suggest that internal heating models are not feasible.

1.3. Jurassic silicic province of Patagonia and Antarctic Peninsula

The recognition of silicic large igneous provinces in the geological record (e.g. the Etendeka–Parana (Bryan *et al.* 2010)) has led to the reassessment of many continental margin volcanic

provinces worldwide (Bryan *et al.* 2002). The Chon Aike province (Fig. 1) of Patagonia extends from the Atlantic Coast to the Chilean side of the Andes (Pankhurst *et al.* 1998) and is correlated with the Jurassic silicic volcanic rocks of the Antarctic Peninsula (Riley & Leat 1999; Riley *et al.* 2010). In eastern Patagonia, the volcanic rocks are predominantly flat lying and undeformed where they overlie crystalline basement rocks of Precambrian to earliest Jurassic age and Lower Jurassic, rift-related sedimentary rocks. In contrast, silicic volcanic rocks of the Andean Cordillera form relatively narrow outcrops, which are locally deformed, tilted and strongly affected by hydrothermal alteration. The province is dominated by phenocryst-poor ignimbrites, derived from multiple caldera centers (e.g. Aragón *et al.* 1996; Riley & Leat 1999), and vary in degree of welding from high grade rheomorphic ignimbrites with parataxitic textures, to the volumetrically dominant, non-welded, lithic-rich ignimbrites. Volumetrically minor rhyolite lavas, air fall, debris flow, and epiclastic deposits also occur.

The province is geochemically bimodal, but is dominated by rhyolite, with only rare examples of intermediate (basaltic andesite and/or andesite) compositions (Riley *et al.* 2003a). The eruptive ages of silicic volcanic rocks from Patagonia and the Antarctic Peninsula defined by U–Pb ion microprobe dating (Pankhurst *et al.* 2000) and $^{40}Ar/^{39}Ar$ geochronology (Féraud *et al.* 1999; Pankhurst *et al.* 2000) indicate that volcanism continued for as long as 30 Myr, from the Early Jurassic to Late Jurassic, but occurred in three main phases. The first phase of volcanism (188–178 Ma; V1 of Pankhurst *et al.* 2000) has a peak eruptive age of 184 ± 2 Ma, and brackets the peak of flood basalt volcanism of the Karoo and Ferrar provinces at 183 ± 1 Ma (e.g. Encarnación *et al.* 1996). Volcanic rocks of the V1 group occur in the eastern part of the region (Marifil Formation) and at the southern Antarctic Peninsula (Mt Poster Formation, Rowley *et al.* 1982; Brenneke Formation, Wever & Storey 1992). The V2 episode crops out in the central and western parts of the Chon Aike Province and widely across the north eastern Antarctic Peninsula (Mapple Formation, Riley & Leat 1999; Riley *et al.* 2010). V2 has a peak eruptive age of 169 ± 2 Ma (Pankhurst *et al.* 2000). The Tobífera Formation of southernmost Patagonia, however, yielded ages of 178 and 171 Ma (Pankhurst *et al.* 2000) and may partly span the interval between V1 and V2 (172–162 Ma). The final episode, V3 (157–153 Ma), is confined to the Andean volcanic outcrops of Argentina and Chile, although small granite bodies of this age occur both in western Patagonia and in the western Antarctic Peninsula, and maybe sub-volcanic equivalents.

The three eruptive phases define an age progression of magmatism from an intraplate to continental margin setting, away from the locus of flood basalt volcanism in the Karoo province (Pankhurst *et al.* 2000). Concomitant with the age progression is a change in rhyolite composition from intraplate (higher Nb, Y; V1, Early Jurassic) to calc-alkaline (lower Nb, Y; V2 and V3, Middle to Late Jurassic) geochemical signatures (Fig. 5). The Early Jurassic rocks (V1) are interpreted as the partial melts of hydrous mafic crust that have mixed with fractionated components and homogenised following long term storage. The stronger within-plate signature in the V1 rocks is a result of their location distal to the continental margin, whereas the V2 and V3 rocks are closer to the Pacific margin. The Middle Jurassic silicic volcanic rocks of the Mapple Formation (Antarctic Peninsula) and those of the Chon Aike Formation (South America) are also thought to have been generated as a result of anatexis of Grenvillian age hydrous mafic lower crust of andesitic composition, linked to pre-Middle Jurassic subduction, and superimposed fractional crystallisation (Pankhurst
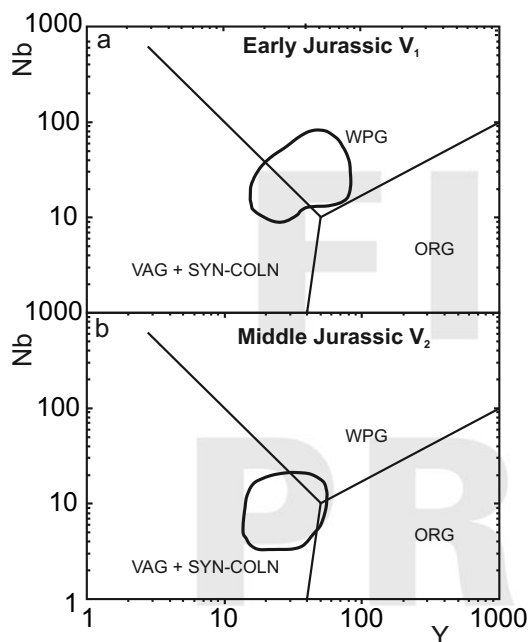
Figure 5 Nb–Y discrimination plots for silicic rocks from the Antarctic Peninsula and Patagonia. The fields characteristic of within-plate granites (WPG), ocean ridge granites (ORG), and volcanic arc/syn-collisional granites (VAG + SYN-COLN) are those defined by Pearce *et al.* 1984.

