Gondwana Research 63 (2018) 15–33

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

The secular development of accretionary orogens: linking the Gondwana magmatic arc record of West Antarctica, Australia and South America

D.A. Nelson *, J.M. Cottle

Department of Earth Science, University of California, Santa Barbara, CA 93106-9630, USA

ARTICLE INFO

Article history:
Received 13 February 2018
Received in revised form 17 May 2018
Accepted 19 June 2018
Available online 21 June 2018

Handling Editor: M. Santosh

Keywords:
Zircon geochronology
Hf isotopes
West Antarctica
Accretionary orogen
Polar Rock Repository

ABSTRACT

Combined zircon geochronology and Hf isotopes of plutonic rocks from eastern Marie Byrd Land and Thurston Island, Antarctica, provide a detailed record of Phanerzoic arc magmatism along the paleo-Pacific margin of Gondwana. Magmatism along the Antarctic margin initiated in a dominantly contractional arc setting with an isotopically enriched lithospheric mantle source during the Ross Orogeny (c. 540–485 Ma). After termination of the Ross Orogeny through the Cretaceous, detrital zircon and zircon from igneous rocks record relative increases in zircon εHf_i inferred to represent episodes of lithospheric-scale extension and relative decreases during inferred contractional episodes along the Antarctic margin. Comparison of this secular isotopic evolutionary trend with similar data from along the paleo-Pacific margin of Gondwana demonstrates a shared history among Marie Byrd Land, Australia, and Zealandia that contrasts with the shared record of Thurston Island, Antarctic Peninsula, and South America. These two contrasting histories highlight an early Permian along arc geochemical and inferred geodynamic switch from an isotopically enriched contractional arc system in South America, Antarctic Peninsula, and Thurston Island to an isotopically depleted extensional arc system in Marie Byrd Land, Zealandia, and Australia. Despite differences in timing, all segments of the paleo-Pacific margin underwent a similar secular isotopic evolution with dramatic shifts from enriched to juvenile isotopic compositions during extensional collapse.

Published by Elsevier B.V. on behalf of International Association for Gondwana Research.

1. Introduction

Accretionary orogenesis describes the deformation, metamorphism, and crustal growth (i.e., magmatism and accretion) that take place during ongoing subduction at convergent plate boundaries (e.g., Cawood et al., 2009). Accretionary orogens can switch between two contrasting tectonic states; retreating orogens undergoing extension and advancing orogens undergoing contraction (e.g., Collins, 2002a). These tectonic states establish the primary characteristics of continental arcs including the rate and composition of magmatism as well as lithospheric thickness and rheology (Collins, 2002a, 2002b; Behn et al., 2007; Cawood et al., 2009; Decelles et al., 2009; Kemp et al., 2009; Currie et al., 2015). Consequently, the tectonic state of continental arcs may control volcanogenic atmospheric CO_2 output, continental crustal growth and differentiation, and recycling of lithosphere back into the mantle (Hacker et al., 2011; Collins et al., 2011; Currie et al., 2015; McKenzie et al., 2016; Cao et al., 2017). The secular temporal, geochemical, and tectonic (i.e., geodynamic) evolution of accretionary orogens, therefore, remains an important component in resolving Earth's geochemical evolution.

The paleo-Pacific margin of Gondwana was a long-lived active continental margin for ~18,000 km along the west coast of South America, the Transantarctic Mountains, West Antarctica, Zealandia, and the east coast of Australia (Fig. 1; Cawood, 2005; Collins et al., 2011). These regions contain Phanerozoic arc-related plutonic and volcanic rocks, and volcaniclastic sedimentary rocks that preserve the temporal and geochemical history of magmatism within this broad accretionary orogenic systems. Previous workers have characterized the geochemical history of the South American and Australian sectors of the margin (e.g., Kemp et al., 2009; Cawood et al., 2011; Pepper et al., 2016). However, the Antarctic sector, consisting of Zealandia, West Antarctica, and the Transantarctic Mountains remains a missing link between South America and Australia in efforts to reconstruct the large-scale geodynamic history of the paleo-Pacific margin of Gondwana (e.g., Riel et al., 2018). The paucity in the record is, in part, due to poor exposure and inaccessibility of West Antarctica and Zealandia, i.e., ice covered or submerged crust. Furthermore, reconstructing the history of the Antarctic sector is particularly problematic because it has been heavily dissected into numerous 'microplates' that have rotated and translated long distances (up to 2500 km) from their pre-Gondwana-

* Corresponding author.
E-mail address: demian@umail.ucsb.edu (D.A. Nelson).

https://doi.org/10.1016/j.gr.2018.06.002
1342-937X/Published by Elsevier B.V. on behalf of International Association for Gondwana Research.

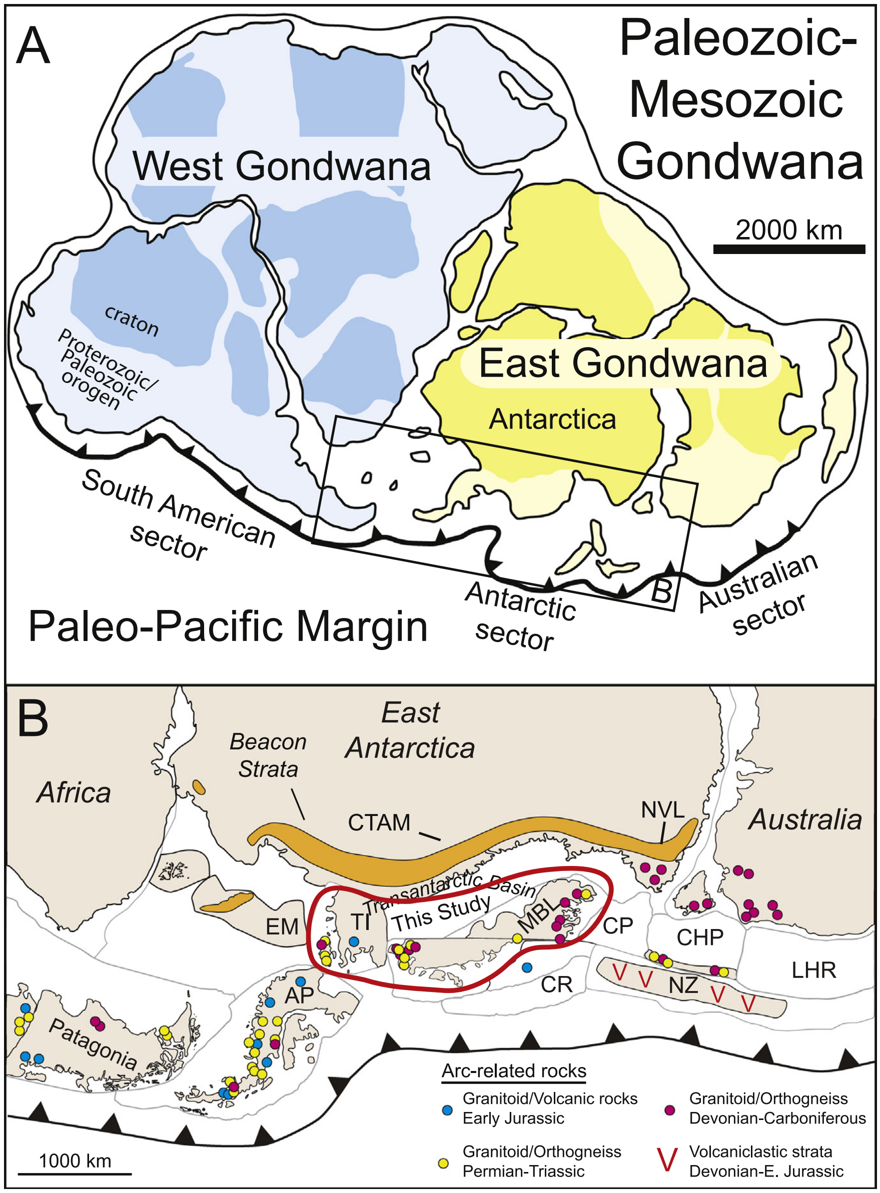

Fig. 1. (A) Paleogeographic reconstruction of supercontinent Gondwana during the Paleozoic–Mesozoic, and the major sectors of the active paleo–Pacific margin of Gondwana (modified from Meert and Lieberman, 2008). (B) Reconstruction of the Antarctic sector of the Gondwana plate margin during the late Paleozoic–early Mesozoic, showing the location of the study area in West Antarctica relative to the distribution of Devonian through early Jurassic arc–related rocks located within the various outboard crustal blocks (Elliot, 2013). West Antarctica: EM, Ellsworth Whitmore; TI, Thurston Island; AP, Antarctic Peninsula; MBL, Marie Byrd Land. Zealandia: CR, Chatham Rise; CP, Campbell Plateau; NZ, East New Zealand; LHR, Lord Howe Rise; CHP, Challenger Plateau and West New Zealand.

breakup configuration (Fig. 1B, Dalziel and Elliot, 1982; Grunow et al., 1987; Storey et al., 1988).

The crustal blocks of West Antarctica–Marie Byrd Land, Thurston Island, and the Antarctic Peninsula–contain Paleozoic–Mesozoic arc-related rocks (Fig. 1) that potentially record the magmatic and tectonic history of the Antarctic sector of the Gondwana arc (summarized in Elliot, 2013). However, U-Pb geochronology and Hf-O isotopes of igneous and detrital zircon, suggest that the Antarctic Peninsula shares a temporal, geochemical, and tectonic history with the Patagonia and the South American sectors of the arc system and may not be representative of the Antarctic sector (Fanning et al., 2011; Bradshaw et al., 2012; Castillo et al., 2016, 2017; Nelson and Cottle, 2017).

Arc-derived Permian–Jurassic volcaniclastic sedimentary rocks deposited on the stable East Antarctic craton, which was not dissected during late Mesozoic supercontinent breakup, provide the most reliable, albeit limited, record of long-lived arc activity in the Antarctic sector (Elliot and Fanning, 2008; Elliot et al., 2016, 2017; Nelson and Cottle, 2017). Based on paleogeographic reconstructions and paleocurrent data, the source of this volcanic detritus is considered to be the outboard volcanic arc located in Marie Byrd Land (e.g., Elliot et al., 2017). It follows then that Marie Byrd Land is an ideal location to investigate the geologic history of the Antarctic sector of the Gondwana margin. Pioneering geochronology and geochemistry studies provided preliminary ages and a tectonic framework for Marie Byrd Land (Pankhurst et al., 1998a, 1998b; Mukasa and Dalziel, 2000) with more recent workers refining the record exclusively for western Marie Byrd Land and its relation to the broader evolution of the Gondwana margin (Siddoway and Fanning, 2009; Korhonen et al., 2010; Saito et al., 2013; Yakymchuk et al., 2013, 2015; Brown et al., 2016). However, modern petrochronologic (i.e., combined geochronologic and geochemical techniques such as Hf isotopes in zircon, e.g., Kylander-Clark, 2017) have yet to be applied over a wide region of eastern Marie Byrd Land, despite early reports that this region potentially contains arc-related rocks spanning a longer time period than western Marie Byrd Land and may therefore provide a longer comprehensive record of arc magmatism. Additionally, zircon Hf isotope compilations for South America, Antarctica, Australia, and Zealandia indicate a significant along arc isotopic transition in arc magmatism from enriched to juvenile in the vicinity of Thurston Island in c. Permian (Nelson and Cottle, 2017). Limited zircon Hf isotope data from Thurston Island (Riley et al., 2017) and eastern Marie Byrd Land prohibit more precise constraints on the exact location of this along arc geochemical and inferred geodynamic shift (Nelson and Cottle, 2017). Consequently, the precise timing and duration of arc magmatism and the relative roles of crustal growth and recycling through time remains poorly understood for eastern Marie Byrd Land and the Antarctic sector of the Gondwana margin overall.

In this study, we present zircon U-Pb geochronology and zircon geochemistry (trace elements and Hf isotopes) to investigate the age of magmatism and crustal evolution of eastern Marie Byrd Land, and the adjacent Thurston Island block, spanning ~200 million years from the Silurian to Triassic. These data are combined with existing data from elsewhere within the Antarctic sector (i.e., eastern Marie Byrd Land and central Transantarctic Mountains), as well as the South American sector, and the Australian sector of the Gondwana margin to determine the nature of along-arc variation in timing geochemistry of arc magmatism, and differences in inferred subduction geodynamics (i.e., contractional/advancing or extensional/retreating arc systems). Finally, our new zircon Hf isotope compilation highlights a possibly shared secular evolution among Phanerozoic accretionary orogens along the entire Gondwana margin.

2. Geologic background

The pre-Jurassic granitoid basement of Marie Byrd Land is subdivided into the western Ross (with 1.5—1.3 Ga Nd model ages) and eastern Amundsen (with 1.3—1.0 Ga Nd model ages) provinces (Fig. 2; Pankhurst et al., 1998a, 1998b). The boundary between these two provinces is loosely located in the vicinity of the Land Glacier region of the Rupert Coast (Fig. 2; Pankhurst et al., 1998a, 1998b). Paleomagnetic data for crustal blocks of the Ross and Amundsen Provinces indicate they were originally separate prior to their amalgamation in the mid-Cretaceous (c. 117 Ma; DiVenere et al., 1995; Luyendyk et al., 1996). Early studies of Marie Byrd Land correlated the Amundsen Province to the Median Tectonic Zone of New Zealand, and Thurston Island and Antarctic Peninsula crustal blocks, while the Ross Province was viewed as a continuation of the Gondwana margin in southeast Australia, western New Zealand, and North Victoria Land (Pankhurst et al., 1998a, 1998b).

2.1. Western Marie Byrd Land (Ross Province)

The Ross Province includes exposed rocks of the Ford Ranges and Edward VII Peninsula (Fig. 2). The oldest unit within the Ross Province is a Neoproterozoic–Cambrian folded metaturbidite sequence, the Swanson Formation, containing detrital zircons ranging from c. 3.03 Ga to c.

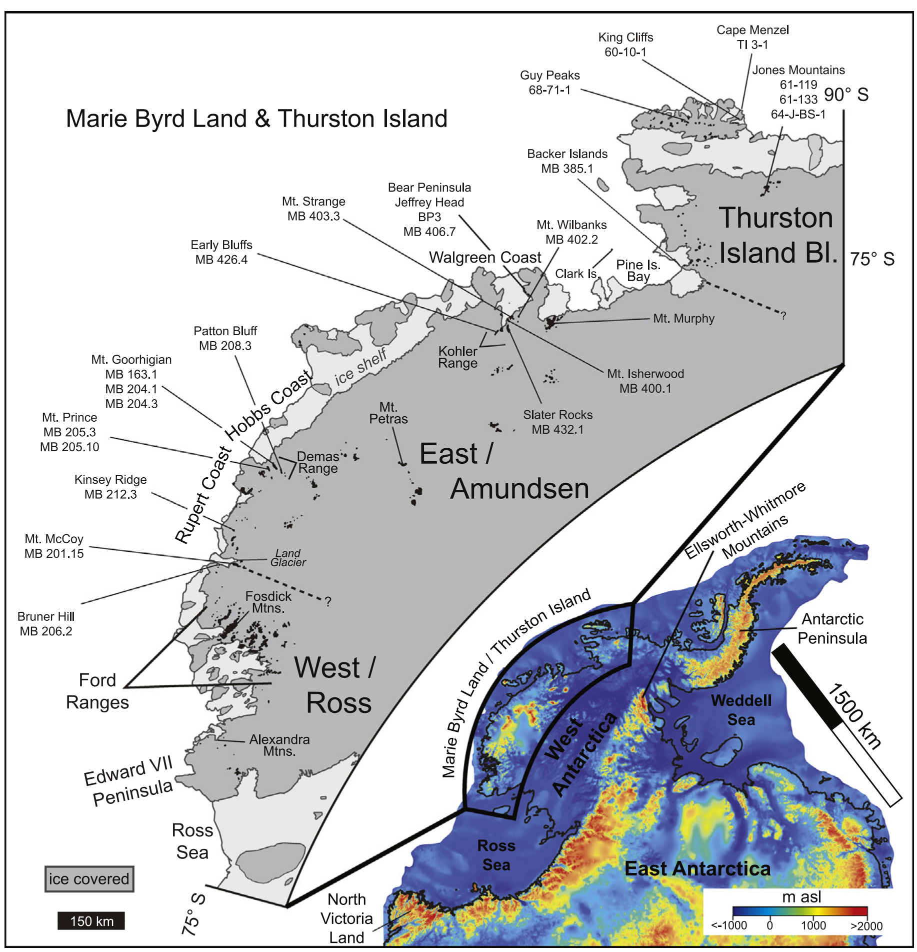

Fig. 2. (Color map) Subice topographic DEM of Antarctica (BEDMAP2) with major crustal blocks and localities identified; asl–above sea level (Fretwell et al., 2013). (B&W map) Enlarged map of Marie Byrd Land and Thurston Island showing sample locations (Pankhurst et al., 1998b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

500 Ma with pronounced peaks at 1.0–1.1 Ga, typical of Grenville-age crust of the East Antarctic Craton (e.g., Goodge and Fanning, 2016) and 500–600 Ma ages, corresponding to the Ross-Delamerian orogen (Cox et al., 2000; Cawood, 2005; Foden et al., 2006; Goodge et al., 2012; Hagen-Peter et al., 2015, 2016; Paulsen et al., 2015). Permian–Triassic metasedimentary rocks in the Alexandra Mountains near the Ross Sea (Fig. 2) were derived from local sources as recorded by 400–320 Ma and ~250 Ma detrital zircon age populations (Pankhurst et al., 1998a, 1998b). The Swanson Formation is intruded by the Ford Granodiorite suite emplaced between 375 and 345 Ma (Yakymchuk et al., 2015), coincident with Gondwana margin arc magmatism in Northern Victoria Land (Admiralty Intrusives, Borg et al., 1986), the Western Province of New Zealand (Karamea Suite, Tulloch et al., 2009), eastern Australia (Melbourne Terrane, Chappell et al., 1988), and southern South America (Pankhurst et al., 2003; Hervé et al., 2016). The Ford Granodiorite suite has zircon Hf and O isotope compositions consistent with mixing of juvenile mantle melts with a melt of the Swanson Formation during arc magmatism (Yakymchuk et al., 2015). High-grade metamorphic equivalents to the Swanson Formation and Ford Granodiorite suite are found in the nearby Fosdick Mountains migmatite-granite complex of western Marie Byrd Land (Fig. 2) contain Devonian–Carboniferous (370–355 Ma) and Cretaceous granites (146–96 Ma) (Siddoway and Fanning, 2009; Korhonen et al., 2010, 2012; Yakymchuk et al., 2013). Metamorphism in the Fosdick complex is interpreted to have occurred at mid-crustal depths during rifting of Zealandia from the Gondwana margin in the mid to late Cretaceous (Siddoway et al., 2004; Korhonen et al., 2010, 2012). Devonian–Carboniferous (370–355 Ma) granites in the Fosdick complex formed via mixing between melts of the Ford Granodiorite suite and the Swanson Formation (Yakymchuk et al., 2013). Cretaceous (146–96 Ma) granites in the Fosdick complex, in contrast, require a juvenile component in addition to the Ford Granodiorite suite and Swanson Formation components (Yakymchuk et al., 2013).

