

Detrital zircon ages and trace element compositions of Permian–Triassic foreland basin strata of the Gondwanide orogen, Antarctica

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ABSTRACT

Detrital zircon U–Pb and trace element data provide new information on the provenance of Permian–Triassic foreland basin deposits of the Gondwanide orogen that belong to the Beacon Supergroup in Antarctica. Zircon U/Th ratios primarily point to dominantly igneous parent rocks with subordinate contributions from metamorphic sources. All three samples (two Permian and one Triassic) analyzed in this study yielded 1200–1000 Ma and 635–490 Ma zircon U–Pb age populations. The Triassic sample also yielded younger 367 Ma and 238 Ma age peaks. The combination of age and trace element proxies for rock type provides important new evidence in support of the common assertion that granitoid parent rocks of the Terra Australis and Gondwanide orogens served as a major source for the siliciclastic sediments. The results also point to smaller, but significant, contributions from Triassic (236 Ma) and Cambrian (539 Ma) mafic rocks and Ediacaran (ca. 559 Ma) alkaline source rocks from these regions.

INTRODUCTION

Mountain building associated with the construction of the Permian–Triassic Gondwanide orogenic belt (Fig. 1A) commenced during a period of plate kinematic changes associated with collisional tectonism involved in the assembly of the Pangea supercontinent (Cawood, 2005; Boger, 2011). Foreland basin sedimentary rocks deposited during Gondwanide deformation within the Beacon Supergroup (Collinson et al., 1994) are of widespread interest because of their significance for understanding the tectonic and volcanic processes (Collinson et al., 1994; Elliot, 2013; Elliot et al., 2017) operating around the time interval of supercontinent assembly, which was also marked by significant extinctions in Earth's geologic record at the Permian–Triassic boundary (Retallack et al., 2006; Elliot et al., 2017). They are also of interest because of their potential for providing information about the ages and rock types that occur within present ice-covered geologic provinces of East and West Antarctica (Elliot et al., 2015). On a regional scale, the Gondwanide orogenic belt developed in an outboard position with respect to an older (550–300 Ma) subduction-related accretionary

belt found along the Gondwana paleo-Pacific margin known as the Terra Australis orogen (Cawood, 2005; Boger, 2011). Rocks of the Ross orogenic belt sector of the Terra Australis orogen in Antarctica (Fig. 1B) are currently exposed beneath the Kukri erosion surface (Isbell, 1999), a major angular unconformity that separates them from unmetamorphosed Devonian–Jurassic sedimentary rocks of the Beacon Supergroup that are above the unconformity in the Transantarctic Mountains (Fig. 2) (Barrett, 1991).

Sedimentary rocks of the Beacon Supergroup have been the subject of field, paleontological, petrographic, and isotopic studies (Barrett, 1991; Elliot and Fanning, 2008; Goodge and Fanning, 2010; Elsner et al., 2013; Elliot et al., 2015, 2017). Detrital zircon analyses of Permian–Triassic sandstones of this sequence have yielded Archean to Neoproterozoic (2500–900 Ma) age populations, as well as ca. 1000 Ma, 700–500 Ma, 375 Ma, and 260–200 Ma zircon age populations (Elliot and Fanning, 2008; Goodge and Fanning, 2010; Elsner et al., 2013; Elliot et al., 2015, 2017). These studies have provided important insight into the ages of continental crust in East and West Antarctica, but geochronologic studies of Permian–Triassic sandstones of the Beacon Supergroup have largely only been conducted on a reconnaissance basis throughout large sectors of the Transantarctic Mountains (Fig. 3).

A particularly vexing problem facing provenance studies is the difficulty of linking the zircon age populations to parent rock types because of the challenges presented by the extensive ice cover within Antarctica. Therefore, the correlation of detrital zircon age populations with trace element proxies that can be used to determine parent rock types (Belousova et al., 2002) has the potential to lend greater insight into the evolution of continental crust in Antarctica (Veevers et al., 2006; Veevers, 2007). For example, this type of data has the potential to identify the source rock types that contributed to 700–500 Ma zircons that are found within the Beacon Supergroup. Some of these zircons could be attributed to the erosion of Neoproterozoic–Ordovician (565–480 Ma) Granite Harbour intrusive rocks belonging to the late Neoproterozoic–early Paleozoic Ross orogenic belt. It also remains unclear whether these deposits include contributions from alkaline rocks similar in age to those found in the ca. 550 Ma Koettlitz Glacier alkaline province in the south Victoria Land region. There is also the potential to identify the source rock types that contributed to the introduction of volcanoclastic sediments that are associated