& Rapela 1995; Riley *et al.* 2001), but have much stronger subduction-modified trace element abundances (low Nb, Low Y).

A Middle Jurassic (173 ± 3 Ma) intracontinental granitic suite was identified within West Antarctica by Storey *et al.* (1988), varying in composition from A-type granites to crustal melts. The A-type granites were modelled as having being derived by closed system differentiation of a Ferrar mafic magma with varied degrees of crustal contamination. They may represent plutonic equivalents of the silicic volcanic rocks of the Chon Aike province (V2).

The fundamental reason that a large silicic province formed in southern South America, in contrast to the synchronous mafic provinces in the interior of Gondwana, was due to the presence of a fertile crustal source close to the continental margin (Bryan *et al.* 2002). Large degrees of crustal partial melting, essential to produce the large volumes of rhyolitic magma, are controlled by the water content and composition of the crust and the large thermal input from the mantle. Although the thermal budget for mafic and silicic large igneous provinces is considered the same (i.e. a large thermal input), hydrous crustal material is more receptive to melting, and will begin to melt at lower temperatures (Bryan *et al.* 2002). Ancient and active convergent margins tend to be characterised by a fertile, hydrous lower crust that can readily melt. Long-lived subduction promotes the development of a hydrated lower crust and lithospheric mantle that can extend for several hundred kilometres from the active margin (e.g., Karoo, western United States; Fitton *et al.* 1988; Davis *et al.* 1993), particularly if significant lateral accretion has occurred over time. The silicic melts can also act as a density barrier, preventing the mafic magmas from reaching the surface (cf. Huppert & Sparks 1988), as will a lack of deep, crust-penetrating structures that can transfer mafic magma to the surface.

1.4. Mid-Cretaceous alkali magmatism
Mid-Cretaceous igneous rocks of central Marie Byrd Land (Fig. 4) in Antarctica, and on the formerly neighbouring Campbell Plateau, record a rapid change from subduction-

related to rift-related magmatism (Weaver *et al.* 1994). This correlates with the final stages of subduction of the Phoenix plate and the subsequent rifting of New Zealand from West Antarctica prior to opening of the Southern Ocean. The sub-duction-related igneous suite is calc-alkalic I-type diorites, granodiorites and monzogranites (108–124 Ma). Rift magma-tism produced diverse A-type granitoids (monzonites, syenites, syenogranites, and alkali feldspar granites; 95 Ma to 102 Ma) and mafic plutons, dykes and sills (107 ± 5 Ma) of continental flood basalt affinity. The mafic dyke suites have been modelled by mixing between tholeiitic asthenosphere-derived OIB with a HIMU composition and alkaline lithospheric mantle derived alkaline magmas (Storey *et al.* 1999). It has been suggested that rifting was caused by changes in plate boundary forces; however, Weaver *et al.* (1994) have suggested that mantle plume activity may have begun in mid-Cretaceous time, trig-gering melting of the lithosphere and controlling the locus of rifting. A mantle plume hypothesis is supported by evidence of 0·5–1·2 km excess topographic elevation for West Antarc-tica and adjacent sea floor, and by evidence of anomalously high subsidence rates on Campbell Plateau in the Palaeogene as it and New Zealand rifted away from a zone of mantle up-welling on the West Antarctic margin (Sutherland *et al.* 2010).

1.5. Cenozoic alkali magmatic province
A belt of Cenozoic alkaline magmatic rocks (48 Ma to presently active) lies within a broad region of extended crust known as the West Antarctic Rift System (WARS) (Fig. 4; LeMasurier 1990; Behrendt *et al.* 1991). The Cenozoic extension is characterised by thin-crust approximately 20–30 km-thick, deep-rift basins within the Ross Sea region and Marie Byrd Land (Behrendt *et al.* 1991) and significant uplift along the 3500 km-long, 4500 m-high Transantarctic Mountain front which separates the rift from the East Antarctic shield (ten Brink *et al.* 1993). The West Antarctic Rift System is marked by a topographic trough 750–1000 km wide and 3000 km long, running from near the Ellsworth–Whitmore Mountains to the Ross Embayment–northern Victoria Land (Fig. 4) (LeMasurier & Thomson 1990; Behrendt *et al.* 1991, 1992). The WARS is similar in size to the East African rift system and to the Basin and Range province of the western United States (Tessensohn & Wörner 1991) and is geometrically asymmetric. The eastern flank in Marie Byrd Land is characterised by basin-and-range style of topography, with about 3 km of uplift in the central part (LeMasurier & Rex 1989). The opposite flank in northern Vic-toria Land (NVL) consists of the Transantarctic Mountains, the uplifted roots of the early Paleozoic Ross Orogen (Stump 1995).