Zircon Hf isotopic compositions of c. 370–355 granitoids from the Ross Province are more evolved than granites from correlative suites across the Gondwana margin in the Western Province of New Zealand and eastern Australia (Yakymchuk et al., 2015). These isotopic differences are attributed to an along-arc change from typical extensional arc tectonics in eastern Australia to an advancing arc system in West Antarctica (Yakymchuk et al., 2015). Zircon U-Pb and Hf isotopes from volcaniclastic sedimentary rocks in the Transantarctic Mountains, however, suggest that extensional tectonics continued into West Antarctica (Nelson and Cottle, 2017). In this contribution, we investigate the extent of extensional tectonics in West Antarctica by studying in situ plutonic rocks rather than their derivatives. These new data from eastern Marie Byrd Land also represent the first zircon Hf isotope data from this region and uncover a more complete history of arc geochemistry and geodynamics for West Antarctica.

2.2. Eastern Marie Byrd Land (Amundsen Province)

The Amundsen Province extends from the westernmost area of the Rupert Coast through Pine Island Bay, including the Hobbs and Walgreen Coasts and inland regions (Fig. 2). Paleozoic correlatives to the Swanson Formation are absent in the Amundsen Province but paragneisses at Mount Petras and Patton Bluff (Fig. 2) contain Devonian–Carboniferous detrital zircon similar in age to the Alexandra Mountains and the Ford Granodiorite suite in the Ross Province (Pankhurst et al., 1998a, 1998b; Yakymchuk et al., 2015). The Amundsen Province contains a more comprehensive record of arc-related plutonism than the Ross Province, spanning the Cambrian through Triassic, previously constrained by Rb-Sr isochron and multigrain fraction isotope dilution-thermal ionization mass spectrometry (ID-TIMS) zircon U-Pb ages (Pankhurst et al., 1998a, 1998b; Mukasa and Dalziel, 2000). Cretaceous gneisses and granites (128 to 113 Ma) in the Demas Range migmatite complex of the Amundsen Province (Fig. 2) overlap in age with the majority of granites from the Fosdick migmatite complex of the Ross Province and may represent a correlative event. Cretaceous subduction-related calc-alkaline magmatic rocks are scattered throughout the Amundsen Province (Mukasa and Dalziel, 2000). The youngest calc-alkaline granite along the Rupert and Hobbs coast outcrops at Mt. Prince (Fig. 2) and is dated at 110 $\pm$ 1 Ma; further towards the east the youngest calc-alkaline intrusion in Pine Island Bay (Fig. 2) has an age of 96 $\pm$ 1 Ma (Mukasa and Dalziel, 2000). Initial rift-related magmatism at ~100 Ma (e.g., Mt. Prince) is consistent with the inception of Pacific-Antarctic seafloor spreading at c. 81 Ma (Mukasa and Dalziel, 2000).

2.3. Thurston Island

Rocks of the Thurston Island crustal block outcrop on a series of islands and the adjacent Eights Coast and Jones Mountains (Fig. 2). The exposed basement includes Carboniferous to Late Cretaceous volcanic and magmatic calc-alkaline igneous rocks recording subduction-related magmatism along the paleo-Pacific margin of Gondwana (Leat et al., 1993; Pankhurst et al., 1993; Riley et al., 2017). Early studies by Leat et al. (1993) and Pankhurst et al. (1993) documented the geochemistry and geochronology of the Thurston Island block relying exclusively on K-Ar, $^{40}Ar/^{39}Ar$, and Rb-Sr techniques. Recent work by Riley et al. (2017) revised the geochemistry and geochronology record utilizing zircon U-Pb and Hf isotopes for a limited suite of samples, identifying isolated episodes of magmatism at 349 $\pm$ 2 Ma, 239 $\pm$ 4 Ma, ~182 Ma, 151 $\pm$ 2 Ma and 108 $\pm$ 1 Ma. The ~349 Ma granodiorite gneiss from Thurston Island represents juvenile magmatism, indicated zircon εHf_i values from +10 to +2. In contrast, Triassic through Cretaceous magmatic rocks with ages of ~239 Ma, ~151 Ma, and ~108 Ma from Thurston Island incorporated more ancient crustal material in their petrogenesis, represented by εHf_i from 0 to -9 (Riley et al., 2017).

3. Analytical techniques

Twenty three samples from the eastern Amundsen Province of Marie Byrd Land and Thurston Island (Fig. 2) were selected from the Polar Rock Repository (Repository, 2018) and provided by Mukasa and Dalziel (2000) to determine the timing and geochemical history of subduction-related magmatism within the Antarctic sector of the Gondwana margin. Zircon was separated using standard mineral separation techniques (i.e., disk milling, water table, magnetic separation, and heavy liquids), mounted in epoxy, and polished to expose equatorial sections. Prior to isotopic analysis, zircon were imaged via cathodoluminescence (CL) on an FEI Quanta400f scanning electron microscope (SEM) and used to guide selection of locations for laser ablation split-stream analyses (U-Pb and trace elements) followed by Lu-Hf measurements.

Zircon U-Pb isotopes were obtained at the University of California, Santa Barbara, under standard operating conditions (McKinney et al., 2015). Instrumentation consists of a 193 nm ArF excimer laser ablation (LA) system coupled to Nu Plasma high–resolution multi collector–inductively coupled plasma mass spectrometer (MC-ICP-MS). Approximately 60 crystals were measured for U-Pb analysis from each sample. Subsequent Lu-Hf analyses were performed by LA-MC-ICPMS (n = ~20 per sample, and Lu-Hf isotope analysis location was placed directly over previous U-Pb and trace-element ablation pits. Data reduction was performed using Iolite v2.5 (Paton et al., 2010, 2011) and ^{207}Pb-corrected $^{206}Pb/^{238}U$ ages were calculated for zircon younger than 800 Ma using the method of Andersen (2002) and ISOPLOT/EX (Ludwig, 2003). We use $^{206}Pb/^{206}Pb$ ages for zircon older than 800 Ma. Detailed analytical methods, data reduction protocols and results of reference zircon analyses and unknown data are provided in the Supplementary information text S1, and datasets 1 and 2 (Patchett and Tatsumoto, 1980, 1981; Wiedenbeck et al., 1995, 2004; Chu et al., 2002; Jackson et al., 2004; Thirlwall and Anczkiewicz, 2004; Woodhead and Hergt, 2005; Blichert-Toft, 2008; Sláma et al., 2008).

4. Results

Zircon U-Pb ages and Hf isotopic data for 17 samples from eastern Marie Byrd Land and 6 samples from Thurston Island (Hf data for 3 samples) are provided in Supplementary file 1 and summarized in Table 1. Representative cathodoluminescence (CL) images of zircon with locations of U-Pb and Hf isotope measurements are provided in Fig. 3. Tera-Wasserburg Concordia diagrams and ^{207}Pb-corrected weighted mean ^{206}Pb/^{238}U crystallization ages for Paleozoic–Mesozoic samples from both eastern Marie Byrd Land and Thurston Island are plotted in Figs. 4 and 5. Calculated weighted mean crystallization ages with two sigma uncertainties and mean squared weight deviation (MSWD) for samples from this study are discussed below. Zircon Hf isotope data for eastern Marie Byrd Land and Thurston Island are plotted in Figs. 6 and 7 and calculated weighted mean εHf_i values are provided alongside their two standard error uncertainties below. All εHf_i values were calculated using chondritic uniform reservoir (CHUR) parameters of Bouvier et al. (2008) and ^{176}Lu decay constant from (Söderlund et al., 2004). Samples with atypical zircon Th/U ratios (i.e., <0.1) are discussed below, all other samples contain typical igneous zircon Th/U ratios (Rubatto, 2002).

Sample MB 432.1, a biotite-hornblende granodiorite from Slater Rocks (Fig. 2), is the oldest sample in this study with an age of 420 ± 2 Ma, MSWD = 0.8. This new age is consistent with a Rb-Sr isochron age of 419 ± 20 Ma (MSWD = 17) obtained by (Pankhurst et al., 1998a, 1998b). The εHf_i for this sample is +4.7 ± 0.5, more juvenile than the εHf_i of +1.2 calculated using whole rock Nd isotope data (Pankhurst et al., 1998a, 1998b) and the Nd–Hf conversion equation from Vervoort et al. (1999). Samples MB 201.15 from Mt. McCoy (Fig. 2) and MB 206.2 from Brunner Hill (Fig. 2) yield indistinguishable ages of 348 ± 1 Ma (MSWD = 1.7) and 348 ± 8 Ma (MSWD = 0.2), respectively. These new ages are within uncertainty of a previous Rb-Sr isochron age of 330 ± 20 Ma for Mt. McCoy and a zircon U-Pb age of 339 ± 6 Ma for Bruner Hill (Pankhurst et al., 1998a, 1998b). However, they are significantly older than an ID-TIMS multigrain fraction U/Pb zircon lower-intercept age of 320 ± 3 Ma for Mt. McCoy obtained by (Mukasa and Dalziel, 2000). New Hf isotopic data for Mt. McCoy form a fairly tight range of εHf_i values and a weight mean of +5.3 ± 0.4 consistent with whole-rock Nd isotopic data (Pankhurst et al., 1998a, 1998b). Zircon from Bruner Hill does not appear to luminesce under CL and are therefore not included in Fig. 3. The zircon U-Pb data for Bruner Hill are generally discordant (Fig. 4) with an average zircon Th/U of 0.06 (see Supplementary dataset 1). The discordant U-Pb data and Th/U < 0.1 suggest that zircon in the Bruner Hill sample records a high-grade metamorphic/anatectic event rather than magmatism (Rubatto, 2002). The Hf isotopic data for Bruner Hill are highly variable but generally more enriched than Mt. McCoy, with an εHf_i = +0.2 ± 2.0.

Five new Permian magmatic ages were obtained for plutonic rocks of the Walgreen Coast (Fig. 2). A granite from Jeffrey Head (MB 406.7) of the Bear Peninsula (Fig. 2) is the oldest Permian sample, 295 ± 2 Ma (MSWD = 1.6), and has the least radiogenic hafnium isotope composition, εHf_i = +10.2 ± 0.7. This new age is slightly younger than the 312 ± 10 Ma age reported by Pankhurst et al. (1998a, 1998b) but the εHf_i value is within range of their whole rock Nd isotopic composition, εHf_i = +8.5 (using the Nd–Hf conversion equation from (Vervoort et al., 1999)). A granodiorite from the Bear Peninsula (BP3) yields a younger, 287 ± 1 Ma (MSWD = 0.9), age and a similar εHf_i = +9.0 ± 1.1. A granodiorite from Mt. Isherwood (MB 400.1D, Fig. 2) yields an age of 283 ± 1 Ma (MSWD = 1.0) and an εHf_i = +3.0 ± 0.5. This new age contrasts with two multi-fraction ID-TIMS zircon U-Pb lower intercept ages of 243 ± 29 Ma and 414 ± 98 Ma (Mukasa and Dalziel, 2000) from the same zircon separates. Quartz diorites from Mt. Wilbanks (MB 402.2, Fig. 2) and Mt. Strange (MB 403.3, Fig. 2) yielded ages of 287 ± 1 Ma (MSWD = 1.2) and 284 ± 2 Ma (MSWD = 0.6) and εHf_i = +5.8 ± 0.5 and +6.0 ± 0.8, respectively. These ages are within uncertainty of the 283.0 ± 0.5 Ma age for Mt. Wilbanks published by Mukasa and Dalziel (2000) on the same zircon separate and a Rb-Sr isochron age of 276 ± 2 Ma obtained by Pankhurst et al. (1998a, 1998b) for granitoids of the Kohler Range.

The earliest record of Mesozoic magmatism in eastern Marie Byrd Land recorded by our samples is a granite age of 248 ± 1 Ma (MSWD = 0.6), with a εHf_i = +10.9 ± 0.6, from Kinsey Ridge of the Rupert Coast (MB 212.3P, Fig. 2). Six new ages were also determined for plutonic and migmatitic rocks from a migmatite complex in the Demas Range, Rupert Coast, and refine the dominantly discordant U-Pb dates published by Mukasa and Dalziel (2000). A megacrystic

Table 1
Summary of zircon U-Pb geochronology and Hf isotope data for Marie Byrd Land and Thurston Island.

Sample #	Rock type	Location	Lat (S)[a]	Long (W)[a]	Age ± 2σ (Ma)	MSWD	Inherited (Ma)	Mean εHfi (2SE)
Thurston Island								
61-133	Granite	Jones Mtns	73.50	94.40	208 ± 1	2.1		−4.8 (0.7)
64-J-BS-1	Granite	Jones Mtns	73.50	94.37	211 ± 1	2.7	c. 1131 & 1433	n.d.
61-119	Granite	Jones Mtns	73.50	94.37	215 ± 1	1.3		n.d.
68-71-1	Diorite	Guy Peaks	72.15	98.90	276 ± 1	0.9		0.4 (0.7)
60-10-1	Orthogneiss	King Cliffs	72.30	96.02	338 ± 2	1.6		2.1 (1.2)
TI 3-1	Orthogneiss	Cape Menzel	72.06	95.76	347 ± 1	1.0		11.0 (0.6)
Marie Byrd Land								
MB 205.3V	Dike swarm	Mt. Prince	74.97	134.17	100 ± 1	1.6		6.8 (0.7)
MB 205.10M	Granite	Mt. Prince	74.97	134.17	108–120			4.2 (0.7)
MB 208.3	Granite	Patton Bluff	75.22	133.68	110–120			4.7 (0.5)
MB 204.1M	Granite	Mt. Goorhigian	75.05	133.80	103 ± 1	1.0	c. 140 & 247	3.7 (0.5)
MB 426.4	Monzogranite	Early Bluff	75.19	113.97	106 ± 1	1.0	c. 412	0.8 (0.5)
MB 385.1M	Granite	Backer Island	74.47	102.39	117 ± 1	1.0		6.5 (0.9)
MB 163.1M	Granite	Mt. Goorhigian	75.05	133.72	145 ± 1	1.6		3.5 (0.5)
MB 204.3M	Orthogneiss	Mt. Goorhigian	75.05	133.80	150 ± 1	0.5		4.7 (0.5)
MB 212.3P	Granite	Kinsey Ridge	75.37	139.15	248 ± 1	0.6	c. 1089	10.9 (0.6)
MB 400.1D	Granodiorite	Mt. Isherwood	74.98	113.70	283 ± 1	1.0		3.0 (0.5)
MB 403.3	Quartz diorite	Mt. Strange	74.96	113.52	284 ± 2	0.6		6.0 (0.8)
BP3	Granodiorite	Bear Peninsula	74.55	111.89	287 ± 1	0.9		9.0 (1.1)
MB 402.2	Quartz diorite	Mt. Wilbanks	75.00	112.88	287 ± 1	1.2		5.8 (0.5)
MB 406.7	Granite	Jeffrey Head	74.55	111.90	295 ± 2	1.6		10.2 (0.7)
MB 201.15	Granite	Mt. McCoy	75.80	141.00	348 ± 1	1.7	c. 572	5.3 (0.4)
MB 206.2	Orthogneiss	Bruner Hill	75.65	142.40	348 ± 8	0.2		0.2 (2.0)
MB 432.1	Granodiorite	Slater Rocks	75.08	113.88	420 ± 2	0.8		4.7 (0.5)

[a] Reported by the Polar Rock Repository.

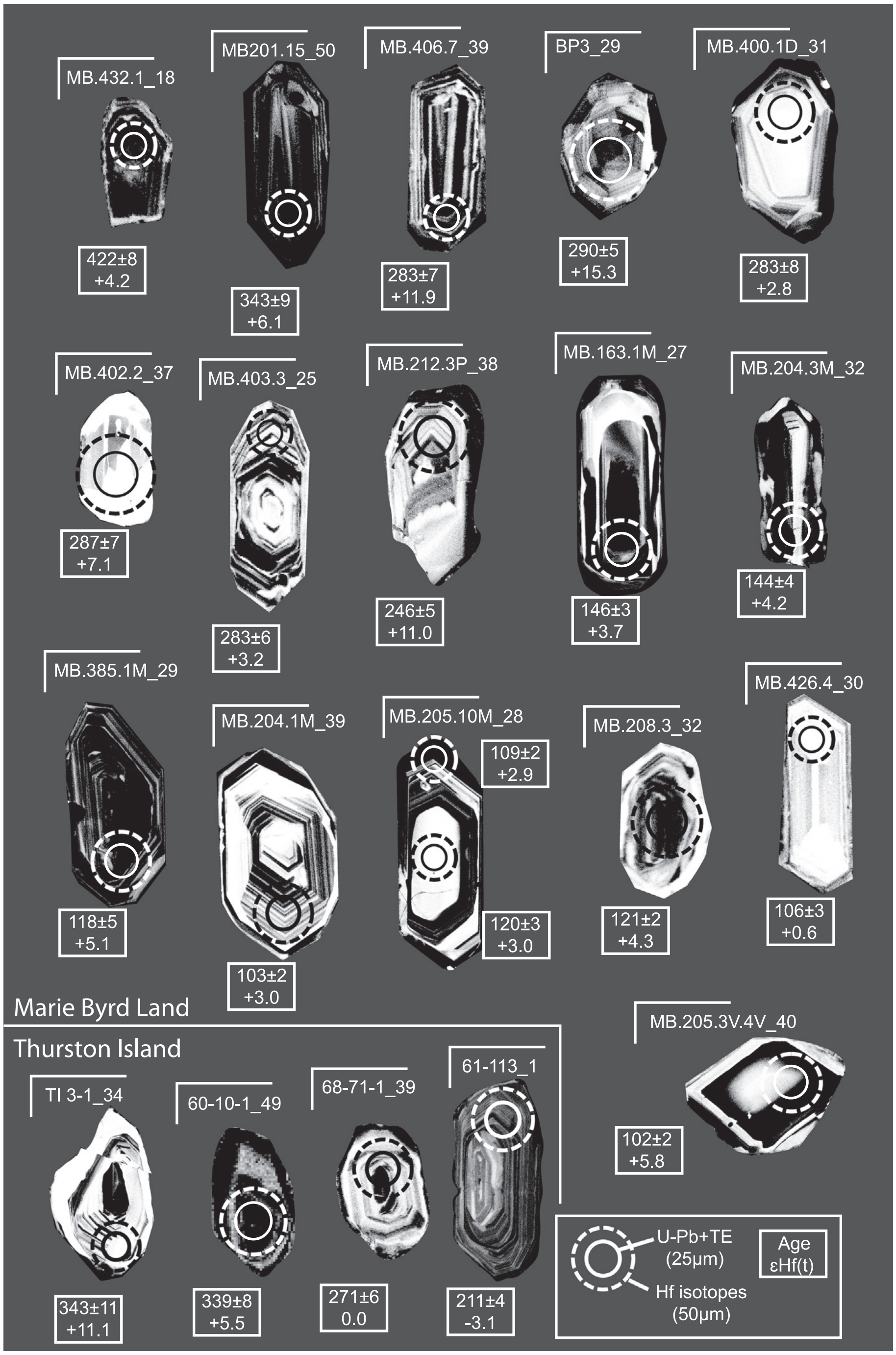

Fig. 3. Representative zircon cathodoluminescent images for each sample showing the location of U-Pb and Hf isotopic analyses with the correlated single spot age and epsilon Hf.

granite (MB 163.1M) and leucogranitic gneiss (MB 204.3M) from Mt. Goorhigian (Fig. 2) have Late Jurassic ages of 145 ± 1 Ma with $\varepsilon Hf_i = +3.5 \pm 0.5$ and 150 ± 1 Ma with $\varepsilon Hf_i = +4.7 \pm 0.5$, respectively. A monzogranite from Early Bluff is the next oldest sample and the most juvenile from eastern Marie Byrd Land with an age of 117 ± 1 Ma and an $\varepsilon Hf_i = +6.5 \pm 0.9$. A Cretaceous granite from Mt. Goorhigian (MB 204.1M, Fig. 2) yielded more complex U-Pb data with an inferred crystallization age of 103 ± 1 Ma and an $\varepsilon Hf_i = +3.7 \pm 0.5$, but also including older concordant dates of 140–102 Ma and ~247 Ma. Complex data were also observed in granites from Mt. Prince (MB 205.10M, Fig. 2) and Patton Bluff (MB 208.3, Fig. 2). The Mt. Prince granite contains a range of Cretaceous zircon ages with peaks at 108 and 120 Ma and an average $\varepsilon Hf_i = +4.2 \pm 0.7$. Similarly, the Patton Bluff granite contains a range of ages with peaks at 109 Ma, 114 Ma, and 120 Ma with an average $\varepsilon Hf_i = +4.7 \pm 0.6$. Younger dates were determined for a monzogranite from Early Bluffs (MB 426.4) and a dike from Mt. Prince (MB 205.3V) of 106 ± 1 Ma with an average $\varepsilon Hf_i = +0.8 \pm 0.5$ and 100 ± 0.4 Ma with average $\varepsilon Hf_i = +6.8 \pm 0.7$. This new age is slightly older than a single-fraction zircon U-Pb age of 103.4 ± 0.3 Ma (Mukasa and Dalziel, 2000). Overall, there is a general decrease in the εHf_i from a mean of +6.5 at c. 117 Ma to +0.8 at c. 106 Ma followed by a return to +6.8 at c. 100 Ma.