Figure 1. (A) Permian–Triassic Gondwana reconstruction showing the distribution of Permian–Triassic strata of the Beacon Supergroup with respect to the trace of the Gondwanide deformation front and Permian–Triassic plutonic and metamorphic rocks located in the orogenic hinterland. AP—Antarctic Peninsula, CR—Chatham Rise, CP—Campbell Plateau, CHP—Challenger Plateau, CTAM—central Transantarctic Mountains, LHR—Lord Howe Rise, MBL—Marie Byrd Land, NVL—north Victoria Land, NZ—New Zealand, QMM—Queen Maud Mountains, SVL—south Victoria Land, TI—Thurston Island. (B) Gondwana reconstruction (Cambrian–Ordovician) showing the major cratons and mobile belts surrounding the East Antarctica interior. The Beacon Supergroup is exposed above the eroded Ross orogenic belt in the Transantarctic Mountain rift flank uplift, which separates rocks belonging to the East Antarctic craton from outboard rock assemblages of West Antarctica (Fig. 3). White circles show approximate locations of sample sites. Figures modified from Goodge et al. (2004) and Elliot (2013).

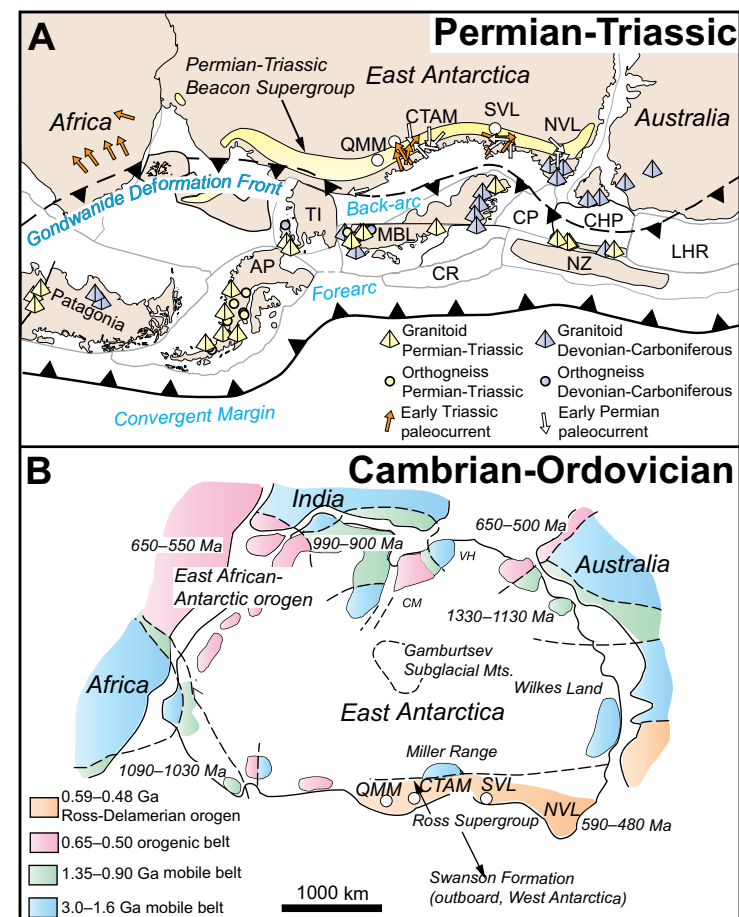
with a major change in paleoflow directed toward the East Antarctic craton in Late Permian and Triassic sections of the Beacon Supergroup (Figs. 1A and 2) (Collinson et al., 1994). Devonian and Permian–Triassic zircon populations are found within these sections of the Beacon Supergroup and have logically been attributed to the erosion of Devonian and Permian–Triassic granitoids (e.g., Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Yakymchuk et al., 2015) found in outboard localities (away from East Antarctica). However, it remains unclear whether these zircon age populations also record contributions from mafic and alkaline igneous rocks, which represent possible products of active back-arc volcanism that has been previously postulated for the margin (Fig. 1A) (Elliot et al., 2016a, 2016b, 2017; McKay et al., 2016). Despite the potential for providing us with crucial, and otherwise unobtainable, information regarding source rock types, to date, trace element analyses (other than U, Pb, Th) of detrital zircons from these Permian–Triassic siliciclastic rock packages have yet to be obtained for the Transantarctic Mountains.