Eighteen major alkaline volcanoes and many smaller centres are found within the Marie Byrd Land province (Fig. 4). The volcanoes are large, mostly 3000 m in height, and are composed predominantly of felsic alkaline lavas, phonolite, trachyte, rhyo-lite and intermediate differentiates. Smaller basaltic centres com-posed of alkali basalt, basanite and hawaiite are also present and are common as parasitic vents and basal flows at the larger volcanoes. The majority of the large composite volcanoes in Marie Byrd Land are found in linear chains that become pro-gressively younger towards the perimeter of the province. The pattern of volcanism has been explained by the sequential re-lease of magmas from shallow chambers along a propagating relict fracture system reactivated during Cenozoic extension (LeMasurier & Rex 1989; Panter *et al.* 1994). In Northern Victoria Land, Cenozoic bimodal plutons with gabbroic and syenitic portions, and alkali basalt–basanite–tephrite dykes are some of oldest parts of the province, dating back to 48 Ma (Rocchi *et al.* 2002). Large volcanic edifices, present in the McMurdo Sound region near Ross Island, are basaltic shield

volcanoes, strato-volcanoes with dominant trachytic and pho-nolitic compositions, and small, isolated basaltic scoria cones and lava flows.

The alkaline basalts have similar trace-element concentrations and isotope ratios that approach the HIMU compositions of oceanic islands (Hofmann 1997). The origin of the extreme HIMU signature has been attributed to recycling of ancient oceanic crust within plumes rising from the deep mantle (Hofmann & White 1982; Hart *et al.* 1992). Geochemical studies of basalts from the West Antarctic rift support plume-related sources for volcanism (Hart *et al.* 1995, 1997; Rocholl *et al.* 1995). Plume models have also been used to explain tectonic doming and the spatial pattern of volcanic centres within the Marie Byrd Land province (LeMasurier & Rex 1989; Hole & LeMasurier 1994; LeMasurier & Landis 1996). Some models appeal to a single young 'active' plume concurrent with the onset of volcanism 28–35 Ma ago (Kyle *et al.* 1994; LeMasurier & Landis 1996), while others favour a passive model involving a "fossilised" plume head fixed at the base of the lithosphere (Rocholl *et al.* 1995; Hart *et al.* 1997). In the fossil plume model, the arrival of a plume head prior to the mid-Cretaceous breakup of New Zealand from Antarctica may explain the extremely broad distribution (over 5000 km) and significant age-span (100 Ma) of HIMU-type alkaline volcanism found throughout the continental borderlands of the southwest Pacific (Lanyon *et al.* 1993; Hart *et al.* 1997; Panter *et al.* 1997). Magmatism associated with either Jurassic; 184 Ma (Encarna-ción *et al.* 1996) or Cretaceous; 100 Myr (Weaver *et al.* 1994) rifting events may signal early plume–lithosphere interaction. Seismic tomography (Spasojevic *et al.* 2010) and subsidence data (Sutherland *et al.* 2010) support evidence for a very long-lived deep mantle thermal anomaly off West Antarctica, prob-ably triggered by cessation of subduction along the Gondwana margin.

Panter *et al.* (2000) proposed a variant on the fossil plume model; one that calls upon a Cretaceous plume composed solely of the HIMU component overlain by a much more ex-tensive pre-existing metasomatised layer within the Gondwana lithosphere. The plume-driven metasomatism may have been related to the Jurassic Bouvet-plume having enriched the Gondwana lithosphere in highly incompatible trace-elements. The plume-modified lithosphere was then underplated by a smaller HIMU-plume in mid-Cretaceous times. A Cretaceous plume-head with a diameter of 600–800 km would encompass these HIMU localities prior to continental breakup. Extension and rifting of New Zealand from Antarctica would have lead to adiabatic decompression melting of the fossil plume and overlying plume-modified lithosphere within widely dispersed fragments of the former Gondwanaland supercontinent.

Finn *et al.* (2005) reviewed the different tectonic models and concluded that the diffuse alkaline magmatic province in the south west Pacific, of which the Antarctic Cenozoic alkaline province is a part, was formed by sudden detachment and sinking of subducted slabs in the late Cretaceous that induced instabilities along the former Gondwana margin that in turn triggered lateral and vertical flow of warm Pacific mantle. According to Finn *et al.* (2005) the combination of metasoma-tised lithosphere underlain by mantle at slightly elevated tem-peratures was key to generating Cenozoic magmatism.

Alternative interpretations to both plume-driven and passive rifting have been proposed by Rocchi *et al.* (2002, 2003, 2005), which suggest that magma genesis and emplacement is due to the reactivation of pre-existing NW–SE translithospheric faults (Salvini *et al.* 1997), which promoted local decompression melting of an enriched mantle previously veined during a Late Cretaceous amagmatic extensional rift phase.