Three new ages spanning the Carboniferous–Permian were determined for rocks from Thurston Island. An orthogneiss from Cape Menzel (TI 3-1, Fig. 2) yielded an igneous age of 347 ± 1 Ma with $\varepsilon Hf_i = 11.0 \pm 0.6$ and an orthogneiss from King Cliffs (60-10-1, Fig. 2) provided a metamorphic age (average zircon Th/U = 0.06) of 338 ± 2 Ma with

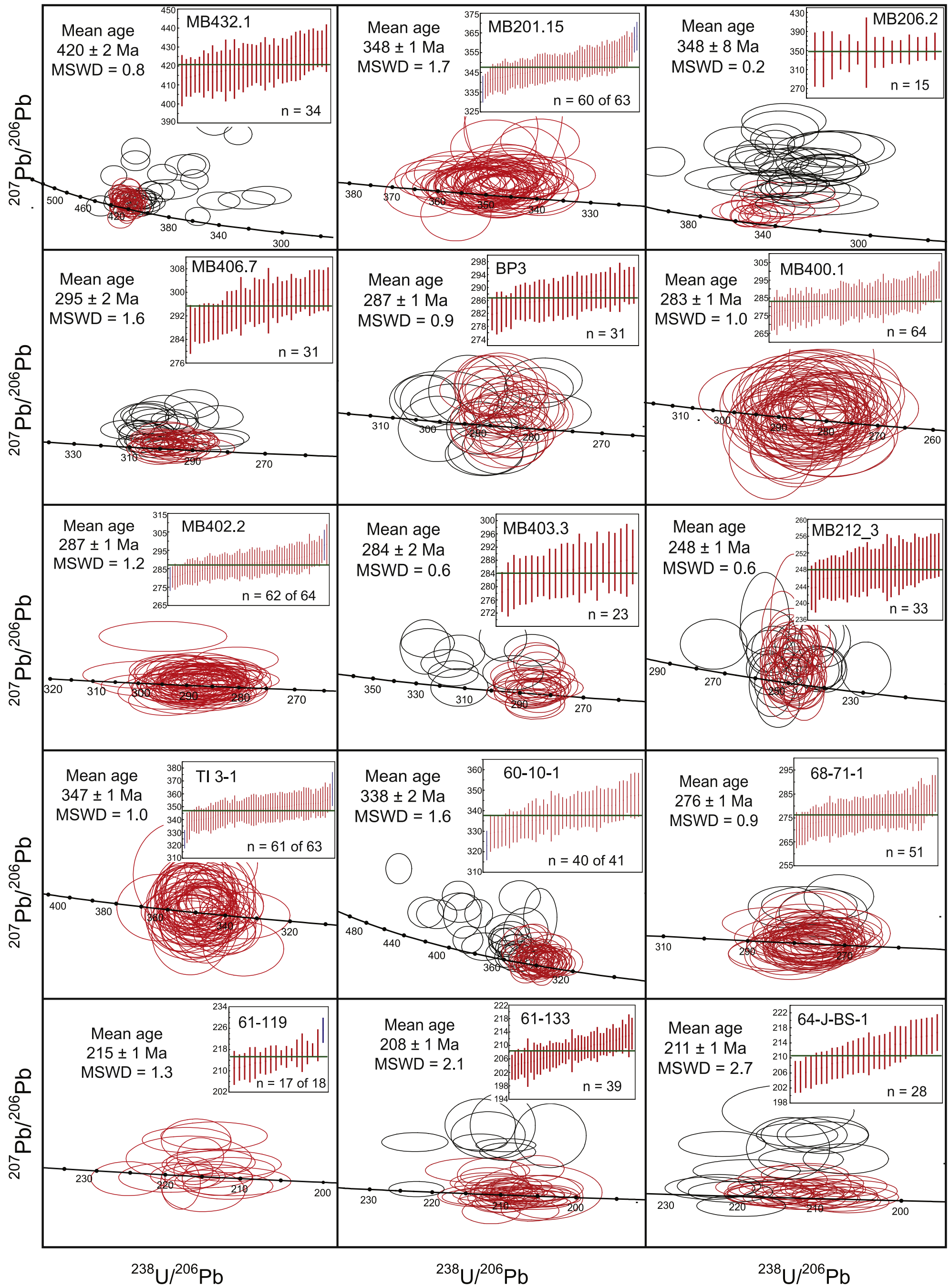

Fig. 4. Zircon LASS U-Pb geochronology data for Silurian to Triassic aged samples of eastern Marie Byrd Land and Thurston Island in Tera-Wasserburg Concordia plots and calculated weighted mean ^{207}Pb corrected–^{206}Pb/^{238}U ages provided for select analyses in red. See Dataset S1 for full zircon U-Pb dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$\varepsilon Hf_i = +2.1 \pm 1.2$. A diorite from Guy Peaks (68-71-1, Fig. 2) yielded the only Permian age for Thurston Island of 276 ± 1 Ma with $\varepsilon Hf_i = 0.4 \pm 0.7$. Three granites from Jones Mountains (61-119, 61-133, and 64-J-BS-1, Fig. 2) have Triassic ages of 208 ± 1, 211 ± 1, and 208 ± 1 Ma. Zircon Hf isotope compositions were determined for sample 61-133 and yielded $\varepsilon Hf_i = -4.8 \pm 0.7$.

5. Discussion

5.1. Zircon record of West Antarctica (Cambrian–Cretaceous) magmatism

The new ages reported here combined with previously reported ages indicate that basement exposures in eastern Marie Byrd Land span a longer time period than western Marie Byrd Land. The oldest igneous rock dated so far from eastern Marie Byrd Land is a 505 ± 5 Ma orthogneiss from Mt. Murphy (Pankhurst et al., 1998a, 1998b), indicating the basement of eastern Marie Byrd Land is composed, at least, partly of plutonic rocks associated with the Ross Orogen. The oldest rock dated in this study is a Silurian granodiorite at Slater Rocks (420 ± 1.8 Ma) but an Ordovician Rb-Sr isochron age of 446 ± 16 Ma (MSWD = 0.4; Pankhurst et al., 1998a, 1998b) for gneisses from Clark Island in Pine Island Bay indicates Ordovician rocks also exist in Marie Byrd Land. The 420 ± 1.8 Ma crystallization age from Slater Rocks is contemporaneous with the Lachlan Orogen in Australia (Foster et al., 2009), Silurian (c. 435 to 422 Ma) orthogneisses from the Antarctic Peninsula (Millar et al., 2002), contemporaneous granitoids in southern Patagonia

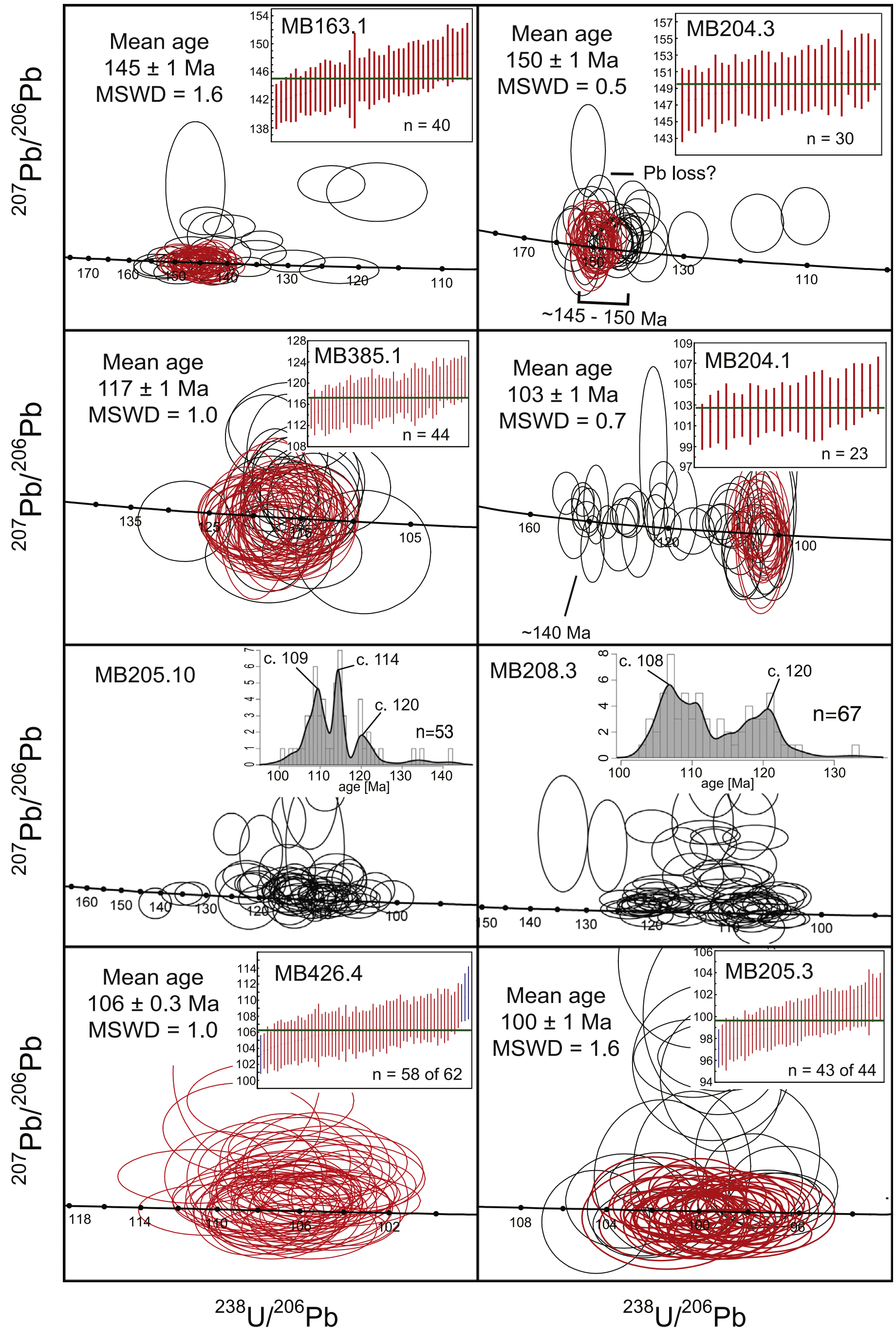

Fig. 5. Zircon LASS U-Pb geochronology data for Late Jurassic to Cretaceous aged samples of eastern Marie Byrd Land in Tera-Wasserburg Concordia plots and calculated weighted mean ^{207}Pb corrected–^{206}Pb/^{238}U ages provided for select analyses in red. Normal kernel density estimates with a bandwidth of 1 and histograms are provided when no single age is dominant (Vermeesch, 2012). See Dataset S1 for full zircon U-Pb dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Pankhurst et al., 2003), but older than known igneous rocks from western Marie Byrd Land (Yakymchuk et al., 2015).

The two Marie Byrd Land provinces do, however, share a record of magmatic and metamorphic activity during the Carboniferous, with a granite from Mt. McCoy (348 ± 1 Ma) and an orthogneiss from Brunner Hill (348 ± 8 Ma) falling within the age range of the Ford Granodiorite Suite (374–345 Ma) and within uncertainty of the timing of peak metamorphism in the Fosdick migmatite-granite complex (346 Ma) in western Marie Byrd Land (Siddoway and Fanning, 2009; Korhonen et al., 2010; Yakymchuk et al., 2013). Devonian–Carboniferous orthogneisses are also found on Thurston Island (347 ± 1 and 338 ± 2 Ma, this study) and the Antarctic Peninsula (397 ± 8, 393 ± 1, and 327 ± 9 Ma, Millar et al., 2002). Volcaniclastic sedimentary rocks in the central Transantarctic Mountains also contain abundant 367–328 Ma zircon thought to be sourced from West Antarctica (Elliot and Fanning, 2008; Elsner et al., 2013; Elliot et al., 2016, 2017; Nelson and Cottle, 2017; Paulsen et al., 2017). Mt. McCoy and Bruner Hill straddle the eastern – western Marie Byrd Land boundary and, in this study, are the closest rocks to the Ford Ranges of eastern Marie Byrd Land. Based solely on the geochronology it is unclear whether this juxtaposition of contemporaneous rocks is coincidental or indicative of a shared melting event that either extends beyond a true crustal boundary or suggests the boundary should be shifted to include Mt. McCoy within the western province. Regardless of the boundary location, the new dates presented here along with known correlative units in Zealandia (e.g., Tulloch et al., 2009), Australia (e.g., Chappell et al., 1988), Northern Victoria Land (e.g., Borg et al., 1986), and the central Transantarctic Mountains (e.g., Nelson and Cottle, 2017) suggest that widespread magmatism occurred in the Devonian–Carboniferous consistent with an orogen-wide magmatic flare-up event.

The Permian record of arc magmatism is sparse in West Antarctica. Our new ages for Permian granites from the Walgreen Coast record a major magmatic event from 295 to 283 Ma (Fig. 2). The rock closest to this time interval is a 276 ± 1 Ma diorite from Thurston Island (this study), approximately 500 km east of the Walgreen Coast. Other Permian magmatic ages have, however, been reported for a limited number of rocks from the Antarctic Peninsula (Millar et al., 2002; Riley et al., 2012). The 295–283 Ma event is also not preserved in Permian volcaniclastic sedimentary rocks of the Transantarctic Mountains (Elliot and Fanning, 2008; Elsner et al., 2013; Elliot et al., 2016, 2017; Nelson and Cottle, 2017; Paulsen et al., 2017). Magmatic rocks from Patagonia and detrital zircon from the Antarctic Peninsula and Patagonia do however have abundant ages overlapping with Walgreen Coast magmatism (e.g., Hervé et al., 2006; Pankhurst et al., 2006, 2014; Fanning et al., 2011; Castillo et al., 2016). Granites from the New England Orogen in Australia also have similar early Permian (296–288 Ma) ages (e.g., Rosenbaum et al., 2012; Kemp et al., 2009b). There are however, very few early Permian detrital zircon U-Pb ages in sedimentary rocks from Australia and New Zealand but a prominent early Permian peak in zircon age spectra for Patagonia sedimentary rocks (see Fig. 7 of Nelson and Cottle, 2017). Zircon geochronology alone, therefore, cannot distinguish if the Walgreen Coast event is more closely related to discrete early Permian magmatism akin to the Australian arc record or, more widespread early Permian magmatism as in South America.

The Triassic record of arc magmatism in Marie Byrd Land is limited to granite from Kinsey Ridge of the Rupert Coast (Fig. 2, 248 ± 1 Ma, this study). The age of the Kinsey Ridge granite overlaps with the Permian–Triassic peak in detrital zircon U-Pb ages from Mesozoic sedimentary rocks in the Transantarctic Mountains and, therefore, is consistent with its proposed role as the source region (Elliot and Fanning, 2008; Elsner et al., 2013; Elliot et al., 2016, 2017; Nelson and Cottle, 2017; Paulsen et al., 2017). Although there is a scarcity of Triassic and late Permian dates from Marie Byrd Land igneous rocks, the abundance of Triassic and late Permian aged detrital zircon in the central Transantarctic Mountains suggests that significant Permian–Triassic crust remains ice covered in Marie Byrd Land. Triassic magmatic rocks are more common in the Antarctic Peninsula but most formed over a brief period from c. 237 to 227 Ma (Millar et al., 2002; Riley et al., 2012; Flowerdew et al., 2006). On Thurston Island, a diorite from Mount Bramhall (239 ± 4 Ma, Riley et al., 2017) is similar in age to Triassic rocks from the Antarctic Peninsula. However, our new ages for granites from Jones Mountains (215 to 208 Ma) have no identifiable plutonic correlatives in West Antarctica, other than a 208 Ma granite in the Ellsworth-Whitmore terrane (Craddock et al., 2017). Furthermore, zircons similar in age to the Jones Mountains granite are uncommon in the detrital record of Patagonia, New Zealand, and Australia (see compilation in Nelson and Cottle, 2017).

The Early Jurassic subduction-related magmatic record in West Antarctica consists of c. 188 to 181 Ma granitoids from the Antarctic Peninsula that correlate to the subcordilleran plutonic belt of Patagonia (Riley et al., 2017). These granites appear unrelated to contemporaneous volcanic rocks of the Ferrar large igneous province (LIP) of the Transantarctic Mountains or the Chon Aike silicic LIP of Patagonia, the Ellsworth-Whitmore terrane, and Thurston Island (Pankhurst et al., 2000; Burgess et al., 2015). The emplacement of the Ferrar and Chon Aike LIPs is thought to be synchronous with the initial break-up of Gondwana in the Early Jurassic (Encarnación et al., 1996). Younger within-plate granites (c. 178–174 Ma) in the Ellsworth-Whitmore terrane are also interpreted to be related to Gondwana break-up rather than subduction (Craddock et al., 2017). In contrast, Early Jurassic volcaniclastic sedimentary rocks of the Hanson Formation in the central Transantarctic Mountains are inferred to be subduction-related and represent prolonged arc volcanism from c. 202 to 183 Ma with no identifiable source in West Antarctica (Elliot et al., 2016; Nelson and Cottle, 2017).