The intent of this research note is to present new detrital zircon U–Pb age ($n = 3$ samples) and trace element data ($n = 1$ sample) from these poorly studied Permian–Triassic stratigraphic packages that crop out in the Queen Maud Mountains and south Victoria Land sectors of the Transantarctic Mountains to better constrain their provenance (Fig. 3).

METHODS

Heavy mineral concentrates were isolated from the $<350\ \mu\text{m}$ fraction of samples PRR10991, PRR38521, and PRR33328. The rock samples were disaggregated using electric-pulse disaggregator followed by traditional magnetic and heavy liquid techniques at ZirChron LLC (Tucson, Arizona). Zircons from the nonmagnetic fraction were hand-picked under the microscope and mounted in a 1-inch-diameter epoxy puck and polished using standard laboratory procedures.

After cathodoluminescence imaging, laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) U–Pb analyses were conducted on samples PRR10991 (Queen Maud Mountains) and PRR33328 (south Victoria Land) using a New Wave Nd:YAG UV 213 nm laser coupled to a Thermo Finn-



gan Element 2 single collector, double-focusing, magnetic sector ICP–MS. Operating procedures and parameters are similar to those of Chang et al. (2006). Laser spot size and repetition rate were $30\ \mu\text{m}$ and 10 Hz, respectively. He and Ar carrier gases delivered the sample aerosol to the plasma. Each analysis consists of a short blank analysis followed by 250 sweeps through masses 202, 204, 206, 207, 208, 232, 235, and 238, taking ~ 30 s. Time-independent fractionation was corrected by normalizing U/Pb and Pb/Pb ratios of the unknowns to the zircon standards (Chang et al., 2006). U and Th concentration were monitored by comparison to the 91500 zircon standard. Two zircon standards were used: Plesovice, with an age of 338 Ma (Sláma et al., 2008), and FC-1, with an age of 1099 Ma (Paces and Miller, 1993). U–Pb ages were calculated using Isoplot (Ludwig, 2003).



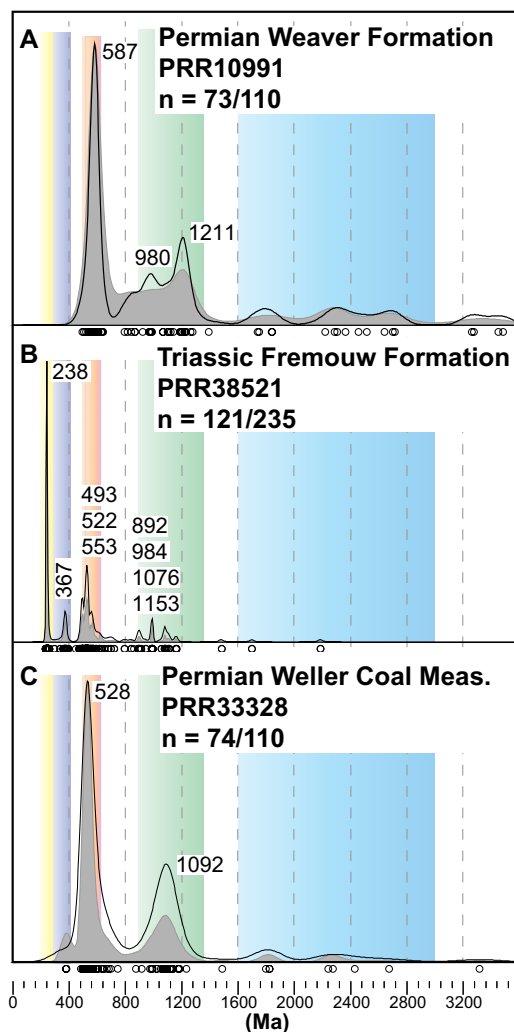
Figure 3. Physiographic map of the Antarctic continent showing the locations of previous detrital zircon analyses (green circles) of Permian–Triassic sandstones belonging to the Beacon Supergroup in the Transantarctic Mountains and possible stratigraphic equivalents in outboard localities in West Antarctica (Elliot and Fanning, 2008; Goodge and Fanning, 2010; Elsner et al., 2013; Elliot et al., 2015, 2016b, 2017; Craddock et al., 2017). Pink circles mark locations of sample analyses reported in this paper. Image modified from public domain; NASA figure available at <https://commons.wikimedia.org/wiki/File:Antarctica.svg>.