2. Links to continental break-up mechanisms

Having summarised the main features and petrogenesis of the large igneous provinces, the next section reviews the tectonic processes that may have contributed to Gondwana breakup and formation of the igneous provinces.

2.1. Plate margin processes

The parallelism of the current exposure of the Ferrar province to the active margin of Gondwana and to the Permo–Triassic Gondwanian fold belt has inevitably drawn attention to the role of plate margin processes in the initial mid Jurassic breakup of Gondwana (Storey 1995), as has their broad calc alkaline geochemistry (Hergt *et al.* 1989b). Gondwana may have been pulled apart by plate boundary processes operating on either side of the supercontinent to form back arc basins and rift zones akin to the formation the Rocas Verdes in late Jurassic times (Dalziel *et al.* 1974), although recent modelling suggests that this process is complex and many aspects of it are not well understood (Mikhailov *et al.* 2010; Siddoway 2010; Ghosh & Holt 2012). A similar plate margin model can also be used to explain the mid-Cretaceous alkaline province in Marie Byrd Land. Marine geophysical studies have shown that approaching spreading ridges stalled close to the active margin, causing the potential transfer of Marie Byrd Land to the Pacific plate and back arc rifting (Luyendyk 1995).

2.2. Thermal anomaly/mantle plume/hotspot

In 1963, Wilson (1963) first suggested that the Hawaiian Islands were produced by oceanic lithosphere moving over a stationary "hot spot" in the mantle, and in 1971 Morgan (1971) suggested that lower mantle plumes exist in the Earth's mantle and may play an important role in convection and continental break-up. However, there has been considerable debate recently about the existence of lower mantle plumes (Foulger *et al.* 2005), with a variety of thermal plumes (King & Ritsema 2000; Davies & Bunge 2006; Wilson & Dowes 2006) having been described as focused vertical upwellings that are not directly rooted in the lower mantle, as predicted by the original hotspot model (Morgan 1971). Moreover, high-resolution seismological images have shown many apparent small-scale convective heterogene-ities in the uppermost mantle at margins such as the western US (e.g. Sigloch *et al.* 2008; West *et al.* 2009) and the Mediter-ranean (Faccenna & Becker 2010). Subcontinental small-scale convection may be initiated by sharp temperature gradients at a craton's edge, where decompression melting may cause volcanism (King & Anderson 1995). An indirect connection to slab return flow, which may interact with a hydrated layer in the transition zone to facilitate localised upwellings along active plate margins, has also been suggested (Leahy & Bercovici 2007; Faccenna *et al.* 2010; Rey & Mueller 2010).