The onset of supercontinent break-up in the Early Jurassic began a period of relative arc inactivity that persisted until the Late Jurassic. Consequently, a younger age of 166 ± 3 Ma for zircon from a leucocratic dike from the Antarctic Peninsula is the only Mid-Jurassic zircon crystallization age reported for West Antarctica (Flowerdew et al., 2006). Jurassic ages have also been discovered for a mafic gneiss in western Marie Byrd Land that contains inherited ~146 Ma zircon that could be igneous or metamorphic (Yakymchuk et al., 2013). Similar-aged magmatism in Thurston Island is represented by a 151 ± 2 Ma granite (Riley et al., 2017). Other suspected Late Jurassic–Early Cretaceous granitoids occur throughout western and southern Thurston Island (Leat et al., 1993; Pankhurst et al., 1993). Late Jurassic–Early Cretaceous magmatism on the Antarctic Peninsula is absent aside from a 141 ± 2 Ma granite in northwest Palmer Land (Vaughan and Millar, 1996). Overall, scattered Mid to Late Jurassic magmatic rocks in West Antarctica are contemporaneous with and may represent an extension of the Triassic–Cretaceous magmatic rocks of the Darran Suite in New Zealand (Mortimer et al., 2015).

Mid- to Late-Cretaceous magmatic rocks are prevalent throughout West Antarctica. Recent zircon U-Pb data for the Lassiter Coast intrusive suite from the Antarctic Peninsula indicates a magmatic flare-up event characterized by the emplacement of voluminous granitoid batholiths over three distinct episodes at ~127 Ma, ~117 Ma, and ~106 Ma (Riley et al., 2018). Both the North Patagonian Batholith and the Divisadero Group Volcanic rocks of the North Patagonian Andes share these same distinct episodes of increased magmatic flux (e.g., Pankhurst et al., 1999; Echaurren et al., 2017). In western Marie Byrd Land, 115 to 98 Ma granitoids in the Fosdick Mountains overlap in age with the proposed Cretaceous magmatic flare-up (e.g., Korhonen et al., 2010). Our new U-Pb zircon ages for Mid to Late Cretaceous magmatic rocks from eastern Marie Byrd Land are synchronous with episodic Cretaceous magmatism in both western Marie Byrd Land and the Antarctic Peninsula, indicating a major magmatic flare-up event occurred along the Antarctic margin related to major episodes of compression referred to as the Palmer Land Event (Vaughan et al., 2012; Riley et al., 2018).

5.2. Zircon Hf isotopes and geodynamic evolution of the Gondwana margin

5.2.1. The zircon Hf isotope proxy

The relative change in zircon εHf_i through time in magmatic arcs has been linked to the tectonic evolution of the arc (Kemp et al., 2009). In particular, Kemp et al. (2009) argued that a relative increase in zircon εHf_i is indicative of an extensional arc system associated with an outboard migration of subduction zone magmatism during slab rollback and associated crustal extension and thinning. Outboard migration of the arc increases zircon εHf_i by reducing assimilation due to magma ascent through thinner possibly juvenile crust and/or melting of upwelling depleted asthenospheric mantle (e.g., Chapman et al., 2017). Conversely, contractional arc systems produce a decrease in zircon εHf_i during an inboard migration of magmatism due to slab shallowing and arc contraction (i.e., crustal thickening). The relative decrease in εHf_i associated with contractional arc systems is inferred to result from increasing crustal assimilation during crustal thickening, underthrusting of fertile crust to the melt source region, and/or an inboard shift of the arc magma source region towards increased melting of ancient enriched lithospheric mantle (e.g., Chapman et al., 2017). This model for tectonic switching between extension and contraction within accretionary orogens relies on plate boundary processes that adjust the angle of the subducting slab, and include decreased convergence rates (extension) and subduction of buoyant oceanic plateaus (contraction) (Collins, 2002a, 2002b; Kemp et al., 2009).

This model of 'tectonic switching' or 'accordion tectonics' (e.g., Collins, 2002b; Aitchison and Buckman, 2012) provides one conceptual framework within which to interpret our new zircon Hf isotope data and previously published data from West Antarctica and the Transantarctic Mountains. It should be noted, however, that alternatives to the (Collins, 2002a) model used here have been proposed for the paleo-Pacific margin of Gondwana (Crawford, 2003; Aitchison and Buckman, 2012; Gibson et al., 2015). These models generally support "quantum tectonics" which refers to switching of subduction polarity resulting in periods of island arc formation, accretion, and a switch to continental arc formation (Aitchison and Buckman, 2012). These models predict that zircon Hf isotope compositions should shift rapidly to near depleted mantle values during polarity switching and associated island arc formation. Following island arc accretion, zircon Hf isotope compositions should reflect melting of the accreted juvenile island arc lithosphere and/or ancient continental arc lithosphere. For the purposes of this paper, zircon Hf isotopes are interpreted within the framework of accretionary orogenesis because this model has been widely applied to zircon Hf isotope datasets along the paleo-Pacific margin of Gondwana (e.g., Kemp et al., 2009; Phillips et al., 2011; Li et al., 2015; del Rey et al., 2016; Pepper et al., 2016). Furthermore, our zircon Hf isotope data contain no indication that rapid formation of an island arc with near depleted mantle isotope compositions, similar to the Macquarie island arc in the Australian sector (see Aitchison and Buckman, 2012), occurred in the Antarctic sector, making it difficult to interpret our data from Antarctica within a quantum tectonics framework.

Another important consideration for the accordion tectonic model (Collins, 2002b; Aitchison and Buckman, 2012) and zircon Hf isotope proxy established by Kemp et al. (2009) is the role of internal processes such as catastrophic lithospheric thinning (e.g., foundering) rather than plate boundary processes in generating extensional collapse in accretionary orogens (Dewey, 1988). Accretionary orogens undergoing magma flare-ups during upper-plate shortening and lithospheric recycling are associated with the generation of thick (>30 km) dense granulite and garnet pyroxenite (eclogite) roots in the lower crust and lithospheric mantle (Decelles et al., 2009; Lee and Anderson, 2015). These arc roots are significantly denser than the underlying mantle and eventually founder into the asthenosphere (e.g., Currie et al., 2015). Catastrophic foundering or thinning of the mantle lithosphere can cause rapid uplift and a rise in the geothermal gradient leading to gravitationally driven extensional collapse of the orogen, ignimbrite flare-ups, and a shift to juvenile magmatism due to asthenospheric upwelling (e.g., Dewey, 1988; Decelles et al., 2009; Wang and Currie, 2015). Consequently, distinctions and interrelations of arc root foundering and slab rollback are poorly constrained within the record of secular evolution of continental arcs due in part to the two processes producing similar geological signals and the potential for them to occur simultaneously (Lister and Forster, 2009). In this contribution we will discuss periods where both plate boundary and internal processes may be driving extension.

5.2.2. Antarctic sector

Initial subduction along the Antarctic sector during the Ross Orogeny occurred in a dominantly contractional tectonic setting and produced enriched magmas with unradiogenic initial Hf isotopic compositions sourced from an enriched continental lithospheric mantle (Hagen-Peter et al., 2015, 2016; Hagen-Peter and Cottle, 2018). Consequently, the positive zircon εHf_i values younger than the Ordovician from West Antarctica cannot be explained without the addition of a depleted asthenospheric mantle component to the arc magma source region (s) following the Ross Orogeny (i.e. the increase in zircon εHf_i requires juvenile mantle input) (Cawood and Buchan, 2007; Kemp et al., 2009; Chapman et al., 2017). For this reason the markedly more juvenile zircon εHf_i from Silurian–Triassic plutonic rocks in Marie Byrd Land and Carboniferous rocks in Thurston Island and the Antarctic Peninsula is here interpreted as a broad change in the tectonic conditions from contraction during the Ross Orogeny to extension via slab rollback and/or lithosphere removal.

The role of foundering in this tectonic switching event is unknown, but the Ross Orogeny was a dominantly advancing system undergoing lithospheric recycling with a documented magmatic flare-up capable of developing a dense arc root. Lithospheric mantle thinning/removal and asthenospheric upwelling consistent with extensional collapse perhaps due to arc root foundering have been used to explain the emplacement of isotopically enriched lamprophyre dikes emplaced at the end of the Ross Orogeny (Rocchi et al., 2009). The period between the Ordovician and Silurian (c. 485–425 Ma) contains no identified in-situ magmatic rocks in West Antarctica and, therefore, the lack of age and geochemical control during the first ~60 million years following the Ross Orogeny is poor (Fig. 6). Granitic cobbles from conglomerates in the Antarctic Peninsula with c. 485–425 Ma ages record an increase in the εHf_i immediately following the Ross Orogeny, consistent with extension (Fig. 6; Bradshaw et al., 2012). Geophysical data have identified an ~100 km thick segment of foundered lithospheric mantle at ~200 km depth beneath the Transantarctic Mountains, providing evidence for an exceptionally thick arc lithosphere at some point in the Phanerozoic (Shen et al., 2018). There are no constraints on when or why lithospheric foundering initiated but it has been generally associated with previous major episodes of extension along the Antarctic margin.

Even though Ordovician–Carboniferous (c. 485–320 Ma) zircon Hf isotope data from Thurston Island, the Antarctic Peninsula, and eastern Marie Byrd Land represent increased juvenile asthenospheric mantle melting compared to the Ross Orogeny, the zircon initial εHf_i is still far below the depleted mantle evolution line and also varies considerably (Fig. 6). The variation in zircon Hf composition during this, and later time periods, is interpreted to represent either a heterogeneous mantle source (i.e., lithospheric and asthenospheric sources) and/or variable crustal assimilation during magma ascent. Only a few of the lowest zircon εHf_i values from the Silurian–Carboniferous (c. 420–320 Ma) from Thurston Island, the Antarctic Peninsula, and eastern Marie Byrd Land can be explained by complete recycling of Ross–aged or older crust (assuming a Lu/Hf = 0.0115, Rudnick and Gao, 2003).

Fig. 6 demonstrates that almost all Devonian–Carboniferous (c. 350–340 Ma) zircon from both Thurston Island and eastern Marie Byrd Land have juvenile isotopic compositions and are viable sources for Devonian–Carboniferous zircon found within volcaniclastic sedimentary rocks in the central Transantarctic Mountains (Nelson and Cottle, 2017). However, Devonian–Carboniferous zircon from western Marie Byrd Land are more isotopically evolved than eastern Marie Byrd Land and Thurston Island and can be accounted for by remelting of Ross-aged or Grenville-aged lithosphere (e.g., Proterozoic lithospheric mantle) or sedimentary derivatives (Fig. 6). The inferred high degree of ancient lithospheric recycling in western Marie Byrd Land during a period with juvenile magmatism in eastern Marie Byrd Land is problematic (Yakymchuk et al., 2015). The isotopic difference between eastern Marie Byrd Land and western Marie Byrd Land may result from western Marie Byrd Land's position inboard of the rest of West Antarctica during this time and, consequently, was composed of thicker crust (and/or with a more ancient enriched composition) that led to increased crustal assimilation consistent with spatial isotopic trends within other Cordilleran style magmatic systems (e.g., Chapman et al., 2017). The inferred inboard shift of arc magmatism in the Devonian–Carboniferous may have been caused by an episode of contraction and arc/slab advancement in the Antarctic sector. Enriched Ross-aged or Grenville-aged lithosphere would have been melted during shortening and underthrusting and/or in regions where ancient lithospheric mantle persisted (i.e., western Marie Byrd Land). This scenario is supported by petrogenetic modeling utilizing zircon Hf and O isotopes that

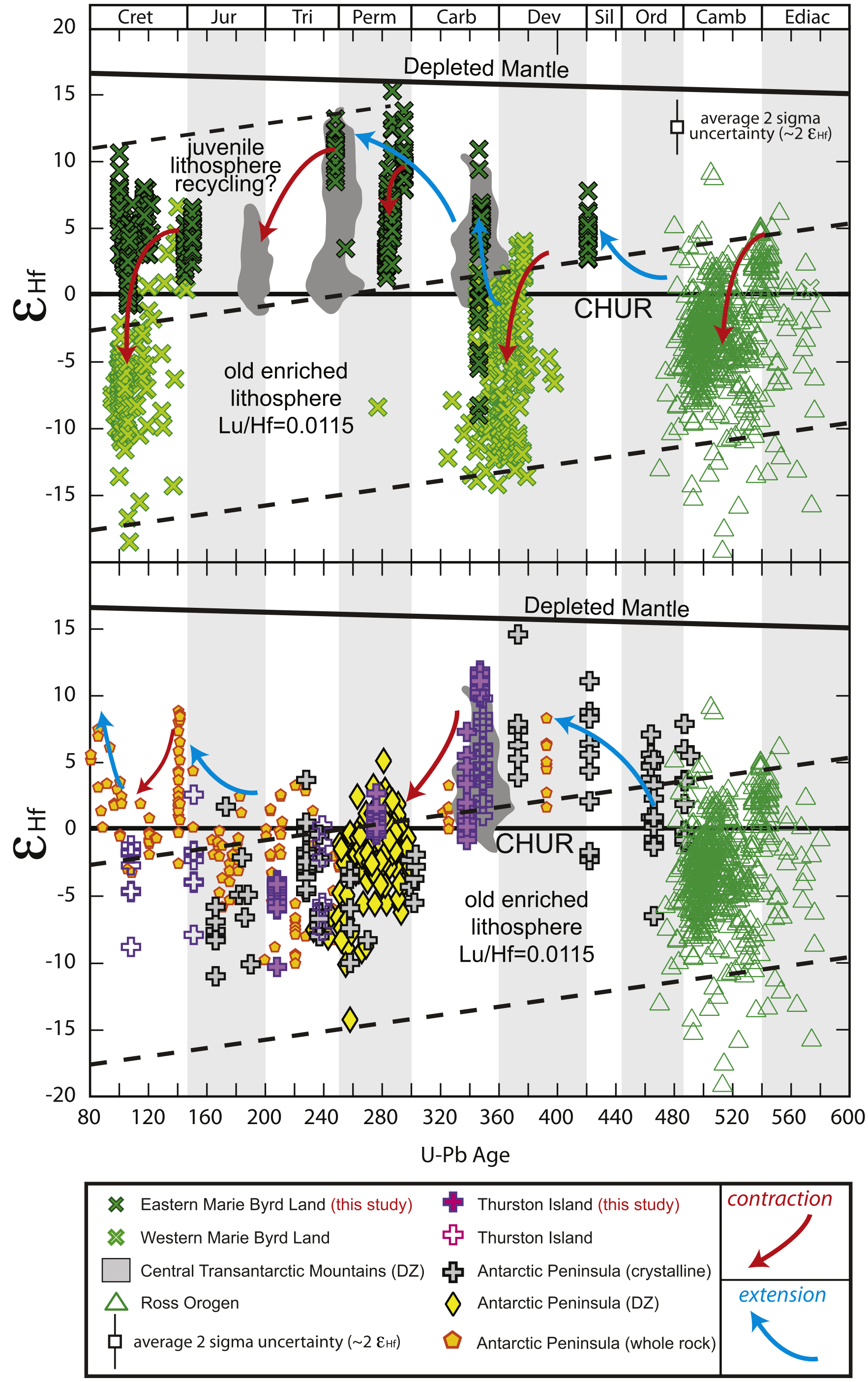

Fig. 6. Zircon age versus initial ε_{Hf} plot summarizing all Hf isotopic data from this study combined with available data for the Ross Orogen (Hagen-Peter et al., 2015; Yakymchuk et al., 2015; Hagen-Peter and Cottle, 2018), the central Transantarctic Mountains (Nelson and Cottle, 2017), western Marie Byrd Land (Yakymchuk et al., 2013, 2015), Thurston Island (Riley et al., 2017), and the Antarctic Peninsula (Millar et al., 2001; Fanning et al., 2011; Bradshaw et al., 2012; Castillo et al., 2016). Dashed lines outline fields of crustal recycling assuming a Lu/Hf = 0.0115 (Rudnick and Gao, 2003). Colored arrows correspond to geodynamic interpretations of extension or contraction based on relative increases and decreases in zircon ε_{Hf}. Hf isotopic values for depleted mantle are from Vervoort and Blichert-Toft (1999). CHUR—chondritic uniform reservoir. DZ = detrital zircon and CZ = zircon from crystalline rocks. Whole rock Hf isotope data from were converted from Nd isotope data (Millar et al., 2001) using the terrestrial array equation of (Vervoort et al., 1999). See Dataset S2 for full zircon Hf isotope dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicate a possible enriched lithospheric mantle source in western Marie Byrd Land and Proterozoic Os model ages for peridotite xenoliths of Marie Byrd Land (Handler et al., 2003; Yakymchuk et al., 2015).

Juvenile magmatism in eastern Marie Byrd Land identified in this study (c. 348 Ma) and by detrital zircon in the Transantarctic Mountains (Nelson and Cottle, 2017) occurs either immediately after or during the waning stages of isotopically enriched magmatism in western Marie Byrd Land (c. 375–345 Ma, Yakymchuk et al., 2015). This observation suggests that the Devonian–Carboniferous time period may represent a classic cordilleran-style cycle of contraction (early enriched inboard magmatism in western Marie Byrd Land) followed by extensional collapse (late juvenile outboard magmatism in eastern Marie Byrd Land), consistent with slab advance and subsequent rollback and/or arc root foundering (Fig. 6). This contractional episode is not observed in Thurston Island and the Antarctic Peninsula, which may reflect continued extension in those regions.