We applied the Long classification and regression tree analysis (CART) to the zircon trace element data following Belousova et al. (2002), who showed that igneous parent rock type could be distinguished with >80% confidence for carbonites (84%), syenites (100%), Ne-syenite and syenite pegmatites (93%), and dolerites (84%). Zircons from other granitoids (65%–70% SiO_2 , 70%–75% SiO_2 , >75% SiO_2 , and larvikites, a high-K granitoid) were distinguished with a >80% confidence, with further subdivision into SiO_2 classes commonly yielding misclassification primarily into higher or lower SiO_2 content and therefore lower confidence (Belousova et al., 2002). Basalts were distinguished with a 47% confidence (Belousova et al., 2002). We excluded zircons with U/Th ratios >10 ppm

($n = 7$) from the CART analysis because the higher ratio can develop as a consequence of metamorphism (Hoskin and Schaltegger, 2003; Gehrels et al., 2009).

The resulting interpreted U–Pb ages are shown on kernel density estimation diagrams in Figure 4 (Vermeesch, 2012). For sample PRR38521, the U–Pb zircon ages are shown on kernel density estimation diagrams according to rock type in Figure 5 (Vermeesch, 2012). These kernel density estimation diagrams smooth the age distributions without considering analytical uncertainties (Vermeesch, 2012). We use the 2015 International Commission on Stratigraphy *International Chronostratigraphic Chart* time scale (Cohen et al., 2013) where we discuss the age results in the following.

Figure 4. Kernel density estimation plots (used adaptive kernel function) for detrital zircon U-Pb age data collected from Beacon Supergroup sandstone samples. (A) PRR10991. (B) PRR38521. (C) PRR33328. Gray filled lines represent all age analyses regardless of concordance; unfilled black line represents age analyses within concordance limits. Vertical color bands correlate with colors depicting the spatial distribution of similar age bedrock sources in Figure 1.



RESULTS

A total of 268 U-Pb age analyses from 3 samples meet acceptable concordance thresholds. Of the U-Pb age analyses that meet acceptable concordance thresholds, 97% have U/Th ratios of <10, suggesting the zircons we analyzed primarily grew during igneous processes (Rubatto, 2002; Hoskin and Schaltegger, 2003), a result consistent with the presence of zircon grains with oscillatory zoned interiors (Corfu et al., 2003). The samples analyzed in this study show polymodal age spectra indicating derivation from an age-varied protolith.

Weaver Formation, Queen Maud Mountains

Sample PRR10991 is a fine- to medium-grained sandstone collected from the middle member of the Permian Weaver Formation of the Victoria Group at Mount Weaver at the head of Scott Glacier (86.9667°S, 153.8333°W) by Velon Minshew in 1962 (Polar Rock Repository, 2017). The cumulative zircon age suite yielded 73 of 100 analyses within concordance limits that range from 3482 Ma (Paleoarchean) to 498 Ma (Cambrian, Series 3). These zircon ages have three dominant peaks at 1211 Ma, 980 Ma, and 587 Ma. Analysis of all of the zircon U-Pb ages yields age peaks similar to those shown by analyses within our concordance limits. One U-Pb age analysis (1125 Ma) has a metamorphic U/Th ratio (>10).