However, in addition to indications from geoid anomalies, the presence of long-lived thermal anomalies in the mantle has been demonstrated by seismic velocity distribution models based on tomographic techniques using both P- and S-waves (e.g. van der Hilst *et al.* 1997; Montelli *et al.* 2004; 2006; Stein-berger & Torsvik 2012). Large, low-velocity seismic anomalies have been detected in the Earth's lower mantle at the core–mantle boundary beneath Africa and the Pacific Ocean, with the chemically distinct sub-Pacific and sub-African large low shear velocity provinces (LLSVPs) becoming a robust feature (Fig. 6) (Wang & Wen 2004; Steinberger & Torsvik 2012). Density heterogeneities, imaged using seismic tomography, con-tain information about time-dependent mantle flow and mantle structure that existed in the past (Torsvik *et al.* 2008). During the Mesozoic, an associated modelled topographic high is situated near Gondwana rifting, raising the possibility that this
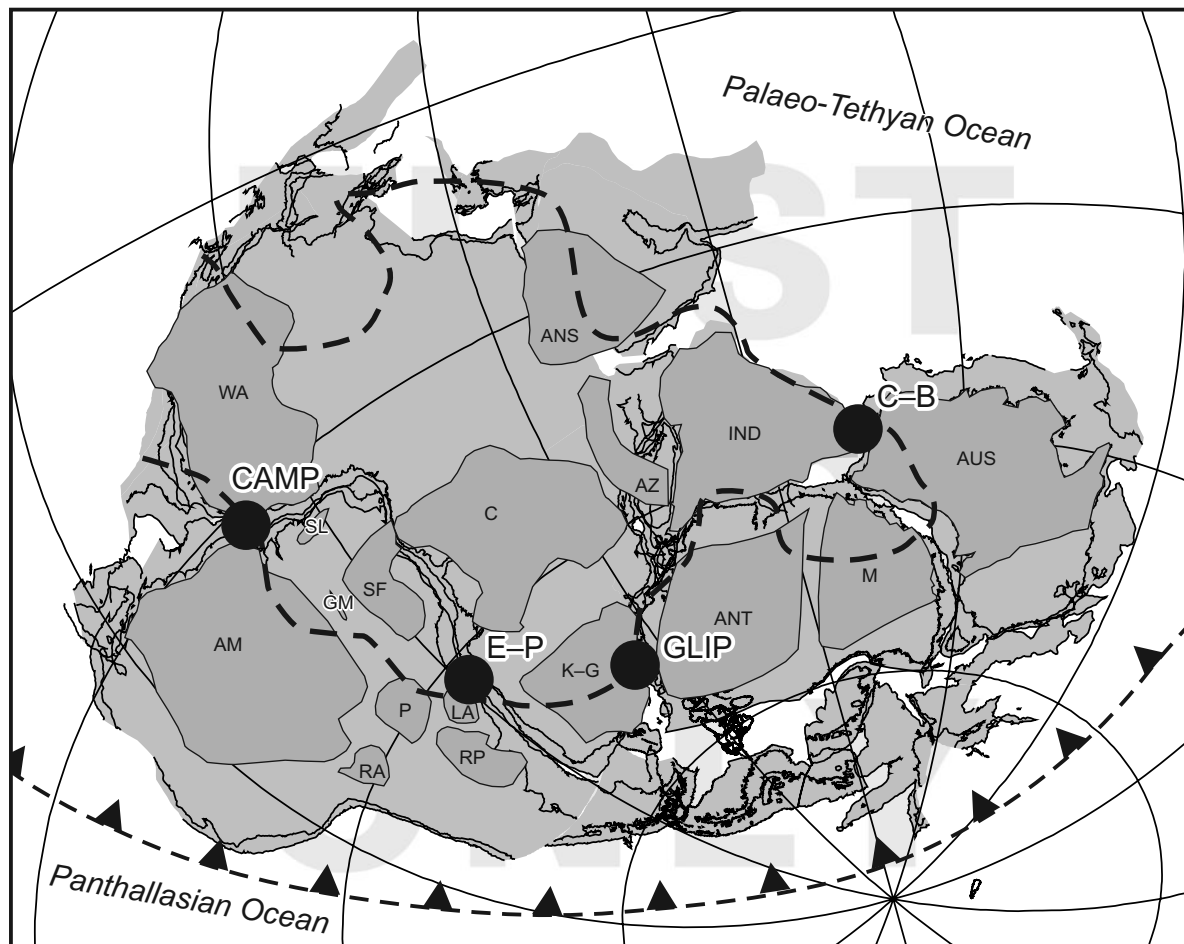
Figure 6 Gondwana reconstruction for 180 Ma (modified after Pankhurst & Vaughan 2009) showing major cratons and projected outline of the African LLSVP (heavy dashed line) from Torsvik *et al.* 2010. Major post-Permian large igneous province centres associated with the break-up of Gondwana are marked: CAMP = Central Atlantic Magmatic Province, 200 Ma (after Marzoli *et al.* 1999); GLIP = Gondwana Large Igneous Province, 180 Ma (after Storey & Kyle 1997); C–B = Comei–Bunbury LIP, 134 Ma (after Zhu *et al.* 2009); E–P = Etendeka–Paraná, 132 Ma (after Peate 1997). Craton labels are after Pankhurst & Vaughan 2009, as follows: AM = Amazonia; ANS = Arabian–Nubian Shield; ANT = Antarctica; AUS = Australian cratons; AZ = Azania; C = Congo; GM = Goias Massif; IND = Indian cratons; K–G = Kalahari–Grunehogna; LA = Luis Alves; M = Mawson; P = Paraná; RA = Rio Apa; RP = Rio de la Plata; SF = Sao Francisco; SL = San Luis; WA = West Africa.

buoyant structure may have been involved with Gondwana breakup (Conrad & Gurnis 2003). Burke *et al.* (2008) have shown that LIP eruption sites of the past 300 m.y. lie vertically above the horizontal edges of the African and Pacific LLSVPs at the core-mantle boundary, and this spatial association is demonstrated for Gondwana break-up LIPs in Figure 6. Near the core–mantle boundary, the association of the high temperature of the outer core with an inclined thermal boundary layer at the margins of LLSVPs facilitates the generation of mantle plumes in the plume generation zones (Tronnes 2010). Seismic tomography studies associated with examination of large low shear velocity provinces also indicate that whole mantle convection is occurring beneath the Pacific Ocean (Schmerr *et al.* 2010; Liu *et al.* 2011), making non-plume models significantly less tenable.

Ideas vary on the role of mantle plumes in continental breakup, from the original active mantle hypothesis of Morgan (1971, 1981), who considered that plumes drive the plates and initiate continental breakup by doming and cracking the continents and pushing the continents apart, to passive models, where the plume plays no part in breakup except that the chance unroofing of a pre-existing or incubating plume results in rapid outpouring of flood basalt provinces (White & McKenzie

1989). Some hybrid models combine aspects of both passive and active models; the forces that drive plate motions place the continents under tension when subduction is taking place on both sides of the continent, but it is the arrival of a new plume that weakens them and causes them to split and form a new ocean (Hill 1991; Bott 1992; White 1992). With the initial breakup of Gondwana, many authors suggested that one or more centres of thermal activity responsible for the three Middle Jurassic igneous provinces (Karoo, Ferrar and Chon Aike) were situated in the Weddell Sea sector between South America, southern Africa and Antarctica (Storey & Kyle 1997; Elliott & Fleming 2000; Ferris *et al.* 2000, 2003; Storey *et al.* 2001). The thermal anomalies may have been responsible for Gondwana breakup by doming of the lithosphere and gravitational collapse, leading to continental rifting (active rifting model; Storey & Kyle 1997). Storey *et al.* (2001) also suggested that within a regional anomaly or superplume, three hotspots may have existed: beneath the Mozambique Basin (Discovery hotspot); beneath the Weddell Sea embayment region (Shona hotspot); and beneath the Dufek intrusion in the Pensacola Mountains (Bouvet hotspot). If the Weddell Sea region was the centre of magmatic activity at the time of breakup, then, in the case of the Ferrar province, magma would have been

transported through dyke or sill complexes for distances in excess of 3000 km (Fig. 1).