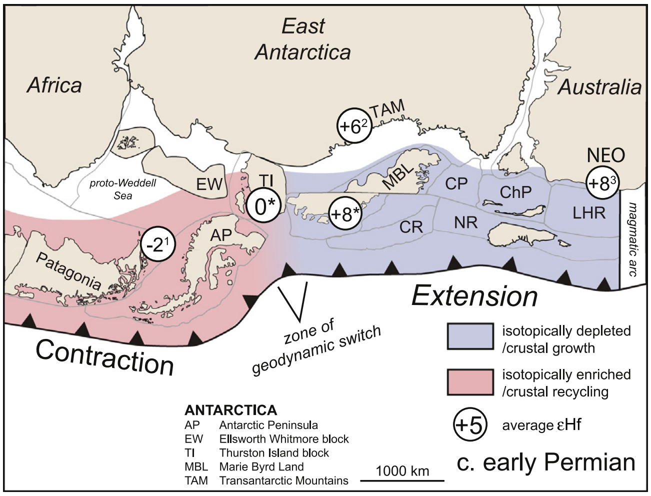

Fig. 7. Reconstruction of the Gondwana plate margin, c. Permian (Elliot, 2013). Shown are the inferred limits of the isotopically depleted and extensional arc (red) and the isotopically enriched and contractional arc (blue). Average Hf isotope compositions are calculated using Permian aged zircon Hf isotope data from: *this study, [1]Antarctic Peninsula and Patagonia (Castillo et al., 2016), [2]central Transantarctic Mountains (Nelson and Cottle, 2017), and the New England Orogen (Kemp et al., 2009; Phillips et al., 2011; Shaw et al., 2011). These data suggest a zone of geochemical and geodynamic switch occurs in the region between the Thurston Island block and Marie Byrd Land in the early Permian. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Highly positive zircon εHf_i values persisted in eastern Marie Byrd Land through the Permian and into the Early Triassic (c. 248 Ma), consistent with a decreasing contribution of ancient lithosphere to the melt source and/or ascending magmas following Devonian–Carboniferous contraction. A second-order episode of contraction may be recorded in our Permian data with a shift in εHf_i from +10 to +3 from c. 295 to 283 Ma. Despite this possible episode of contraction the secular trend is towards increasingly juvenile isotopic values consistent with a major extensional episode throughout the Carboniferous and Permian. However, during this same time period, Thurston Island and the Antarctic Peninsula switched to enriched εHf_i values indicative of ancient lithosphere recycling during contraction and slab advance that continued through the Jurassic (Flowerdew et al., 2007; Riley et al., 2017). We argue that the Permian shift to enriched zircon Hf isotope compositions similar to the Ross Orogeny in Thurston Island and the Antarctic Peninsula is evidence for possible preservation of an ancient lithospheric mantle that avoided foundering. This is further supported by mantle-like zircon oxygen isotope compositions ($\delta^{18}O$ = ~5.3‰) for Permian detrital zircon with enriched Hf isotope compositions ($\varepsilon Hf_i = 0$ to +3) from the Antarctic Peninsula (Castillo et al., 2016). The dramatic difference in zircon Hf isotopes for the Permian and Early Triassic between Marie Byrd Land/central Transantarctic Mountains (juvenile) and those for Thurston Island/Antarctic Peninsula (enriched) reflect an along arc geochemical difference and inferred geodynamic switch as previously postulated by Nelson and Cottle (2017). Our new data indicate that this along arc geodynamic change from extension to contraction was originally established in the early Permian and occurs between Thurston Island and Marie Byrd Land Figs. 6 and 7.

Magmatic rocks of mid-Triassic to mid-Jurassic age are absent from Marie Byrd Land but decreasing zircon εHf_i values from the Permian–Triassic to the mid-Jurassic in detrital zircon from the cTAM may suggest Marie Byrd Land was under contraction or was a stationary arc at that time (Fig. 6). By the Late Jurassic and Cretaceous almost all zircon εHf_i from zircon of West Marie Byrd Land can be explained by melting of juvenile crust formed after the Ross Orogeny (Fig. 6, assuming a Lu/Hf = 0.0115, Rudnick and Gao, 2003). During the Early Cretaceous in western Marie Byrd Land zircon εHf_i undergo a dramatic isotopic pull-down or shift from relatively juvenile, or positive, compositions to highly enriched, or negative (Yakymchuk et al., 2013), signifying an episode of contraction that is also identified by an isotopic pull-down and compressional deformation in Cretaceous granites in the Antarctic Peninsula (Riley et al., 2018). Our new data from eastern Marie Byrd Land also contain a minor isotopic pull-down consistent with contraction followed by extension at c. 100 Ma, similar to that reported for western Marie Byrd Land (e.g., Korhonen et al., 2010). These observations support previous studies that report contraction-related Cretaceous magmatic flare-ups in West Antarctic and Zealandia that likely resulted from major plate reorganization in the late Early Cretaceous (Matthews et al., 2012, 2016; Seton et al., 2012; Milan et al., 2017; Riley et al., 2018).

Eastern Marie Byrd Land again is more juvenile than western Marie Byrd Land, which we attribute to an outboard position for eastern Marie Byrd Land and a history of juvenile magmatism that has either not yet been observed or may not have occurred in western Marie Byrd Land. Therefore, Cretaceous contraction resulted in juvenile mantle melts and juvenile lithospheric recycling in eastern Marie Byrd Land (Chapman et al., 2017). This hypothesis is further supported by evidence for an enriched lithospheric mantle source for Cretaceous magmatism in western Marie Byrd Land (e.g., Saito et al., 2013). Earliest Cretaceous magmatism in western Marie Byrd Land, however, was relatively more juvenile than Devonian–Carboniferous magmatism in western Marie Byrd Land (Yakymchuk et al., 2013, 2015). This juvenile source may have resulted from lithospheric thinning prior to the onset of Cretaceous magmatism in western Marie Byrd Land.

5.2.3. Comparisons with adjacent sectors

New zircon U-Pb and Hf isotope compositions for West Antarctica, combined with previously published values for the Antarctic sector of the paleo-Pacific margin of Gondwana provide the first opportunity to compare the long-term evolution of Antarctica with that of adjacent arc sectors. To do so we compiled, Hf isotope data from igneous and detrital zircon, as well as igneous whole rock Hf isotope data (Fig. 8, see references in caption) separated into two regions, Australia and Zealandia (blue), and South America (red). Zircon Hf isotopes can, however, vary greatly within a single igneous rock sample (>10 εHf_i) and even more so within a given arc, requiring the need for large compilations over extended periods of time (~100 million years or more). Even then, sampling bias, complex arc dynamics and regional variations in magmatic processes and the age of the lithosphere on which the arc was built complicate interpretations. For this reason every attempt has been made to compile data available over a large geographic distribution and for diverse lithologies.

The Pampean Orogeny in South America and the Delamerian Orogeny in Australia are broadly synchronous with the Ross Orogeny of Antarctica and collectively represent the initial pulse of subduction along the paleo-Pacific margin of Gondwana (Cawood, 2005). The first important observation to make for initial subduction-related magmatism along the arc is that the εHf_i values across all of these regions during this period are remarkably similar and enriched. We argue that the isotopic composition of the magmatism in these regions is representative of the ancient lithosphere (specifically enriched mantle lithosphere) upon which these different sectors of the Gondwana margin were built, similar to the interpretation for the origin of Ross Orogeny magmatism (Hagen-Peter et al., 2015; Hagen-Peter and Cottle, 2018). The regional tectonic histories of these sectors may vary but the Hf isotopic record indicates that initial subduction across all segments occurred in a dominantly contractional arc system built on lithosphere with fairly uniform Hf isotope composition. This is an important starting point for the discussion because it provides a single reference frame to evaluate relative changes in Hf isotope composition through time in a single arc sector and also establish variations between different sectors. Significant time-dependent changes in zircon Hf isotope compositions

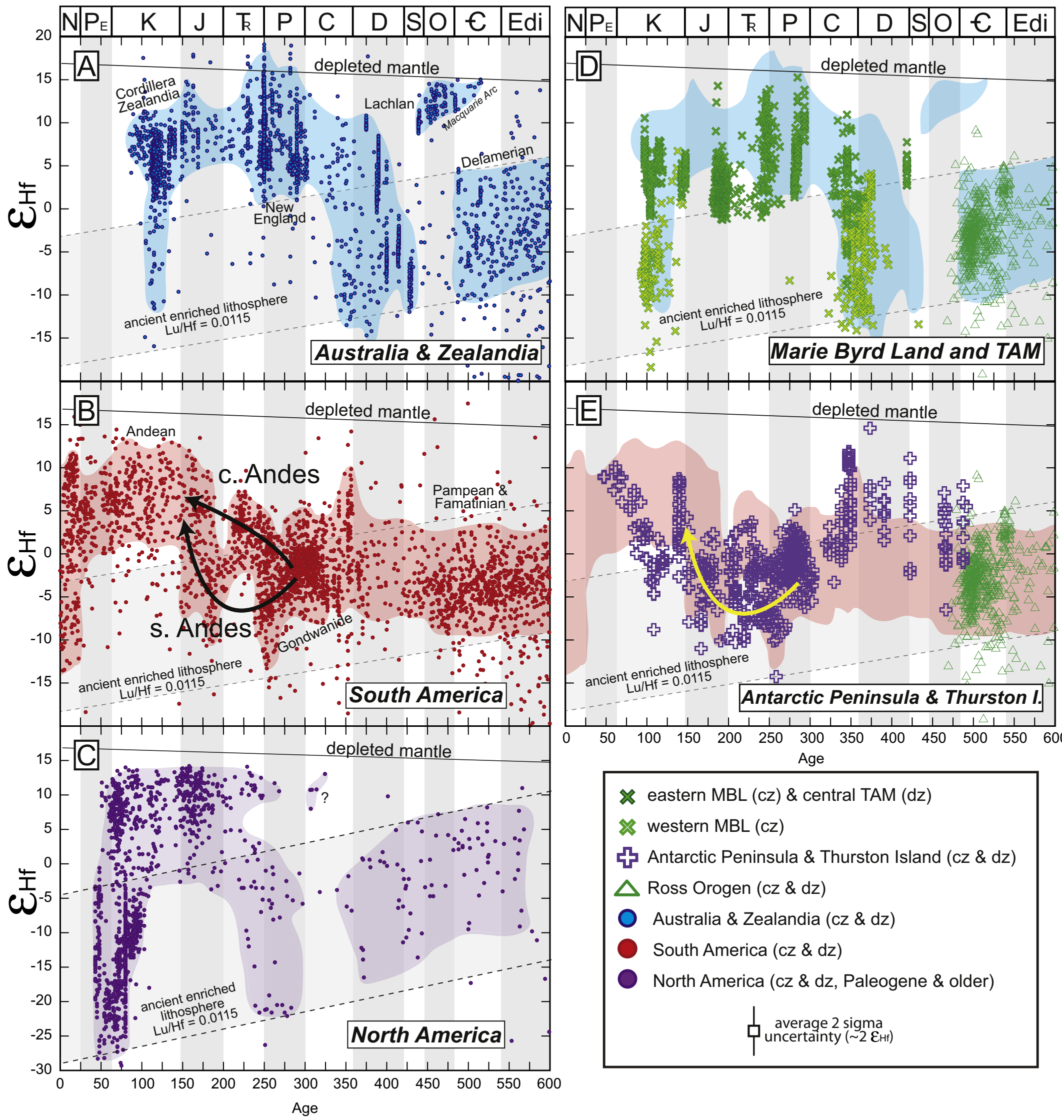

Fig. 8. Compilation of zircon Hf isotope data from (A) Australia–Zealandia (blue), (B) South America (red), and (C) North America (purple) with hand drawn fields to outline dominant geochemical envelopes. Data for Australia–Zealandia are from: Belousova et al. (2005), Kemp et al. (2005), Veevers et al. (2006), Kemp et al. (2007), Murgulov et al. (2007), Nebel et al. (2007), Kemp et al. (2009), Allibone et al. (2009), Nebel-Jacobsen et al. (2011), Phillips et al. (2011), Shaw et al. (2011), Glen et al. (2011), Jeon et al. (2014), Hiess et al. (2015), Li et al. (2015), Purdy et al. (2016), Tucker et al. (2016), Martin et al. (2017), Milan et al. (2017), Schwartz et al. (2017), and Decker et al. (2017). Data from South America are from: Flowerdew et al. (2006), Munizaga et al. (2008), Willner et al. (2008), Bahlburg et al. (2009), Mišković and Schaltegger (2009), Fanning et al. (2011), Bradshaw et al. (2012), Hervé et al. (2013, 2014, 2016), Augustsson et al. (2016), Pankhurst et al. (2016), Pepper et al. (2016), Canile et al. (2016), Castillo et al. (2016, 2017), del Rey et al. (2016), Ortiz et al. (2017), Balgord (2017), and Dahlquist et al. (2018). Data from North America are from: Cecil et al. (2011), Lackey et al. (2012), Gaschnig et al. (2013), Gehrels and Pecha (2014), Garver and Davidson (2015), Barth et al. (2016), and Sauer et al. (2017). Paleozoic and Triassic data from Gehrels and Pecha (2014) are from Triassic strata in British Columbia through Sonora in North America. D and E compare Antarctica data presented in Fig. 6 with compilations from A and B. Dashed lines outline fields of crustal recycling assuming a Lu/Hf = 0.0115 (Rudnick and Gao, 2003). Hf isotopic values for depleted mantle and new crust are from Vervoort and Blichert-Toft (1999). CHUR—chondritic uniform reservoir. CZ refers to crystalline rock zircon and DZ refers to detrital zircon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are therefore most likely a result of geodynamic changes rather than dramatic variations in initial ancient lithospheric Hf composition.

Following initial subduction during the Ross-Delamerian Orogeny at c. 485 Ma the Hf isotope data for Australia and Zealandia reveal a period of juvenile arc formation represented by the Macquarie arc (c. 480–443 Ma) that may have resulted from slab rollback and extension or subduction polarity switch (Aitchison and Buckman, 2012; Rosenbaum, 2018). The termination of the Macquarie arc occurred during a period of persistent contraction from c. 443 to 340 Ma during the Lachlan Orogeny (including contraction in the Thomson and Mossman Orogenies) represented by enriched isotopic compositions that transition to juvenile compositions related to asymmetric slab rollback and extension (Kemp et al., 2009; Rosenbaum, 2018). Progressive slab rollback culminated in a major widespread period of extension in the early Permian (c. 300–270 Ma, Rosenbaum, 2018) corresponding to a dramatic secular shift from enriched isotopic compositions to juvenile isotopic compositions (Kemp et al., 2009). Following major early Permian extension, juvenile isotopic compositions persist during contractional episodes (e.g., Permian Hunter-Bowen Orogeny) excluding a major contractional episode during formation of Cordillera Zealandia in the Cretaceous (e.g., Milan et al., 2017). Extensional collapse this contractional episode may have been responsible for emplacement of voluminous ignimbrite deposits of the Whitsunday Volcanic Province that have uniformly juvenile isotopic compositions (Tucker et al., 2016). Our new data for eastern Marie Byrd Land combined with data from the central Transantarctic Mountains and western Marie Byrd Land share a similar zircon Hf isotopic history and provide strong evidence for a shared geochemical and geodynamic history throughout the

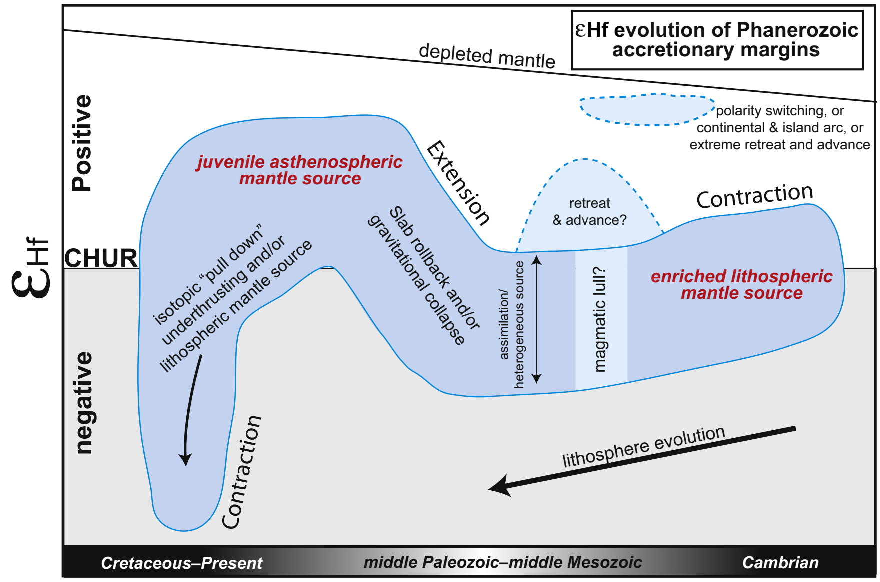

Fig. 9. Generalized zircon Hf isotope evolution curve for Phanerozoic accretionary orogens. All orogens record c. Cambrian magmatism with an enriched lithospheric mantle source and an inferred contractional tectonic regime. Early Paleozoic records vary with episodes of extension and contraction, terrane accretion, magmatic lulls, etc. All orogens, however, undergo a profound isotopic shift from enriched to juvenile compositions during major extensional collapse in the middle Paleozoic to middle Mesozoic that may be caused by plate boundary processes (i.e., slab rollback) and/or internal processes (i.e., gravitational collapse related to root foundering). In the Cretaceous, isotopic pull-downs occur during major contractional episodes.

Phanerozoic for the Australian sector and the Marie Byrd Land and Transantarctic Mountains components of the Antarctic sector (Fig. 9).

In contrast, the South American sector maintains evolved εHf_i values (primarily negative) similar to that of the Pampean Orogeny from the Ordovician to early Permian reflecting crustal recycling in a dominantly advancing or contractional arc system. Limited zircon Hf isotope data from c. 450 to 360 Ma may be associated with a magmatic lull during accretion of exotic terranes or flat slab subduction in the early and middle Paleozoic (Cawood, 2005; Ramos, 2009; Dahlquist et al., 2018). A minor early Carboniferous (c. 359–322 Ma) episode of slab rollback related extension is recorded by a brief increase in the zircon Hf isotope composition (Dahlquist et al., 2018). The most pronounced period of sustained extension in South America's tectonic history, however, occurred from the late Permian to Early Cretaceous (c. 250 to 140 Ma, Horton, 2018 and references therein). This period is considered to include a major extensional collapse of the proto-Andean arc (San Rafael Orogen) attributed to changing convergence rates generating slab rollback (Ramos, 2009) and is recorded in the zircon Hf record of South America as a shift from enriched Hf isotopic compositions to juvenile isotopic compositions (del Rey et al., 2016; Pepper et al., 2016; Balgord, 2017). Importantly, the shift from enriched to juvenile Hf isotopic compositions occurs in the late Permian in the central Andes (del Rey et al., 2016) and the Jurassic in the southern Andes (Pepper et al., 2016; Balgord, 2017; Castillo et al., 2017). Both isotopic and tectonic shifts are contemporaneous with large ignimbrite flare-ups, the Choiyoi Province in the central Andes and the Chon Aike in Patagonia (e.g., Kay et al., 1989; Pankhurst et al., 1998a; Rocha-Campos et al., 2011). When contraction is resumed during the initial stage of arc advancement at c. 100 Ma (Ramos, 2009) the zircon Hf isotopes do not return to enriched compositions. The central Andes do, however, return to ancient lithosphere Hf isotope compositions in the Neogene due to shallow slab subduction and eastward migration of the arc possibly towards regions with more preserved ancient lithospheric mantle (Pepper et al., 2016; Chapman et al., 2017).

The Thurston Island and the Antarctic Peninsula Hf isotope record matches well with the trend for the southern Andes indicating a coupling of these arc segments, particularly that of the Southern Andes. The mismatch between these records in the Ordovician–Devonian suggests these arc segments may have experienced an uncoupling, perhaps caused by regional tectonics in South America such as terrane accretion or flat slab subduction. However the shared zircon Hf isotopic history in the early Permian among Antarctic Peninsula, Thurston Island, and South America highlights a geochemical and inferred geodynamic switch along the entire paleo-Pacific margin from enriched compositions during contraction in South America to depleted compositions during extension in Australia at c. 300–270 Ma. The limited data for in-situ rocks from West Antarctica and Zealandia don't allow us to determine whether this transition is gradual or abrupt but the locus of the switch is constrained to somewhere between Thurston Island and Marie Byrd Land (Fig. 10, Nelson and Cottle, 2017).