Fremouw Formation, Queen Maud Mountains

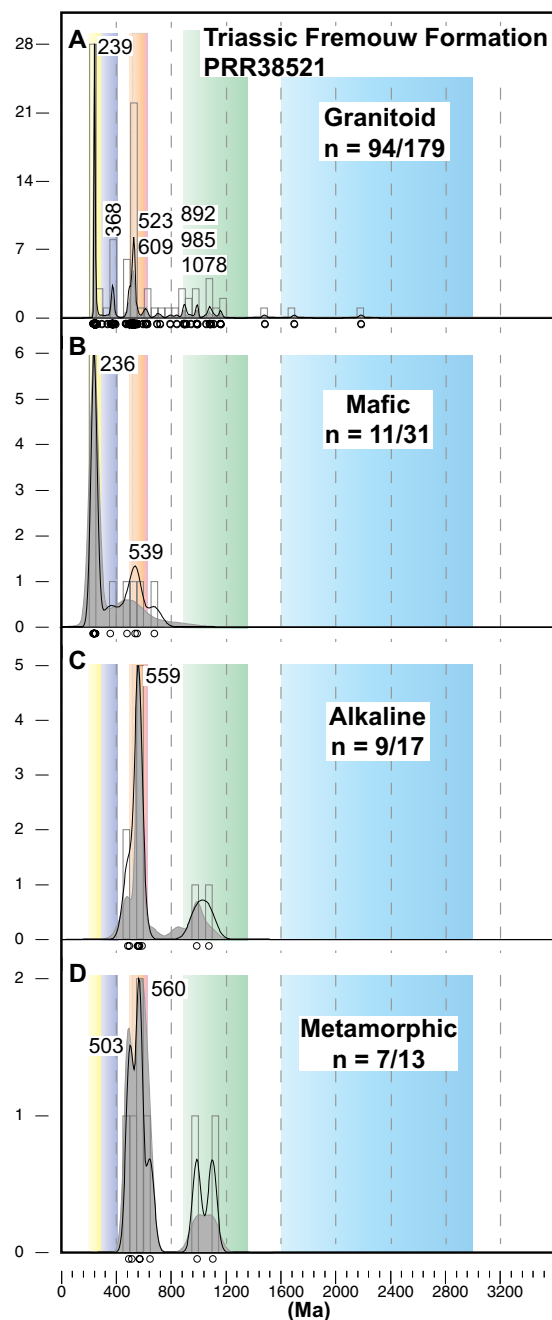
Sample PRR38521 is a fine- to medium-grained sandstone collected from the Triassic Fremouw Formation at Layman Peak (84.833°S, 179.750°E) in the Ramsay Glacier region by Molly Miller in the 1995–96 field season (Polar Rock Repository, 2017). The cumulative zircon age suite yielded 121 of 235 analyses within concordance limits that range from 2181 Ma (Paleoarchean) to 228 Ma (Late Triassic). These zircon ages show a dominant age peak at 238 Ma, with subsidiary age peaks at 1153 Ma, 1076 Ma, 984 Ma, 894 Ma, 892 Ma, 553 Ma, 522 Ma, 493 Ma, and 367 Ma. Analysis of all of the zircon U-Pb ages yields age peaks similar to those shown by analyses within our concordance limits. The detrital zircon age populations yielded by the sample are similar to detrital zircon ages previously reported by Elliot and Fanning (2008) and Elliot et al. (2017) for Permian Buckley and upper Triassic Fremouw Formation samples collected from the areas around the Shackleton to Beardmore Glaciers.

CART classification of the trace element analyses of 121 age concordant zircons with trace element U/Th ratios <10 yields 94 granitoid (granitoid >65% SiO₂ and larvikite in Belousova et al., 2002), 11 mafic (dolerite, *n* = 8; basalt, *n* = 3), and 9 alkaline (syenite, *n* = 5; Ne-syenite and/or syenite pegmatite, *n* = 3; carbonatite, *n* = 1) protoliths. Those zircons classified as derived from granitoids yield age peaks that are similar to the overall U-Pb zircon age data set; there is a dominant age peak at 239 Ma, with subsidiary age peaks at 1078 Ma, 985 Ma, 892 Ma, 609 Ma, 523 Ma, and 368 Ma. The zircons classified as having been derived from mafic rocks show a dominant age peak at 236 Ma, with a subsidiary age peak at 539 Ma. Zircons classified as derived from alkaline rocks ranges show a dominant age peak at 559 Ma. Seven trace element analyses (1101, 987, 645, 571, 565, 512, and 488 Ma) yield metamorphic U/Th ratios (>10), with a primary age peak at 560 Ma.