Another intriguing aspect of the geological evolution of the Weddell Sea–South Atlantic region in the Middle Jurassic was the formation of rotated microplates (Dalziel & Elliot 1982; Mitchell *et al.* 1986). An Ellsworth microplate, formed at the time of breakup, rotated clockwise more than 90° and migrated from an original position between South Africa and Antarctica to its present position at the head of the Weddell Sea (Schopf 1969; Grunow *et al.* 1987). The Falkland Islands, like the Ellsworth Mountains, rotated 180° from a similar position between African and Antarctica to join South America on the opposite side of the Atlantic. We cannot be sure exactly how and why these microplates and rotations occurred, or why Gondwana should have broken up in this way, but it has been suggested that they were in some way linked to the formation of the volcanic province at the start of rifting and the presence of a thermal anomaly or anomalies beneath the Weddell Sea sector of Gondwana, with the microplates forming on a thermal dome of the lithosphere and rotating to their present positions during sea floor spreading (Storey 1995; Storey *et al.* 2001). Martin (2007) provides an alternative explanation for Gondwana breakup via what he terms double-saloon-door rifting and sea-floor spreading in a backarc basin during subduction rollback.

Interestingly, displaced microplates are also a significant component of the final separation of South America from the Antarctic Peninsula and the opening of Drake Passage in the Scotia Sea region: the South Georgia block has moved from a position much closer to southern South America to its present position; the South Orkney block separated from the northern tip of the peninsula to form the Powell Basin; and the South Shetland Islands has separated from the peninsula by sea floor spreading in Bransfield Strait. Although the driving mechanisms may not always be the same, the history of rotated microplates has been repeated in the South Atlantic region and raises intriguing questions about breakup processes.

2.3. Plume capture

Various other models involving mantle plumes have also been produced, most notably a plume capture model (Dalziel *et al.* 2000) where a mantle plume located beneath oceanic lithosphere was subducted along the active margin of Gondwana in the Permo–Triassic forming the Gondwanian fold belt, heating the Gondwana continental lithosphere, ultimately leading to rifting, emplacement of LIPs and sea floor spreading. This model for the first time successfully linked the Gondwanian fold belt with the locus of rifting and the formation of the LIPs of the Karoo. It is based on a long-lived mantle plume derived from a deep-seated thermal anomaly in the mantle, unrelated to the insulation of continental lithosphere.

2.4. Supercontinental cycles

There is a growing consensus that supercontinent assembly and breakup is a self-organising process (e.g. Vaughan & Storey 2007; Gutierrez-Alonso *et al.* 2008), largely driven by the expansion and contraction of convection cell systems in the upper mantle as their thermal evolution interacts with an overlying supercontinent and its surrounding ocean (e.g. Yoshida & Santosh 2011), or triggers deep-sourced mantle plumes (e.g. Vaughan & Storey 2007). Various models exist for modification and evolution of upper mantle convection as a result of thermal insulation by thick continental lithosphere (Anderson 1982; Trubitsyn *et al.* 2008; Heron & Lowman 2010), which can ultimately drive supercontinent fragmentation. However, recent modelling studies (Heron & Lowman 2011) indicate that supercontinent evolution is insufficient to change upper

mantle temperatures on the timescale of supercontinent assembly, and that large subcontinental mantle plumes develop as a result of subduction patterns rather than thermal insulation by supercontinents. Modelling of large low shear velocity provinces also confirms this result (Tan *et al.* 2011). Although the original thermal blanketing idea of Anderson (1982) was conceived prior to mantle plume theories of continental break-up (e.g. White & McKenzie 1989; Storey 1995), it has been reconciled in part with mantle plume-related mechanisms by Condie *et al.* (2002) and Condie (2004) via a form of the superplume event concept of Larson (1991a, b; Condie *et al.* 2001). Convection-based models can also explain supercontinent creation by providing a convergent force, driven by large scale downflow driven by subduction that draws continental fragments together (e.g. Yoshida & Santosh 2011).