5.3. Implications for Phanerozoic accretionary orogens

The Hf isotopic records for the Antarctic, Australian, and South American sectors of the Gondwana margin are different but contain broadly similar patterns. For instance, the Permian to Cretaceous (c. 250 to 140 Ma) record of extension in South America is comparable to extension and the isotopic shift observed from c. 430 to 270 Ma in Australia, Zealandia, and Antarctica. Evidence for the propagation of major extension along the Gondwana margin has also been documented using zircon Th/U (McKay et al., 2018). Together these periods of extension in which the continental arc shifts to persistently juvenile isotopic compositions exemplify the process of lithosphere rejuvenation and continental crustal growth characteristic of accretionary orogens (Collins et al., 2011). Our compilation indicates that lithosphere rejuvenation along the Gondwana margin is not necessarily an ongoing process that occurred progressively throughout the Phanerozoic but instead occurred during episodes of major extensional orogenic collapse.

Regional models for extensional orogenic collapse invoke plate boundary processes, i.e., slab rollback (e.g., Kemp et al., 2009; del Rey et al., 2016; Mckibbin et al., 2017), as the driving mechanism. In the Chilean Frontal Andes, however, the shift from enriched to juvenile magmatism (c. 300 to 250 Ma) does not correlate with an outboard migration of arc magmatism that may be expected for slab rollback (Aitchison and Buckman, 2012; del Rey et al., 2016). Numerous models for extensional collapse of other active margins have been suggested as alternatives to slab rollback including slab detachment and lithospheric removal (i.e., foundering) (e.g., Platt et al., 2003). Slab detachment may be unlikely to produce a secular change to juvenile isotopic compositions considering it is often associated with a shallowing of the subducting slab that may lead to contraction (Haschke et al., 2002). In South America, persistently enriched zircon Hf isotopes related to prolonged lithospheric melting during contraction throughout most of the Paleozoic, a shift to juvenile isotopic compositions without outboard arc migration, and the presence of ignimbrite flare-ups during extensional collapse, could be evidence of ancient catastrophic root removal (Dewey, 1988; Decelles et al., 2009). Collins et al. (2011) considered lithospheric mantle removal to occur in the backarc due to mantle flow-induced gravitational instability of a normal thickness lithosphere (Currie et al., 2008). However, the fate of overthickened dense arc roots and their relationship to secular evolution of continental margins remains underexplored. We speculate that catastrophic root foundering may have played a critical role in major extensional collapse episodes of the middle Paleozoic to middle Mesozoic in Antarctica, Australia, and South America.

There is the possibility that slab rollback may induce lithospheric mantle foundering or vice-a-versa. For instance, slab rollback could create a step change in density between mantle lithosphere and upwelling asthenosphere that may trigger gravitational instability (Stern et al., 2013). Ramos (2009) described extensional collapse of an Andean-type orogenic cycle as an initial period of slab rollback followed by lithospheric root removal. In contrast, the model of extensional collapse driven initially by lithosphere removal, gravitational forces, and an elevated thermal gradient may occur independent of or be enhanced by subsequent plate boundary driven extension (Dewey, 1988; Lister and Forster, 2009). There remains no clear distinction between the roles of plate boundary and internal processes during major middle Paleozoic–middle Mesozoic lithospheric rejuvenation of Phanerozoic accretionary orogens that limits our understanding of the secular evolution of accretionary orogens (Collins et al., 2011).

There are numerous possible explanations for why South America and Antarctica and Australia underwent major extensional collapse and lithosphere rejuvenation at different times. In the case of changing plate boundary processes extensional collapse is dependent on the timing of major plate reorganization and the absolute motion of Gondwana (and Pangea) that established varied convergence rates along the Gondwana margin (Lallemand et al., 2005; Matthews et al., 2016; Riel et al., 2018). If catastrophic root foundering is responsible for extensional collapse then differences in the timing of extension would have been controlled primarily by magma addition rates and the rheology of the arc root and mantle that may have varied along the margin (Behn et al., 2007; Currie et al., 2015).

Our evaluation of the zircon Hf isotope record of Gondwana margin identifies broad characteristics of the secular evolution of accretionary orogens through geologic time. Initial subduction along the entire paleo-Pacific margin of Gondwana was well established by the Cambrian and occurred during contraction with an enriched lithospheric mantle source and high amounts of supracrustal assimilation. The early to middle Paleozoic history is fairly complicated for all segments of the Gondwana margin with short-term or second-order processes occurring such as possible polarity switching, retreat and advance, terrane accretion, etc., however, the first-order secular evolution of the arc chemistry maintains an enriched composition due to melting of ancient lithosphere. During the middle Paleozoic to middle Mesozoic the entire Gondwana margin undergoes a major segmented extensional collapse perhaps caused by slab rollback and/or catastrophic root foundering that begins a secular shift in arc geochemistry towards more juvenile compositions. As contraction is reestablished the arc maintains a juvenile composition except during major magma flare-ups associated with underthrusting, shallow subduction, and/or arc advancement (i.e., isotopic pulldowns). Importantly, this secular isotopic evolution is also observed in a compilation of zircon Hf isotopes from the western margin of North America indicating that a global change in external plate boundary forces during the middle Paleozoic to middle Mesozoic and/or gravity driven catastrophic extensional collapse is an inherent result of over thickened accretionary orogens.

6. Conclusions

Zircon geochronology and Hf isotope compositions of magmatic rocks in eastern Marie Byrd Land and Thurston Island provide new constraints on the age and geochemical development of West Antarctica. Both eastern Marie Byrd Land and Thurston Island record crustal growth and extension from the termination of the Ross Orogeny through to the Carboniferous. In eastern Marie Byrd Land, extension may have initiated in the early Carboniferous and continued until the Permian–Triassic following Late Devonian contraction documented in Forge Ranges of western Marie Byrd Land. A switch to contraction is indicated by more negative zircon εHf_i through the Cretaceous in the central Transantarctic Mountains and western Marie Byrd Land. In contrast, Thurston Island switched to enriched εHf_i values and contraction in early Permian through Jurassic time followed by an increase in εHf_i and extension in the Cretaceous.

Comparing these records to zircon Hf isotope compilations from adjacent sectors of the arc demonstrates a shared geochemical and tectonic history for Marie Byrd Land, Australia, and Zealandia that contrasts with the history of Thurston Island, the Antarctic Peninsula, and South America. Our compilation also demonstrates the presence of a significant along arc geochemical and inferred geodynamic switch from enriched isotopic compositions and contraction in South America, the Antarctic Peninsula, and Thurston Island to depleted isotopic compositions and extension in Marie Byrd Land during the early Permian. This variation highlights the difference in timing of major extensional collapse and lithospheric rejuvenation between Australia and Marie Byrd Land (c. 430–270) and South America (c. 250–140) that is evidenced by a shift to persistent juvenile zircon Hf isotopic compositions during these times. Plate boundary processes related to plate reconfiguration (e.g., slab rollback) and/or internal processes (e.g., lithospheric foundering, gravitational collapse, and heating) may have driven extensional collapse and lithospheric rejuvenation of Phanerozoic accretionary orogens. We conclude that Phanerozoic accretionary orogens have undergone comparable secular Hf isotope evolutionary histories.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2018.06.002.

Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1650114 and support from NSF—ANT–1443296, NSF–ANT–1043152. This research used samples and/or data provided by the Polar Rock Repository (PRR). The PRR is sponsored by the National Science Foundation Office of Polar Programs. We are grateful to Anne Grunow and the PRR for providing samples and assisting with sample selection. We also acknowledge the original sample collectors: C. Craddock, I. Dalziel, V. DiVenere, P. Schmidt, B. Sporli, and C. White. Special thanks to S. Mukasa and F. Fahnestock for providing zircon separates. Constructive reviews from M. McKay and two anonymous reviewers greatly improved this manuscript. Additional analytical details and data tables are available in the Supplementary information and datasets.

References

Aitchison, J.C., Buckman, S., 2012. Accordion vs. quantum tectonics: insights into continental growth processes from the Paleozoic of eastern Gondwana. Gondwana Research 22:674–680. https://doi.org/10.1016/j.gr.2012.05.013.

Allibone, A.H., Jongens, R., Scott, J.M., Tulloch, A.J., Turnbull, I.M., Cooper, A.F., Powell, N.G., Ladley, E.B., King, R.P., Rattenbury, M.S., 2009. Plutonic rocks of the Median Batholith in eastern and central Fiordland, New Zealand: field relations, geochemistry, correlation, and nomenclature. New Zealand Journal of Geology and Geophysics 52: 101–148. https://doi.org/10.1080/00288300909509882.

Andersen, T., 2002. Correction of common lead in U–Pb analyses that do not report 204Pb. Chemical Geology 192:59–79. https://doi.org/10.1016/S0009-2541(02)00195-X.
Augustsson, C., Willner, A.P., Rüsing, T., Niemeyer, H., Gerdes, A., Adams, C.J., Miller, H., 2016. The crustal evolution of South America from a zircon Hf-isotope perspective. Terra Nova 28:128–137. https://doi.org/10.1111/ter.12200.
Bahlburg, H., Vervoort, J.D., Du Frane, S.A., Bock, B., Augustsson, C., Reimann, C., 2009. Timing of crust formation and recycling in accretionary orogens: insights learned from the western margin of South America. Earth-Science Reviews 97:215–241. https://doi.org/10.1016/j.earscirev.2009.10.006.
Balgord, E.A., 2017. Triassic to Neogene evolution of the south-central Andean arc determined by detrital zircon U-Pb and Hf analysis of Neuquén Basin strata, central Argentina (34°S–40°S). Lithosphere 9:453–462. https://doi.org/10.1130/L546.1.
Barth, A.P., Wooden, J.L., Mueller, P.A., Economos, R.C., 2016. Granite provenance and intrusion in arcs: evidence from diverse zircon types in Big Bear Lake Intrusive Suite, USA. Lithos 246–247:261–278. https://doi.org/10.1016/j.lithos.2015.12.009.
Behn, M.D., Hirth, G., Kelemen, P.B., 2007. Trench-parallel anisotropy produced by foundering of arc lower crust. Science 317:108–111. https://doi.org/10.1126/science.1141269.
Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., 2005. Zircon crystal morphology, trace element signatures and Hf isotope composition as a tool for petrogenetic modelling: examples from Eastern Australian granitoids. Journal of Petrology 47:329–353. https://doi.org/10.1093/petrology/egi077.
Blichert-Toft, J., 2008. The Hf isotopic composition of zircon reference material 91500. Chemical Geology 253:252–257. https://doi.org/10.1016/j.chemgeo.2008.05.014.
Borg, S.G., Stump, E., Holloway, J.R., 1986. Granitoids of Northern Victoria Land, Antarctica: A Reconnaissance Study of Field Relations, Petrography, and Geochemistry. :pp. 115–188 https://doi.org/10.1029/AR046p0115.
Bouvier, A., Vervoort, J.D., Patchett, P.J., 2008. The Lu-Hf and Sm-Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. Earth and Planetary Science Letters 273:48–57. https://doi.org/10.1016/j.epsl.2008.06.010.
Bradshaw, J.D., Vaughan, a.P.M., Millar, I.L., Flowerdew, M.J., Trouw, R.a.J., Fanning, C.M., Whitehouse, M.J., 2012. Permo-Carboniferous conglomerates in the Trinity Peninsula Group at View Point, Antarctic Peninsula: sedimentology, geochronology and isotope evidence for provenance and tectonic setting in Gondwana. Geological Magazine 149:626–644. https://doi.org/10.1017/S001675681100080X.
Brown, C.R., Yakymchuk, C., Brown, M., Fanning, C.M., Korhonen, F.J., Piccoli, P.M., Siddoway, C.S., 2016. From source to sink: petrogenesis of Cretaceous anatectic granites from the Fosdick Migmatite–Granite Complex, West Antarctica. Journal of Petrology 57:1241–1278. https://doi.org/10.1093/petrology/egw039.
Burgess, S.D., Bowring, S.A., Fleming, T.H., Elliot, D.H., 2015. High-precision geochronology links the Ferrar large igneous province with early-Jurassic ocean anoxia and biotic crisis. Earth and Planetary Science Letters 415:90–99. https://doi.org/10.1016/j.epsl.2015.01.037.
Canile, F.M., Babinski, M., Rocha-Campos, A.C., 2016. Evolution of the Carboniferous-Early Cretaceous units of Paraná Basin from provenance studies based on U-Pb, Hf and O isotopes from detrital zircons. Gondwana Research 40:142–169. https://doi.org/10.1016/j.gr.2016.08.008.
Cao, W., Lee, C.-T.A., Lackey, J.S., 2017. Episodic nature of continental arc activity since 750 Ma: a global compilation. Earth and Planetary Science Letters 461:85–95. https://doi.org/10.1016/J.EPSL.2016.12.044.
Castillo, P., Fanning, C.M., Hervé, F., Lacassie, J.P., 2016. Characterisation and tracing of Permian magmatism in the south-western segment of the Gondwanan margin; U–Pb age, Lu–Hf and O isotopic compositions of detrital zircons from metasedimentary complexes of northern Antarctic Peninsula and western Patagonia. Gondwana Research 36:1–13. https://doi.org/10.1016/j.gr.2015.07.014.
Castillo, P., Fanning, C.M., Pankhurst, R.J., Hervé, F., Rapela, C., 2017. Zircon O- and Hf-isotope constraints on the genesis and tectonic significance of Permian magmatism in Patagonia. Journal of the Geological Society of London 174:803–816. https://doi.org/10.1144/jgs2016-152.
Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. Earth-Science Reviews 69:249–279. https://doi.org/10.1016/j.earscirev.2004.09.001.
Cawood, P.A., Buchan, C., 2007. Linking accretionary orogenesis with supercontinent assembly. Earth-Science Reviews 82:217–256. https://doi.org/10.1016/j.earscirev.2007.03.003.
Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009. Accretionary orogens through Earth history. Geological Society of London, Special Publication 318:1–36. https://doi.org/10.1144/SP318.1.
Cawood, P.A., Leitch, E.C., Merle, R.E., Nemchin, A.A., 2011. Orogenesis without collision: stabilizing the terra australis accretionary Orogen, Eastern Australia. Bulletin Geological Society of America 123:2240–2255. https://doi.org/10.1130/B30415.1.
Cecil, M.R., Gehrels, G., Ducea, M.N., Patchett, P.J., 2011. U-Pb-Hf characterization of the central Coast Mountains batholith: implications for petrogenesis and crustal architecture. Lithosphere 3:247–260. https://doi.org/10.1130/L134.1.
Chapman, J.B., Ducea, M.N., Kapp, P., Gehrels, G.E., Decelles, P.G., 2017. Spatial and temporal radiogenic isotopic trends of magmatism in Cordilleran orogens. Gondwana Research 48:189–204. https://doi.org/10.1016/J.GR.2017.04.019.
Chappell, B.W., White, A.J.R., Hine, R., 1988. Granite provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. Australian Journal of Earth Sciences 35:505–521. https://doi.org/10.1080/08120098808729466.
Chu, N.-C., Taylor, R.N., Chavagnac, V., Nesbitt, R.W., Boella, R.M., Milton, J.A., German, C.R., Bayon, G., Burton, K., 2002. Hf isotope ratio analysis using multi-collector inductively coupled plasma mass spectrometry: an evaluation of isobaric interference corrections. Journal of Analytical Atomic Spectrometry 17:1567–1574. https://doi.org/10.1039/b206707b.
Collins, W.J., 2002a. Hot orogens, tectonic switching, and creation of continental crust. Geology 30:535–538. https://doi.org/10.1130/0091-7613(2002)030<0535:HOTSAC>2.0.CO;2.
Collins, W.J., 2002b. Nature of extensional accretionary orogens. Tectonics 21:6-1–6-12. https://doi.org/10.1029/2000TC001272.
Collins, W.J., Belousova, E.A., Kemp, A.I.S., Murphy, J.B., 2011. Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data. Nature Geoscience 4:333–337. https://doi.org/10.1038/ngeo1127.
Cox, S.C., Parkinson, D.L., Allibone, A.H., Cooper, A.F., 2000. Isotopic character of Cambro-Ordovician plutonism, southern Victoria Land, Antarctica. New Zealand Journal of Geology and Geophysics 43:501–520. https://doi.org/10.1080/00288306.2000.9514906.
Craddock, J.P., Schmitz, M.D., Crowley, J.L., Larocque, J., Pankhurst, R.J., Juda, N., Konstantinou, A., Storey, B., 2017. Precise U-Pb zircon ages and geochemistry of Jurassic granites, Ellsworth-Whitmore terrane, central Antarctica. Geological Society of America Bulletin 129:118–136. https://doi.org/10.1130/B31485.1.
Crawford, A., 2003. 120 to 0 Ma tectonic evolution of the southwest Pacific and analogous geological evolution of the 600 to 220 Ma Tasman Fold Belt System. Special Publication. Geological Society of Australia 22:377–397. https://doi.org/10.1130/0-8137-2372-8.383.
Currie, C.A., Huismans, R.S., Beaumont, C., 2008. Thinning of continental backarc lithosphere by flow-induced gravitational instability. Earth and Planetary Science Letters 269:436–447. https://doi.org/10.1016/J.EPSL.2008.02.037.
Currie, C.A., Ducea, M.N., Decelles, P.G., Beaumont, C., 2015. Geodynamic models of Cordilleran orogens: gravitational instability of magmatic arc roots. Geological Society of America Memoirs 212:1–22. https://doi.org/10.1130/2015.1212(01).
Dahlquist, J.A., Alasino, P.H., Basei, M.A.S., Morales Cámera, M.M., Macchioli Grande, M., da Costa Campos Neto, M., 2018. Petrological, geochemical, isotopic, and geochronological constraints for the Late Devonian–Early Carboniferous magmatism in SW Gondwana (27–32°LS): an example of geodynamic switching. International Journal of Earth Sciences:1–29 https://doi.org/10.1007/s00531-018-1615-9.
Dalziel, I.W.D., Elliot, D.H., 1982. West Antarctica: problem child of Gondwanaland. Tectonics 1:3–19. https://doi.org/10.1029/TC001i001p00003.
Decelles, P.G., Ducea, M.N., Kapp, P., Zandt, G., 2009. Cyclicity in Cordilleran orogenic systems. Nature Geoscience 2:251–257. https://doi.org/10.1038/ngeo469.
Decker, M., Schwartz, J.J., Stowell, H.H., Klepeis, K.A., Tulloch, A.J., Kitajima, K., Valley, J.W., Kylander-Clark, A.R.C., 2017. Slab-triggered arc flare-up in the Cretaceous median batholith and the growth of lower arc crust, Fiordland, New Zealand. Journal of Petrology 58:1145–1171. https://doi.org/10.1093/petrology/egx049.
del Rey, A., Deckart, K., Arriagada, C., Martínez, F., 2016. Resolving the paradigm of the late Paleozoic–Triassic Chilean magmatism: isotopic approach. Gondwana Research 37:172–181. https://doi.org/10.1016/j.gr.2016.06.008.
Dewey, J.F., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1139.
DiVenere, V., Kent, D.V., Dalziel, I.W.D., 1995. Early Cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica: implications for the Weddellia collage of crustal blocks. Journal of Geophysical Research - Solid Earth 100:8133–8151. https://doi.org/10.1029/95JB00042.
Echaurren, A., Oliveros, V., Folguera, A., Ibarra, F., Creixell, C., Lucassen, F., 2017. Early Andean tectonomagmatic stages in north Patagonia: insights from field and geochemical data. Journal of the Geological Society of London 174:405–421. https://doi.org/10.1144/jgs2016-087.
Elliot, D.H., 2013. The geological and tectonic evolution of the Transantarctic Mountains: a review. Geological Society of London, Special Publication 381:7–35. https://doi.org/10.1144/SP381.14.
Elliot, D.H., Fanning, C.M., 2008. Detrital zircons from upper Permian and lower Triassic Victoria Group sandstones, Shackleton Glacier region, Antarctica: evidence for multiple sources along the Gondwana plate margin. Gondwana Research 13:259–274. https://doi.org/10.1016/j.gr.2007.05.003.
Elliot, D.H., Larsen, D., Fanning, C.M., Fleming, T.H., Vervoort, J.D., 2016. The Lower Jurassic Hanson Formation of the Transantarctic Mountains: implications for the Antarctic sector of the Gondwana plate margin. Geological Magazine 154:777–803. https://doi.org/10.1017/S0016756816000388.
Elliot, D.H., Fanning, C.M., Isbell, J.L., Hulett, S.R.W., 2017. The Permo-Triassic Gondwana sequence, central Transantarctic Mountains, Antarctica: zircon geochronology, provenance, and basin evolution. Geosphere 13:155–178. https://doi.org/10.1130/GES01345.1.
Elsner, M., Schöner, R., Gerdes, A., Gaupp, R., 2013. Reconstruction of the early Mesozoic plate margin of Gondwana by U–Pb ages of detrital zircons from northern Victoria Land, Antarctica. Geological Society of London, Special Publication 383:211–232. https://doi.org/10.1144/SP383.5.
Encarnación, J., Fleming, T.H., Elliot, D.H., Eales, H.V., 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana. Geology 24:535–538. https://doi.org/10.1130/0091-7613(1996)024<0535.
Fanning, C.M., Hervé, F., Pankhurst, R.J., Rapela, C.W., Kleiman, L.E., Yaxley, G.M., Castillo, P., 2011. Lu–Hf isotope evidence for the provenance of Permian detritus in accretionary complexes of western Patagonia and the northern Antarctic Peninsula region. Journal of South American Earth Sciences 32:485–496. https://doi.org/10.1016/j.jsames.2011.03.007.
Flowerdew, M.J., Millar, I.L., Vaughan, A.P.M., Horstwood, M.S.A., Fanning, C.M., 2006. The source of granitic gneisses and migmatites in the Antarctic Peninsula: a combined U–Pb SHRIMP and laser ablation Hf isotope study of complex zircons. Contributions to Mineralogy and Petrology 151:751–768. https://doi.org/10.1007/s00410-006-0091-6.
Flowerdew, M.J., Millar, I.L., Curtis, M.L., Vaughan, A.P.M., Horstwood, M.S.A., Whitehouse, M.J., Fanning, C.M., 2007. Combined U-Pb geochronology and Hf isotope geochemistry of detrital zircons from early Paleozoic sedimentary rocks, Ellsworth-Whitmore Mountains block, Antarctica. Bulletin Geological Society of America 119:275–288. https://doi.org/10.1130/B25891.1.