Weller Coal Measures, South Victoria Land

Sample PRR33328 is a fine- to medium-grained sandstone collected from the middle of the Permian Weller Coal Measures of the Victoria Group ~30 m from the upper dolerite sill at the end of Aztec ridge (77.802°S, 160.552°E) in the

Figure 5. Kernel density estimation plots and histograms (50 m.y. bins) for U-Pb ages of zircons from sample PRR38521. (A) Derived from granitoid parent rocks. (B) Derived from mafic parent rocks. (C) Derived from alkaline parent rocks. (D) Derived from metamorphic parent rocks. Adaptive kernel used for granitoid age populations, whereas bandwidth = 20 for mafic, alkaline, and metamorphic age populations. Gray filled lines represent all age analyses regardless of concordance; unfilled black line represents age analyses within concordance limits. Vertical color bands correlate with colors depicting the spatial distribution of similar age bedrock sources in Figure 1.



Taylor Glacier region by Anne Grunow in 1988 (Polar Rock Repository, 2017). The cumulative zircon age suite yielded 74 of 110 analyses within concordance limits that range from 3314 Ma (Paleoarchean) to 374 Ma (Late Devonian). These zircon ages show a dominant age peak at 528 Ma, with a subsidiary age peak at 1092 Ma. Analysis of all of the zircon U-Pb ages yields age peaks similar to those shown by analyses within our concordance limits. Three U-Pb age analyses (1121, 631, 554 Ma) have metamorphic U/Th ratios (>10).

DISCUSSION AND CONCLUSIONS

The detrital zircon results presented here provide new constraints on the age and provenance of the siliciclastic material that composes a portion of the Permian–Triassic sections of the Beacon Supergroup. These new data indicate that the Permian–Triassic siliciclastic sediments were primarily derived from sources dominated by Mesoproterozoic to Triassic (1211–238 Ma) zircons, consistent with previous studies of similar-age Beacon sandstone in the Ramsay and Shackleton Glaciers regions of the Queen Maud Mountains (Elliot and Fanning, 2008), the Beardmore Glacier region of the central Transantarctic Mountains (Elliot et al., 2015), and north Victoria Land (Goodge and Fanning, 2010; Elsner et al., 2013) (Fig. 3). The results also indicate that these zircons are likely derived from igneous rocks with only minor contributions from rocks that record significant metamorphic zircon growth.

Paleoflow indicators indicate both outboard (away from East Antarctica) and inboard (toward East Antarctica) directed flow during the deposition of Permian sections of the Beacon Supergroup (Fig. 1A) (Collinson et al., 1994). The 1211–980 Ma age peaks, as well as those at 587 Ma and 528 Ma, are similar to and possibly derived from recycling of detrital zircon age populations found in the Neoproterozoic–Ordovician siliciclastic rocks of the inboard Ross Supergroup in the Transantarctic Mountains or the outboard Swanson Formation in West Antarctica (Fig. 1B) (Goodge et al., 2004; Yakymchuk et al., 2015; Paulsen et al., 2015, 2016b); the outboard Swanson Formation was likely at least in part ultimately derived from erosion of Ross orogenic belt. The 1211–980 Ma (Mesoproterozoic–Neoproterozoic, Tonian) age peaks could also reflect erosion and transport of sediment from late Mesoproterozoic to Neoproterozoic mobile belts found within the East Antarctic craton (Fig. 1B) (Fitzsimons, 2000, 2003; Goodge et al., 2010; Boger, 2011; Loewy et al., 2011). However, it is also possible that older zircon age populations are at least in part derived from West Antarctica sources, where isotopic analyses suggest the presence of such older crust (Millar and Pankhurst, 1987; Mukasa and Dalziel, 2000; Craddock et al., 2016, 2017). Archean zircon ages (3481–2518 Ma) are few ($n = 10$ within concordance limits) and mainly found within the Permian sample (PRR10991) from the Queen Maud Mountains. These ages are similar to detrital zircon ages reported from the Ellsworth Mountains (Craddock et al., 2017), which may source from the Minnesota River Valley of the Superior Province, although sources from the East Antarctic craton cannot be ruled out (Craddock et al., 2017).