Despite the focus on upper mantle processes as the main driver for the supercontinent cycle, geological evidence suggests that lower mantle processes, hot rising plumes from the core-mantle boundary in particular, are also important (e.g. Vaughan & Livermore 2005). Upper mantle convection-driven models indicate that supercontinent formation should occur by process of "extroversion" (Murphy *et al.* 2009). "Extroversion" is a process of supercontinent formation that conforms to models of thermal insulation of the mantle beneath a supercontinent changing upper mantle convection (e.g. Trubitsyn *et al.* 2008) and driving initial supercontinent fragmentation and formation of a young internal ocean. Supercontinent fragmentation and breakup then proceeds by expansion of the internal ocean and subduction of the thermally older and colder external ocean, ultimately resulting in the formation of a new supercontinent as this ocean closes (Murphy *et al.* 2009). In the process of "extroversion" supercontinents turn themselves inside out (Murphy & Nance 2005).

Gondwana breakup conforms to the "extroversion" model, with the supercontinent breaking up by formation of young internal oceans, such as the Indian and South Atlantic oceans, and consumption of exterior oceans, such as neo-Tethys or the Pacific Ocean outboard of New Zealand. The involvement of deep-sourced mantle heat in the breakup of Gondwana remains a subject of discussion (e.g. Eagles & Konig 2008; Heinonen *et al.* 2010), although the demonstrated coincidence between the centres of Gondwana large igneous provinces and the margins of the African LLSVP (Fig. 6) argues strongly in favour of it. Geological evidence indicates that mantle plumes were responsible for the large volumes of basaltic and silicic magmatism that erupted during the onset of breakup (e.g. Riley *et al.* 2003b). Recent plate kinematic analyses, however, suggest that breakup may not have been totally dependent on mantle plumes (Eagles & Konig 2008; Eagles & Vaughan 2009).

3. Environmental impacts

Increasing evidence links the formation of large igneous provinces with climate change, environmental effects and extinction events throughout the Phanerozoic (Wignall 2001, 2005). In general, LIP eruptions are temporally associated with some or all of the following climatic/environmental effects: phases of rapid global warming/cooling; changes in pCO_2 and other atmospheric trace gases (CH_4, SO_2, halogens); changes in the hydrological cycle; sea-level change (Wignall & Bond 2008); oceanic anoxia and/or increased oceanic fertilisation; calcification crises; mass extinction/evolutionary radiations; and release of gas hydrates (as interpreted from rapid negative shifts of $\delta^{13}C$). Although many mechanisms have been proposed to explain these associations, no simple relationship has yet been identified. However, Sobolev *et al.* (2011) have demonstrated

a strong relationship between the lethality of a LIP and the volume of recycled oceanic crust in the plume head.

Superplume events (Larson 1991a) cause fundamental reorganisations of Earth surface processes, inferred to be triggered by changes in mantle convection. They are multi-million-year periods characterised by globally high sea levels, increased sea-floor spreading rate, plate reorganisation, eruption of >100,000 km^2 basalt plateaux, and reduced reversal rate frequency of the geomagnetic field (in some cases creating so-called magnetically "quiet zones" in oceanic crust). Superplumes are associated with elevated levels of atmospheric carbon dioxide, increased temperature and major perturbations of the global carbon cycle, with deposition of huge accumulations of carbon-rich sediments (e.g. chalk, coal, oil source rocks) (Larson 1991b). In the case of the best-known superplume event, which happened in the mid-Cretaceous ($\sim$120–80 million years ago), the range of effects also includes: ocean margin deformation (Vaughan 1995; Vaughan & Livermore 2005); widespread emplacement of diamondiferous kimberlites (Larson & Kincaid 1996; Haggerty 1999); marine anoxia (e.g. Larson & Erba 1999); and a substantial evolutionary radiation of both marine and terrestrial taxa (Vermeij 1995; Benton 1996; Lupia 1999; Leckie et al. 2002).

The link between the Karoo–Ferrar eruptions and contemporaneous environmental and climatic changes is well established. Good radiometric dates indicate that the eruptions began in the early Toarcian Stage of the Early Jurassic (Pálfy & Smith 2000). This coincides with a well-documented, oceanic anoxic event, a warming trend, a calcification crisis in equatorial latitudes and marine mass extinction (Wignall 2001; Erba 2004). Examination of carbon isotopes in wood from this time indicate major carbon isotope perturbations, including a sharp negative excursion roughly coincident with the onset of ocean anoxia that is interpreted as the product of a catastrophic release of methane from gas hydrate reservoirs from marine continental margin reservoirs (Hesselbo et al. 2000; Beerling & Royer 2002; Jenkyns 2003). At the peak warming, the increase of continental weathering rates, probably associated with a change in the hydrological cycle, appears to have been reflected by a decline in $^{187}Os/^{188}Os$ ratios (Cohen et al. 2004). The environmental changes are generally connected to volcanic CO_2 emissions. CO_2 levels and, probably atmospheric temperatures, were also substantially elevated across the boundaries of the Triassic–Jurassic (Beerling & Royer 2002) and Pliensbachian–Toarcian (Hesselbo et al. 2000), and also in the early Middle Jurassic (174–170 Ma: Hesselbo et al. 2003). Stable isotope analyses of pedogenic carbonates interbedded with the Triassic–Jurassic Central Atlantic Magmatic Province lavas in the Newark Basin show a doubling of pCO to from 2000 ppm to 4400 ppm immediately after the first volcanic unit, with a steady decrease towards pre-eruptive levels over the subsequent 300,000 years (Schaller et al. 2011). This pattern is also observed following the second and third flow units, providing strong support for direct perturbation of atmospheric CO_2 levels by large igneous province related volcanism.