Foden, J., Elburg, M.A., Dougherty-Page, J., Burtt, A., 2006. The timing and duration of the Delamerian orogeny: correlation with the Ross Orogen and implications for Gondwana Assembly. Journal of Geology 114:189–210. https://doi.org/10.1086/499570.

Foster, D.A., Gray, D.R., Spaggiari, C., Kamenov, G., Bierlein, F.P., 2009. Palaeozoic Lachlan orogen, Australia; accretion and construction of continental crust in a marginal ocean setting: isotopic evidence from Cambrian metavolcanic rocks. Geological Society of London, Special Publication 318:329–349. https://doi.org/10.1144/SP318.12.

Fretwell, P., Pritchard, H.D., Vaughan, D.G., Bamber, J.L., Barrand, N.E., Bell, R., Bianchi, C., Bingham, R.G., Blankenship, D.D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A.J., Corr, H.F.J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J.A., Hindmarsh, R.C.A., Holmlund, P., Holt, J.W., Jacobel, R.W., Jenkins, A., Jokat, W., Jordan, T., King, E.C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K.A., Leitchenkov, G., Leuschen, C., Luyendyk, B.P., Matsuoka, K., Mouginot, J., Nitsche, F.O., Nogi, Y., Nost, O.A., Popov, S.V., Rignot, E., Rippin, D.M., Rivera, A., Roberts, J., Ross, N., Siegert, M.J., Smith, A.M., Steinhage, D., Studinger, M., Sun, B., Tinto, B.K., Welch, B.C., Wilson, D., Young, D.A., Xiangbin, C., Zirizzotti, A., 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. The Cryosphere 7:375–393. https://doi.org/10.5194/tc-7-375-2013.

Garver, J.I., Davidson, C.M., 2015. Southwestern Laurentian zircons in Upper Cretaceous flysch of the Chugach-Prince William terrane in Alaska. American Journal of Science 315:537–556. https://doi.org/10.2475/06.2015.02.

Gaschnig, R.M., Vervoort, J.D., Lewis, R.S., Tikoff, B., 2013. Probing for Proterozoic and Archean crust in the northern U.S. Cordillera with inherited zircon from the Idaho batholith. Geological Society of America Bulletin 125:73–88. https://doi.org/10.1130/B30583.1.

Gehrels, G., Pecha, M., 2014. Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America. Geosphere 10:49. https://doi.org/10.1130/GES00889.1.

Gibson, G.M., Champion, D.C., Ireland, T.R., 2015. Preservation of a fragmented late Neoproterozoic-earliest Cambrian hyper-extended continental-margin sequence in the Australian Delamerian Orogen. Geological Society of London, Special Publication:269–299 https://doi.org/10.1144/SP413.8.

Glen, R.A., Saeed, A., Quinn, C.D., Griffin, W.L., 2011. U–Pb and Hf isotope data from zircons in the Macquarie Arc, Lachlan Orogen: implications for arc evolution and Ordovician palaeogeography along part of the east Gondwana margin. Gondwana Research 19: 670–685. https://doi.org/10.1016/j.gr.2010.11.011.

Goodge, J.W., Fanning, C.M., 2016. Mesoarchean and Paleoproterozoic history of the Nimrod Complex, central Transantarctic Mountains, Antarctica: stratigraphic revisions and relation to the Mawson Continent in East Gondwana. Precambrian Research 285:242–271. https://doi.org/10.1016/j.precamres.2016.09.001.

Goodge, J.W., Fanning, C.M., Norman, M.D., Bennett, V.C., 2012. Temporal, isotopic and spatial relations of early paleozoic gondwana-margin arc magmatism, Central Transantarctic Mountains, Antarctica. Journal of Petrology 53:2027–2065. https://doi.org/10.1093/petrology/egs043.

Grunow, A.M., Kent, D.V., Dalziel, I.W.D., 1987. Mesozoic evolution of West Antarctica and the Weddell Sea Basin: new paleomagnetic constraints. Earth and Planetary Science Letters 86:16–26. https://doi.org/10.1016/0012-821X(87)90184-1.

Hacker, B.R., Kelemen, P.B., Behn, M.D., 2011. Differentiation of the continental crust by relamination. Earth and Planetary Science Letters 307:501–516. https://doi.org/10.1016/J.EPSL.2011.05.024.

Hagen-Peter, G., Cottle, J., 2018. Evaluating the relative roles of crustal growth versus reworking through continental arc magmatism: a case study from the Ross orogen, Antarctica. Gondwana Research 55:153–166. https://doi.org/10.1016/j.gr.2017.11.006.

Hagen-Peter, G., Cottle, J.M., Tulloch, A.J., Cox, S.C., 2015. Mixing between enriched lithospheric mantle and crustal components in a short-lived subduction-related magma system, Dry Valleys area, Antarctica: insights from U-Pb geochronology, Hf isotopes, and whole-rock geochemistry. Lithosphere 7:174–188. https://doi.org/10.1130/L384.1.

Hagen-Peter, G., Cottle, J.M., Smit, M., Cooper, A.F., 2016. Coupled garnet Lu-Hf and monazite U-Pb geochronology constrain early convergent margin dynamics in the Ross orogen, Antarctica. Journal of Metamorphic Geology 34:293–319. https://doi.org/10.1111/jmg.12182.

Handler, M.R., Wysoczanski, R.J., Gamble, J.A., 2003. Proterozoic lithosphere in Marie Byrd Land, West Antarctica: Re–Os systematics of spinel peridotite xenoliths. Chemical Geology 196:131–145. https://doi.org/10.1016/S0009-2541(02)00410-2.

Haschke, M.R., Scheuber, E., Gunther, A., Reutter, K.-J., 2002. Evolutionary cycles during the Andean orogeny: repeated slab breakoff and flat subduction? Terra Nova 14: 49–55. https://doi.org/10.1046/j.1365-3121.2002.00387.x.

Hervé, F., Miller, H., Pimpirev, C., 2006. Patagonia — Antarctica connections before Gondwana break-up. Antarctica. Springer-Verlag, Berlin/Heidelberg:pp. 217–227 https://doi.org/10.1007/3-540-32934-X_26.

Hervé, F., Calderón, M., Fanning, C.M., Pankhurst, R.J., Godoy, E., 2013. Provenance variations in the Late Paleozoic accretionary complex of central Chile as indicated by detrital zircons. Gondwana Research 23:1122–1135. https://doi.org/10.1016/J.GR.2012.06.016.

Hervé, F., Fanning, C.M., Calderón, M., Mpodozis, C., 2014. Early Permian to Late Triassic batholiths of the Chilean Frontal Cordillera (28°–31°S): SHRIMP U-Pb zircon ages and Lu-Hf and O isotope systematics. Lithos 184–187:436–446. https://doi.org/10.1016/j.lithos.2013.10.018.

Hervé, F., Calderon, M., Fanning, C.M., Pankhurst, R.J., Fuentes, F., Rapela, C.W., Correa, J., Quezada, P., Marambio, C., 2016. Devonian magmatism in the accretionary complex of southern Chile. Journal of the Geological Society of London 173:587–602. https://doi.org/10.1144/jgs2015-163.

Hiess, J., Yi, K., Woodhead, J., Ireland, T., Rattenbury, M., 2015. Gondwana margin evolution from zircon REE, O and Hf signatures of Western Province gneisses, Zealandia. Geological Society of London, Special Publication 389:323–353. https://doi.org/10.1144/SP389.10.

Horton, B.K., 2018. Sedimentary Record of Andean Mountain Building. https://doi.org/10.1016/j.earscirev.2017.11.025.

Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. Chemical Geology 211:47–69. https://doi.org/10.1016/j.chemgeo.2004.06.017.

Jeon, H., Williams, I.S., Bennett, V.C., 2014. Uncoupled O and Hf isotopic systems in zircon from the contrasting granite suites of the New England Orogen, eastern Australia: implications for studies of Phanerozoic magma genesis. Geochimica et Cosmochimica Acta 146:132–149. https://doi.org/10.1016/j.gca.2014.09.042.

Kay, S.M., Ramos, V.A., Mpodozis, C., Sruoga, P., 1989. Late Paleozoic to Jurassic silicic magmatism at the Gondwana margin: analogy to the Middle Proterozoic in North America? Geology 17:324. https://doi.org/10.1130/0091-7613(1989)017<0324:LPTJSM>2.3.CO;2.

Kemp, A.I.S., Wormald, R.J., Whitehouse, M.J., Price, R.C., 2005. Hf isotopes in zircon reveal contrasting sources and crystallization histories for alkaline to peralkaline granites of Temora, southeastern Australia. Geology 33:797. https://doi.org/10.1130/G21706.1.

Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt, J.M., Gray, C.M., Whitehouse, M.J., 2007. Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon. Science (80-.) 315.

Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M., Blevin, P.L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: the Tasmanides, eastern Australia. Earth and Planetary Science Letters 284:455–466. https://doi.org/10.1016/j.epsl.2009.05.011.

Korhonen, F.J., Saito, S., Brown, M., Siddoway, C.S., Day, J.M.D., 2010. Multiple generations of granite in the Fosdick Mountains, Marie Byrd Land, West Antarctica: implications for polyphase intracrustal differentiation in a continental margin setting. Journal of Petrology 51:627–670. https://doi.org/10.1093/petrology/egp093.

Korhonen, F.J., Brown, M., Grove, M., Siddoway, C.S., Baxter, E.F., Inglis, J.D., 2012. Separating metamorphic events in the Fosdick migmatite-granite complex, West Antarctica. Journal of Metamorphic Geology 30:165–192. https://doi.org/10.1111/j.1525-1314.2011.00961.x.

Kylander-Clark, A.R.C., 2017. Petrochronology by laser-ablation inductively coupled plasma mass spectrometry. Reviews in Mineralogy and Geochemistry 83:183–198. https://doi.org/10.2138/rmg.2017.83.6.

Lackey, J.S., Cecil, M.R., Windham, C.J., Frazer, R.E., Bindeman, I.N., 2012. The Fine Gold Intrusive Suite: the roles of basement terranes and magma source development in the Early Cretaceous Sierra Nevada batholith. Geosphere 8:292. https://doi.org/10.1130/GES00745.1.

Lallemand, S., Heuret, A., Boutelier, D., 2005. On the relationships between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones. Geochemistry, Geophysics, Geosystems 6. https://doi.org/10.1029/2005GC000917 (n/a-n/a).

Leat, P.T., Storey, B.C., Pankhurst, R.J., 1993. Geochemistry of Palaeozoic–Mesozoic Pacific rim orogenic magmatism, Thurston Island area, West Antarctica. Antarctic Science 5: 281–296. https://doi.org/10.1017/S0954102093000380.

Lee, C.-T.A., Anderson, D.L., 2015. Continental crust formation at arcs, the arclogite "delamination" cycle, and one origin for fertile melting anomalies in the mantle. Scientific Bulletin 60:1141–1156. https://doi.org/10.1007/s11434-015-0828-6.

Li, P., Rosenbaum, G., Yang, J.-H., Hoy, D., 2015. Australian-derived detrital zircons in the Permian-Triassic Gympie terrane (eastern Australia): evidence for an autochthonous origin. Tectonics 34:858–874. https://doi.org/10.1002/2015TC003829.

Lister, G., Forster, M., 2009. Tectonic mode switches and the nature of orogenesis. Lithos 113:274–291. https://doi.org/10.1016/j.lithos.2008.10.024.

Ludwig, K.R., 2003. User's manual for Isoplot/EX, version 3.0, a geochronological toolkit for Microsoft Excel. Berkeley Geochronol. Cent. Spec. Publ. 4.

Luyendyk, B., Cisowski, S., Smith, C., Richard, S., Kimbrough, D., 1996. Paleomagnetic study of the northern Ford Ranges, western Marie Byrd Land, West Antarctica: motion between West and East Antarctica. Tectonics 15:122–141. https://doi.org/10.1029/95TC02524.

Martin, E.L., Collins, W.J., Kirkland, C.L., 2017. An Australian source for Pacific-Gondwanan zircons: implications for the assembly of northeastern Gondwana. Geology 45, G39152.1. https://doi.org/10.1130/G39152.1.

Matthews, K.J., Seton, M., Müller, R.D., 2012. A global-scale plate reorganization event at 105−100Ma. Earth and Planetary Science Letters 355–356:283–298. https://doi.org/10.1016/j.epsl.2012.08.023.

Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, R.D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic. Global and Planetary Change 146:226–250. https://doi.org/10.1016/j.gloplacha.2016.10.002.

McKay, M.P., Jackson, W.T., Hessler, A.M., 2018. Tectonic stress regime recorded by zircon Th/U. Gondwana Research 57:1–9. https://doi.org/10.1016/j.gr.2018.01.004.

McKenzie, N.R., Horton, B.K., Loomis, S.E., Stockli, D.F., Planavsky, N.J., Lee, C.-T.A., 2016. Continental arc volcanism as the principal driver of icehouse-greenhouse variability. Science (80-.) 352:444–447. https://doi.org/10.1126/science.aad5787.

Mckibbin, S.J., Landenberger, B., Fanning, C.M., 2017. First magmatism in the New England Batholith, Australia: forearc and arc–back-arc components in the Bakers Creek Suite gabbros. Solid Earth 8:421–434. https://doi.org/10.5194/se-8-421-2017.

McKinney, S.T., Cottle, J.M., Lederer, G.W., 2015. Evaluating rare earth element (REE) mineralization mechanisms in Proterozoic gneiss, Music Valley, California. Geological Society of America Bulletin 127, B31165.1. https://doi.org/10.1130/B31165.1.

Meert, J.G., Lieberman, B.S., 2008. The Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran–Cambrian radiation. Gondwana Research 14:5–21. https://doi.org/10.1016/j.gr.2007.06.007.

Milan, L.A., Daczko, N.R., Clarke, G.L., 2017. Cordillera Zealandia: a Mesozoic arc flare-up on the palaeo-Pacific Gondwana Margin. Scientific Reports 7:261. https://doi.org/10.1038/s41598-017-00347-w.

Millar, I.L., Willan, R.C.R., Wareham, C.D., Boyce, A.J., 2001. The role of crustal and mantle sources in the genesis of granitoids of the Antarctic Peninsula and adjacent crustal blocks. Journal of the Geological Society of London 158:855–867. https://doi.org/10.1144/0016-764900-139.

Millar, I.L., Pankhurst, R.J., Fanning, C.M., 2002. Basement chronology of the Antarctic Peninsula: recurrent magmatism and anatexis in the Palaeozoic Gondwana Margin. Journal of the Geological Society of London 159:145–157. https://doi.org/10.1144/0016-764901-020.

Mišković, A., Schaltegger, U., 2009. Crustal growth along a non-collisional cratonic margin: a Lu–Hf isotopic survey of the Eastern Cordilleran granitoids of Peru. Earth and Planetary Science Letters 279:303–315. https://doi.org/10.1016/J.EPSL.2009.01.002.

Mortimer, N., Turnbull, R.E., Palin, J.M., Tulloch, A.J., Rollet, N., Hashimoto, T., 2015. Triassic–Jurassic granites on the Lord Howe Rise, northern Zealandia. Australian Journal of Earth Sciences 62:735–742. https://doi.org/10.1080/08120099.2015.1081984.

Mukasa, S.B., Dalziel, I.W.D., 2000. Marie Byrd Land, West Antarctica: evolution of Gondwana's Pacific margin constrained by zircon U-Pb geochronology and feldspar common-Pb isotopic compositions. Geological Society of America Bulletin 112: 611–627. https://doi.org/10.1130/0016-7606(2000)112<611:MBLWAE>2.0.CO;2.

Munizaga, F., Maksaev, V., Fanning, C.M., Giglio, S., Yaxley, G., Tassinari, C.C.G., 2008. Late Paleozoic–Early Triassic magmatism on the western margin of Gondwana: Collahuasi area, Northern Chile. Gondwana Research 13:407–427. https://doi.org/10.1016/j.gr.2007.12.005.