The original igneous source rocks for the zircons that contribute to the 528 Ma age peak likely belong to the Neoproterozoic–Ordovician (565–480 Ma) Granite Harbour Intrusives (Stump, 1995; Encarnación and Grunow, 1996; Rocchi et al., 2009; Goodge et al., 2012; Paulsen et al., 2013; Hagen-Peter et al., 2015; Hagen-Peter and Cottle, 2016), which are widespread and exposed beneath the Kukri erosion surface in the Transantarctic Mountains (e.g., Elliot and Fanning, 2008; Elliot, 2013; Elliot et al., 2015). There are also isolated exposures of Cambrian (505 Ma) granitoid gneiss in West Antarctica (Pankhurst et al., 1998; Mukasa and Dalziel, 2000), pointing to the outboard presence of source rocks that are broadly similar in age. The igneous source rocks for the zircons contributing to the 587 Ma age peak is more difficult to determine. This age peak correlates with dates that characterize other Gondwana mobile belts (Boger and Miller, 2004; Squire et al., 2006; Boger, 2011), but derivation from ice-covered, inboard metamorphic-plutonic belts (Goodge et al., 2002; Fitzsimons, 2003; Goodge et al., 2004; Collins and Pisarevsky, 2005; Boger, 2011), including possible ancestral elements of the Ross orogen (Sircombe, 1999; Goodge et al., 2012; Hagen-Peter et al., 2016) in East Antarctica, are plausible.

Paleocurrent indicators show a major reversal in paleoflow predominantly directed inboard (toward East Antarctica) concomitant with the introduction of volcanoclastic sediment in Late Permian and Triassic sections of the Beacon Supergroup (Figs. 1A and 2) (Collinson et al., 1994). Despite the major reversal in paleoflow toward East Antarctica, the U-Pb age results from the Permian–Triassic samples point to the continued transport of significant populations of Cambrian and older zircons from West Antarctic sources, which is consistent with previous detrital zircon U-Pb age analyses in the Transantarctic Mountains (e.g., Elliot and Fanning, 2008; Elliot, 2013; Elliot et al., 2015). The following evidence combined supports the notion that these zircon age populations may in part be derived from sources like those found within the Ross orogenic belt, leading us to conclude that there is similar crust in West Antarctica and/or these zircons are recycled from sedimentary rocks previously shed from the Ross orogen and deposited in outboard localities. (1) The ca. 521 Ma (Cambrian) age peak yielded by zircons classified as granitoid is similar to the ages of early Paleozoic Granite Harbour Intrusives and their equivalents found along the continental margin. (2) The ca. 559 Ma (Ediacaran) age peak yielded by alkaline-carbonatite zircons is similar in age and lithology to the ca. 550 Ma alkaline rocks found in the Koettlitz Glacier alkaline province of the south Victoria Land sector of the Transantarctic Mountains (Cooper et al., 1997; Read et al., 2002; Mellish et al., 2002; Martin et al., 2015; Hagen-Peter and Cottle, 2016). (3) Similar trace element and age patterns have been found for detrital zircons from the Ross Supergroup in the north Victoria Land sector of the Ross orogen (Paulsen et al., 2016a).

The ca. 369 Ma (Devonian) and ca. 239 Ma (Permian–Triassic) granitoid zircons from our Triassic sample were likely derived from Devonian and Permian–Triassic granitoids (e.g., Pankhurst et al., 1998; Mukasa and Dalziel, 2000; Yakymchuk et al., 2015) found in outboard localities (away from East Antarctica) in north Victoria Land and West Antarctica (Fig. 1A) (Elliot, 2013). Our new data also indicate smaller, but significant, contributions from Triassic (236 Ma) mafic

rocks presumably also located in West Antarctica. These mafic zircons may represent important new evidence for extensional backarc volcanism previously postulated to have extended along this section of the Gondwana margin (Fig. 1A) (Elliot et al., 2016b; McKay et al., 2016), although extensive analyses of trace elements in zircons from more deposits along the margin are necessary to further test this model. The large areas over which such data are generally absent along the margin preclude assessment of the magmatic evolution along the margin in greater detail at this time. The new results do, however, emphasize that the detrital zircon trace element record of the Beacon Supergroup shows promise to significantly advance our understanding of continental arc magmatism associated with the Gondwanide orogeny.

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