The mid-Cretaceous, the time of emplacement of the Marie Byrd Land igneous province (Cenomanian–Turonian, C–T boundary) is marked by the type example of the Cretaceous oceanic anoxic events, the culmination of Cretaceous greenhouse warming (and sea-level rise), and a minor extinction event in the marine fossil record (Hallam & Wignall 1999; Jenkyns 1999). It thus has many of the hallmarks of other volcanogenic events, although evidence for gas hydrate release is lacking and there is only weak evidence for a calcification crisis (Erba 2004). All of these events essentially coincide with the eruption of the main phase of the Caribbean–Colombian LIP and part of the Kerguelen LIP, and the Madagascan flood

basalts (Kerr 1998; Courtillot & Renne 2003). The oceanic anoxic event OAE 2 itself provides the most obvious cause of the marine extinctions, and the contribution of volcanism to global warming and fertilisation of the oceans provides a route to link volcanism and extinctions (Sinton & Duncan 1997). Both warming (directly by the oceanic lavas) and possible oceanic acidification would have released CO_2 to the atmosphere, thus exacerbating an already established trend of global warming (Kerr 1998, 2005).

The preponderance of evidence for warming strongly suggests that volcanic carbon dioxide emissions were responsible for the initial environmental changes, with knock-on effects that include the release of gas hydrates, acidification of ocean surface waters and elevation of the oceanic calcite compensation depth (CCD). There is also growing evidence that abundant carbonatites are released with LIPs (Ernst & Bell 2010), providing a mantle source of CO_2. The volcanic CO_2 eruptions may also have served as a trigger for events such as the release of methane from clathrates. However, the evidence for methane release (the rapid negative shifts of $\delta^{13}C$) is seen much less frequently than the evidence for warming. It appears LIP formation can cause changes that range from the relatively benign (Palaeocene–Eocene boundary), to severely damaging (Toarcian) to utterly catastrophic (end-Permian). Factors such as the degree of explosive magmatism (Elliot & Hanson 2001; Ross et al. 2005), whether or not large igneous provinces are erupted on the continent or in submarine settings, pre-eruption atmospheric CO_2 levels, the proportion of recycled oceanic crust in the plume head (Sobolev et al. 2011), and the rate of eruption, may turn out to be key variables in any environmental changes resulting from volcanic eruptions.

4. Concluding remarks

It is very unlikely that a single model can explain the igneous provinces in the Mesozoic and Cenozoic history of Antarctica. However, there seems little doubt, based on the presence of ferropicrites in Dronning Maud Land (DML) and the recent discovery of LLSVPs, that a thermal anomaly was responsible for the DML–Karoo large igneous province, and early Cretaceous large igneous provinces associated with Gondwana breakup. The debate as to whether the anomaly was due to the insulating effect of Gondwana or due to a deep seated mantle plume has largely been resolved by the discovery of LLSVPs, and the evidence they provide for a fixed long-term source for deep seated mantle plumes. The origin of the Ferrar igneous province remains an unresolved issue. It appears likely that the Weddell Sea region, with its volcanic rifted margins, was an important centre of magmatic activity, splitting the Karoo province into an African and Antarctic DML section. However, whether the magmas could have migrated the large distances involved to form the Ferrar province is unproven. A rift along the length of the Transantarctic Mountains driven by changes in plate boundary forces may provide a less dramatic but more compelling case. Similarly, for the Cretaceous Marie Byrd Land province, a link to subduction processes is hard to avoid, although involving the generation of hot rising plumes (Spasojevic et al. 2010). It is also possible that large igneous provinces close to active continental margins may have formed by an indirect connection to slab return flow, which may interact with a hydrated layer in the transition zone to facilitate localised upwellings along active plate margins (Faccenna et al. 2010).

Whatever processes controlled or influenced the breakup of Gondwana, the supercontinent separated into the major continents as we know them today, together with rotated microplates in the Weddell Sea region. We cannot be sure exactly

how and why these microplates and rotations occurred, or why Gondwana should have broken up in this way, but it may in some way have been linked to the formation of the volcanic provinces at the start of rifting and the presence of a thermal anomaly beneath the Weddell Sea sector of Gondwana, with the microplates forming on a thermal dome of the lithosphere and rotating to their present positions. The trajectory, displacement history and rotation mechanisms of the micro plate component of the Gondwana jigsaw remains a mystery. As is often the case, more than one driver may ultimately be responsible for the disintegration of Gondwana. That some of these processes may be linked in a supercontinent model is also entirely feasible. However, at the present time, the evidence is leaning strongly in favour of a deep mantle origin for hot plumes as the source of the bulk of large igneous province magmatism. Periodic emplacement of LIPs during the Earth's history also coincided with, and possibly had a profound effect on, the environmental and climatic conditions throughout the Earth's history.

5. Acknowledgements

6. References

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