Murgulov, V., Beyer, E., Griffin, W.L., O'Reilly, S.Y., Walters, S.G., Stephens, D., 2007. Crustal evolution in the Georgetown Inlier, North Queensland, Australia: a detrital zircon grain study. Chemical Geology 245:198–218. https://doi.org/10.1016/j.chemgeo.2007.08.001.

Nebel, O., Münker, C., Nebel-Jacobsen, Y.J., Kleine, T., Mezger, K., Mortimer, N., 2007. Hf–Nd–Pb isotope evidence from Permian arc rocks for the long-term presence of the Indian–Pacific mantle boundary in the SW Pacific. Earth and Planetary Science Letters https://doi.org/10.1016/j.epsl.2006.11.046.

Nebel-Jacobsen, Y., Münker, C., Nebel, O., Mezger, K., 2011. Precambrian sources of Early Paleozoic SE Gondwana sediments as deduced from combined Lu–Hf and U–Pb systematics of detrital zircons, Takaka and Buller terrane, South Island, New Zealand. Gondwana Research 20:427–442. https://doi.org/10.1016/j.gr.2010.11.014.

Nelson, D.A., Cottle, J.M., 2017. Long-term geochemical and geodynamic segmentation of the paleo-Pacific margin of Gondwana: insight from the Antarctic and adjacent sectors. Tectonics 36:3229–3247. https://doi.org/10.1002/2017TC004611.

Ortiz, A., Hauser, N., Becchio, R., Suzaño, N., Nieves, A., Sola, A., Pimentel, M., Reimold, W., 2017. Zircon U-Pb ages and Hf isotopes for the Diablillos Intrusive Complex, Southern Puna, Argentina: crustal evolution of the Lower Paleozoic Orogen, Southwestern Gondwana margin. Journal of South American Earth Sciences 80:316–339. https://doi.org/10.1016/J.JSAMES.2017.09.031.

Pankhurst, R.J., Millar, I.L., Grunow, A.M., Storey, B.C., 1993. The Pre-Cenozoic magmatic history of the Thurston Island Crustal Block, west Antarctica. Journal of Geophysical Research - Solid Earth 98:11835–11849. https://doi.org/10.1029/93JB01157.

Pankhurst, R.J., Leat, P.T., Sruoga, P., Rapela, C.W., Márquez, M., Storey, B.C., Riley, T.R., 1998a. The Chon Aike province of Patagonia and related rocks in West Antarctica: a silicic large igneous province. Journal of Volcanology and Geothermal Research 81, 113–136.

Pankhurst, R.J., Weaver, S.D., Bradshaw, J.D., Storey, B.C., Ireland, T.R., 1998b. Geochronology and geochemistry of pre-Jurassic superterranes in Marie Byrd Land, Antarctica. Journal of Geophysical Research - Solid Earth 103:2529–2547. https://doi.org/10.1029/97JB02605.

Pankhurst, R.J., Weaver, S.D., Hervé, F., Larrando, P., 1999. Mesozoic-Cenozoic evolution of the North Patagonian Batholith in Aysen, southern Chile. Journal of the Geological Society of London 156:673–694. https://doi.org/10.1144/gsjgs.156.4.0673.

Pankhurst, R.J., Riley, T.R., Fanning, C.M., Kelley, S.P., 2000. Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: chronology of magmatism associated with the break-up of Gondwana. Journal of Petrology 41:605–625. https://doi.org/10.1093/petrology/41.5.605.

Pankhurst, R.J., Rapela, C.W., Loske, W.P., Márquez, M., Fanning, C.M., 2003. Chronological study of the pre-Permian basement rocks of southern Patagonia. Journal of South American Earth Sciences 16:27–44. https://doi.org/10.1016/S0895-9811(03)00017-8.

Pankhurst, R.J., Rapela, C.W., Fanning, C.M., Márquez, M., 2006. Gondwanide continental collision and the origin of Patagonia. Earth-Science Reviews 76:235–257. https://doi.org/10.1016/J.EARSCIREV.2006.02.001.

Pankhurst, R.J., Rapela, C.W., Lopez De Luchi, M.G., Rapalini, A.E., Fanning, C.M., Galindo, C., 2014. The Gondwana connections of northern Patagonia. Journal of the Geological Society of London 171:313–328. https://doi.org/10.1144/jgs2013-081.

Pankhurst, R.J., Hervé, F., Fanning, C.M., Calderón, M., Niemeyer, H., Griem-Klee, S., Soto, F., 2016. The pre-Mesozoic rocks of northern Chile: U–Pb ages, and Hf and O isotopes. Earth-Science Reviews 152:88–105. https://doi.org/10.1016/j.earscirev.2015.11.009.

Patchett, P.J., Tatsumoto, M., 1980. Hafnium isotope variations in oceanic basalts. Geophysical Research Letters 7:1077–1080. https://doi.org/10.1029/GL007i012p01077.

Patchett, P.J., Tatsumoto, M., 1981. A routine high-precision method for Lu-Hf isotope geochemistry and chronology. Contributions to Mineralogy and Petrology 75:263–267. https://doi.org/10.1007/BF01166766.

Paton, C., Woodhead, J.D., Hellstrom, J.C., Hergt, J.M., Greig, A., Maas, R., 2010. Improved laser ablation U-Pb zircon geochronology through robust downhole fractionation correction. Geochemistry, Geophysics, Geosystems 11. https://doi.org/10.1029/2009GC002618 (n/a-n/a).

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J., 2011. Iolite: freeware for the visualisation and processing of mass spectrometric data. Journal of Analytical Atomic Spectrometry 26:2508. https://doi.org/10.1039/c1ja10172b.

Paulsen, T.S., Encarnación, J., Grunow, A.M., Valencia, V.A., Layer, P.W., Pecha, M., Stump, E., Roeske, S., Thao, S., Rasoazanamparany, C., 2015. Detrital mineral ages from the Ross Supergroup, Antarctica: implications for the Queen Maud terrane and outboard sediment provenance on the Gondwana margin. Gondwana Research 27:377–391. https://doi.org/10.1016/j.gr.2013.10.006.

Paulsen, T.S., Deering, C., Sliwinski, J., Valencia, V., Bachmann, O., Guillong, M., 2017. Detrital zircon ages and trace element compositions of Permian–Triassic foreland basin strata of the Gondwanide orogen, Antarctica. Geosphere 13:2085–2093. https://doi.org/10.1130/GES01482.1.

Pepper, M., Gehrels, G., Pullen, A., Ibanez-Mejia, M., Ward, K.M., Kapp, P., 2016. Magmatic history and crustal genesis of western South America: constraints from U-Pb ages and Hf isotopes of detrital zircons in modern rivers. Geosphere 12:1532–1555. https://doi.org/10.1130/GES01315.1.

Phillips, G., Landenberger, B., Belousova, E.A., 2011. Building the New England Batholith, eastern Australia—linking granite petrogenesis with geodynamic setting using Hf isotopes in zircon. Lithos 122:1–12. https://doi.org/10.1016/j.lithos.2010.11.005.

Platt, J.P., Whitehouse, M.J., Kelley, S.P., Carter, A., Hollick, L., 2003. Simultaneous extensional exhumation across the Alboran Basin: implications for the causes of late orogenic extension. Geology 31:251. https://doi.org/10.1130/0091-7613(2003)031<0251:SEEATA>2.0.CO;2.

Purdy, D.J., Cross, A.J., Brown, D.D., Carr, P.A., Armstrong, R.A., 2016. New constraints on the origin and evolution of the Thomson Orogen and links with central Australia from isotopic studies of detrital zircons. Gondwana Research 39:41–56. https://doi.org/10.1016/j.gr.2016.06.010.

Ramos, V.A., 2009. Anatomy and global context of the Andes: main geologic features and the Andean orogenic cycle. Geological Society of America Memoirs 204:31–65. https://doi.org/10.1130/2009.1204(02).

Repository, P.R., 2018. Polar Rock and Dredge Samples Available for Research and Educational Use From the PRR. https://doi.org/10.7289/V5RF5S18 (WWW Document).

Riel, N., Jaillard, E., Martelat, J.-E., Ephane Guillot, S., Braun, J., 2018. Permian-Triassic Tethyan Realm Reorganization: Implications for the Outward Pangea Margin. https://doi.org/10.1016/j.jsames.2017.11.007.

Riley, T.R., Flowerdew, M.J., Whitehouse, M.J., 2012. U-Pb ion-microprobe zircon geochronology from the basement inliers of eastern Graham Land, Antarctic Peninsula. Journal of the Geological Society of London 169:381–393. https://doi.org/10.1144/0016-76492011-142.

Riley, T.R., Flowerdew, M.J., Pankhurst, R.J., Leat, P.T., Millar, I.L., Fanning, C.M., Whitehouse, M.J., 2017. A revised geochronology of Thurston Island, West Antarctica, and correlations along the proto-Pacific margin of Gondwana. Antarctic Science 29:47–60. https://doi.org/10.1017/S0954102016000341.

Riley, T.R., Burton-Johnson, A., Flowerdew, M.J., Whitehouse, M.J., 2018. Episodicity within a mid-Cretaceous magmatic flare-up in West Antarctica: U-Pb ages of the Lassiter Coast intrusive suite, Antarctic Peninsula, and correlations along the Gondwana margin. GSA Bulletin https://doi.org/10.1130/B31800.1.

Rocchi, S., Di Vincenzo, G., Ghezzo, C., Nardini, I., 2009. Granite-lamprophyre connection in the latest stages of the early Paleozoic Ross Orogeny (Victoria Land, Antarctica). Geological Society of America Bulletin 121:801–819. https://doi.org/10.1130/B26342.1.

Rocha-Campos, A.C., Basei, M.A., Nutman, A.P., Kleiman, L.E., Varela, R., Llambias, E., Canile, F.M., da Rosa, O.D.C., 2011. 30 million years of Permian volcanism recorded in the Choiyoi igneous province (W Argentina) and their source for younger ash fall deposits in the Paraná Basin: SHRIMP U-Pb zircon geochronology evidence. Gondwana Research 19:509–523. https://doi.org/10.1016/j.gr.2010.07.003.

Rosenbaum, G., 2018. The Tasmanides: phanerozoic tectonic evolution of Eastern Australia. Annual Review of Earth and Planetary Sciences 46. https://doi.org/10.1146/annurev-earth-082517-010146.

Rosenbaum, G., Li, P., Rubatto, D., 2012. The contorted New England Orogen (eastern Australia): new evidence from U-Pb geochronology of early Permian granitoids. Tectonics 31:1–14. https://doi.org/10.1029/2011TC002960.

Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism. Chemical Geology 184:123–138. https://doi.org/10.1016/S0009-2541(01)00355-2.

Rudnick, R.L., Gao, S., 2003. Composition of the continental crust. Treatise on Geochemistry. Elsevier:pp. 1–64 https://doi.org/10.1016/B0-08-043751-6/03016-4.

Saito, S., Brown, M., Korhonen, F.J., McFadden, R.R., Siddoway, C.S., 2013. Petrogenesis of Cretaceous mafic intrusive rocks, Fosdick Mountains, West Antarctica: melting of the sub-continental arc mantle along the Gondwana margin. Gondwana Research 23:1567–1580. https://doi.org/10.1016/j.gr.2012.08.002.

Sauer, K.B., Gordon, S.M., Miller, R.B., Vervoort, J.D., Fisher, C.M., 2017. Evolution of the Jura-Cretaceous North American Cordilleran margin: insights from detrital-zircon U-Pb and Hf isotopes of sedimentary units of the North Cascades Range, Washington. Geosphere 13:2094–2118. https://doi.org/10.1130/GES01501.1.

Schwartz, J.J., Klepeis, K.A., Sadorski, J.F., Stowell, H.H., Tulloch, A.J., Coble, M.A., 2017. The tempo of continental arc construction in the Mesozoic Median Batholith, Fiordland, New Zealand. Lithosphere 9:343–365. https://doi.org/10.1130/L610.1.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth-Science Reviews 113:212–270. https://doi.org/10.1016/J.EARSCIREV.2012.03.002.

Shaw, S.E., Flood, R.H., Pearson, N.J., 2011. The New England Batholith of eastern Australia: evidence of silicic magma mixing from zircon 176Hf/177Hf ratios. Lithos 126: 115–126. https://doi.org/10.1016/j.lithos.2011.06.011.

Shen, W., Wiens, D.A., Stern, T., Anandakrishnan, S., Aster, R.C., Dalziel, I., Hansen, S., Heeszel, D.S., Huerta, A., Nyblade, A., Wilson, T.J., Winberry, J.P., 2018. Seismic evidence for lithospheric foundering beneath the southern Transantarctic Mountains, Antarctica. Geology 46:71–74. https://doi.org/10.1130/G39555.1.

Siddoway, C.S., Fanning, C.M., 2009. Paleozoic tectonism on the East Gondwana margin: evidence from SHRIMP U–Pb zircon geochronology of a migmatite–granite complex

in West Antarctica. Tectonophysics 477:262–277. https://doi.org/10.1016/J.TECTO.2009.04.021.
Siddoway, C.S., Richard, S.M., Fanning, C.M., Luyendyk, B.P., 2004. Origin and emplacement of a middle Cretaceous gneiss dome, Fosdick Mountains, West Antarctica. Special Paper 380: Gneiss Domes in Orogeny. Geological Society of America:pp. 267–294 https://doi.org/10.1130/0-8137-2380-9.267.
Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon — a new natural reference material for U–Pb and Hf isotopic microanalysis. Chemical Geology 249:1–35. https://doi.org/10.1016/j.chemgeo.2007.11.005.
Söderlund, U., Patchett, P.J., Vervoort, J.D., Isachsen, C.E., 2004. The 176Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. Earth and Planetary Science Letters 219:311–324. https://doi.org/10.1016/S0012-821X(04)00012-3.
Stern, T., Houseman, G., Salmon, M., Evans, L., 2013. Instability of a lithospheric step beneath western North Island, New Zealand. Geology 41:423–426. https://doi.org/10.1130/G34028.1.
Storey, B., Dalziel, I.W., Garrett, S., Grunow, A., Pankhurst, R.J., Vennum, W., 1988. West Antarctica in Gondwanaland: crustal blocks, reconstruction and breakup processes. Tectonophysics 155:381–390. https://doi.org/10.1016/0040-1951(88)90276-4.
Thirlwall, M.F., Anczkiewicz, R., 2004. Multidynamic isotope ratio analysis using MC–ICP–MS and the causes of secular drift in Hf, Nd and Pb isotope ratios. International Journal of Mass Spectrometry 235:59–81. https://doi.org/10.1016/j.ijms.2004.04.002.
Tucker, R.T., Roberts, E.M., Henderson, R.A., Kemp, A.I.S., 2016. Large igneous province or long-lived magmatic arc along the eastern margin of Australia during the Cretaceous? Insights from the sedimentary record. Geological Society of America Bulletin 128: 1461–1480. https://doi.org/10.1130/B31337.1.
Tulloch, A.J., Ramezani, J., Kimbrough, D.L., Faure, K., Allibone, A.H., 2009. U-Pb geochronology of mid-Paleozoic plutonism in western New Zealand: implications for S-type granite generation and growth of the east Gondwana margin. Geological Society of America Bulletin 121:1236–1261. https://doi.org/10.1130/B26272.1.
Vaughan, A.P.M., Millar, I.L., 1996. Early cretaceous magmatism during extensional deformation within the Antarctic Peninsula Magmatic Arc. Journal of South American Earth Sciences 9:121–129. https://doi.org/10.1016/0895-9811(96)00032-6.
Vaughan, A.P.M., Eagles, G., Flowerdew, M.J., 2012. Evidence for a two-phase Palmer Land event from crosscutting structural relationships and emplacement timing of the Lassiter Coast Intrusive Suite, Antarctic Peninsula: implications for mid-Cretaceous Southern Ocean plate configuration. Tectonics 31. https://doi.org/10.1029/2011TC003006 (n/a-n/a).
Veevers, J.J., Belousova, E.A., Saeed, A., Sircombe, K., Cooper, A.F., Read, S.E., 2006. Pan-Gondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700–500 Ma age, TDM of 2.0–1.0 Ga, and alkaline affinity. Earth-Science Reviews 76:135–174. https://doi.org/10.1016/j.earscirev.2005.11.001.
Vermeesch, P., 2012. On the visualisation of detrital age distributions. Chemical Geology 312:190–194. https://doi.org/10.1016/j.chemgeo.2012.04.021.
Vervoort, J.D., Blichert-Toft, J., 1999. Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. Geochimica et Cosmochimica Acta 63:533–556. https://doi.org/10.1016/S0016-7037(98)00274-9.
Vervoort, J.D., Patchett, P.J., Blichert-Toft, J., Albarède, F., 1999. Relationships between Lu–Hf and Sm–Nd isotopic systems in the global sedimentary system. Earth and Planetary Science Letters 168:79–99. https://doi.org/10.1016/S0012-821X(99)00047-3.
Wang, H., Currie, C.A., 2015. Magmatic expressions of continental lithosphere removal. Journal of Geophysical Research - Solid Earth 120:7239–7260. https://doi.org/10.1002/2015JB012112.
Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. Geostandards and Geoanalytical Research 19:1–23. https://doi.org/10.1111/j.1751-908X.1995.tb00147.x.
Wiedenbeck, M., Hanchar, J.M., Peck, W.H., Sylvester, P., Valley, J., Whitehouse, M., Kronz, A., Morishita, Y., Nasdala, L., Fiebig, J., Franchi, I., Girard, J.-P., Greenwood, R.C., Hinton, R., Kita, N., Mason, P.R.D., Norman, M., Ogasawara, M., Piccoli, P.M., Rhede, D., Satoh, H., Schulz-Dobrick, B., Skår, O., Spicuzza, M., Terada, K., Tindle, A., Togashi, S., Vennemann, T., Xie, Q., Zheng, Y.-F., 2004. Further characterisation of the 91500 zircon crystal. Geostandards and Geoanalytical Research 28:9–39. https://doi.org/10.1111/j.1751-908X.2004.tb01041.x.
Willner, A.P., Gerdes, A., Massonne, H.-J., 2008. History of crustal growth and recycling at the Pacific convergent margin of South America at latitudes 29°–36° S revealed by a U–Pb and Lu–Hf isotope study of detrital zircon from late Paleozoic accretionary systems. Chemical Geology 253:114–129. https://doi.org/10.1016/j.chemgeo.2008.04.016.
Woodhead, J.D., Hergt, J.M., 2005. A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. Geostandards and Geoanalytical Research 29:183–195. https://doi.org/10.1111/j.1751-908X.2005.tb00891.x.
Yakymchuk, C., Siddoway, C.S., Fanning, C.M., Mcfadden, R., Korhonen, F.J., Brown, M., 2013. Anatectic reworking and differentiation of continental crust along the active margin of Gondwana: a zircon Hf–O perspective from West Antarctica. Geological Society of London, Special Publication 383:169–210. https://doi.org/10.1144/SP383.7.
Yakymchuk, C., Brown, C.R., Brown, M., Siddoway, C.S., Fanning, C.M., Korhonen, F.J., 2015. Paleozoic evolution of western Marie Byrd Land, Antarctica. Geological Society of America Bulletin 127:1464–1484. https://doi.org/10.1130/B31136.1.