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RESEARCH ARTICLE

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Crustal thickness, rift-drift and potential links to key global events

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Abstract
Orogenic crustal thickening leads to increased continental elevation and runoff into the oceans, but there are fundamental uncertainties in the temporal patterns of thickening through Earth history. U-Pb age and trace element data in detrital zircons from Antarctica are consistent with recent global analyses suggesting two dominant peaks in average crustal thickness from ~2.6 to 2.0 Ga and ~0.8 to 0.5 Ga. Shifts in marine carbonate $^{87}Sr/^{86}Sr$ ratios show two primary peaks that post-date these crustal thickness peaks, suggesting significant weathering and erosion of global continental relief. Both episodes correlate well with zircon trace element and isotope proxies indicating enhanced crustal and fluid input into subduction zone magmas. Increased crustal thickness correlates with increased passive margin abundance and overlaps with snowball Earth glaciations and atmospheric oxygenation, suggesting a causal link between continental rift-drift phases and major transitions in Earth's atmospheric and oceanic evolution.

1 | INTRODUCTION

The temporal patterns of orogenic thickening and associated uplift of Earth's continental crust are of widespread interest because of postulated links to atmospheric oxygenation (Campbell & Allen, 2008), as well as global climate cooling and changes in ocean chemistry (Raymo & Ruddiman, 1992). There are, however, uncertainties about the spatial and temporal patterns of crustal thickness in Earth's past. Previous studies have focused on determining juvenile crustal thickness (i.e. at the time of mantle separation) through time using in situ whole-rock geochemical and isotopic data (Dhuime, Wuestefeld, & Hawkesworth, 2015). Other studies have used detrital zircon trace element ratios to evaluate absolute crustal thickness (i.e. juvenile + recycled/existing crust) at the time of final magmatic crystallization associated with individual continental arcs (Barth, Wooden, Jacobson, & Economos, 2013), and more recently for the evolution of continental crust in India (McKenzie, Smye, Hegde, & Stockli, 2018) and on a global scale (Balica et al., 2020). However, whether crustal thickness estimates from global detrital zircon studies are representative of crustal evolution over Earth history remains uncertain given the small size of datasets with respect to the large areas they cover.

Detrital zircon U-Pb age analyses have provided considerable insight into the age of continental crust of East Antarctica (Goodge, Williams, & Myrow, 2004; Nelson & Cottle, 2017; Squire, Campbell, Allen, & Wilson, 2006). There is a growing recognition that sedimentary rock successions derived from eroding continents hold important archives for understanding the age and physical–chemical evolution of continental crust (Dhuime, Hawkesworth, Delavault, & Cawood, 2017). In particular, detrital zircons retain compositional data that can yield information about the petrotectonic environments in which they formed, but these studies have not taken advantage of the information available in zircon trace element record over Earth history. This study integrates detrital zircon U-Pb age and trace element proxies for an exceptionally large detrital zircon dataset (n = 5,755) from 73 sandstone samples (41 Neoproterozoic-early Palaeozoic and 32 Devonian to Jurassic samples) distributed along ~3,000 km of Gondwana's palaeo-Pacific margin (Figure 1; data from Nelson & Cottle, 2017; Paulsen, Deering, Sliwinski, Bachmann, & Guillong, 2016a, 2016b; Paulsen, Deering, Sliwinski, Bachmann, & Guillong, 2017). We focus

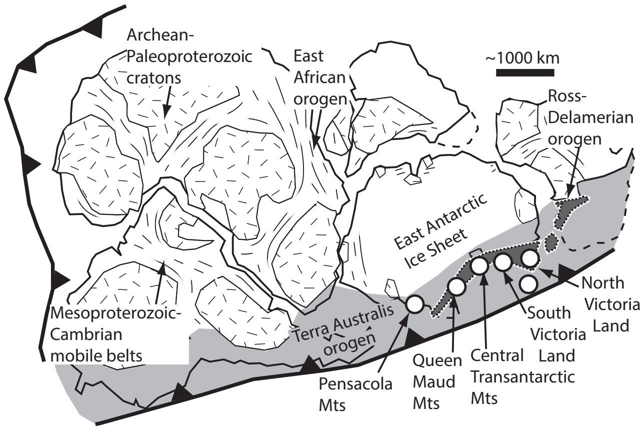

FIGURE 1 Gondwana reconstruction showing the Ross-Delamerian orogen within the greater latest Neoproterozoic to late Palaeozoic Terra Australis orogen. White circles show major provinces from which samples have been analysed in this paper. Mts: mountains. Figure modified from Paulsen et al. (2016*a*)

on developing a better understanding of the global evolution of continental crust and its potential links to major changes in the ocean and atmospheric systems derived from other proxy records.

Statement of Significance

Mountain building is a fundamental tectonic process that commonly occurs in association with crustal thickening along Earth's major convergent plate boundaries. Geologists have long recognized that the generation of significant continental relief has the potential to have profoundly influenced the chemistry of the Earth's oceans and atmosphere as it evolved through time. However, there are significant uncertainties about the spatial and temporal patterns of crustal thickening in Earth's past, especially associated with the ancient rock record leading up to the Cambrian explosion of life. These uncertainties exist because continental relief tends to be subdued during weathering and erosion, leaving in situ rock records of these processes incomplete. However, detrital zircons from sedimentary rocks have been shown to capture a more representative record of Earth history. Here we show that U-Pb age and trace element data obtained for an exceptionally large number of detrital zircons from representative sandstones recovered in Antarctica are consistent with recent global analyses suggesting two prominent peaks in crustal thickness that correlate with proxy records for the rift-drift of the continents. Crustal thickening also overlapped with snowball Earth glaciations and associated steps in atmospheric oxygenation, possibly signifying that there are important links between the evolution of Earth's geosphere and its atmosphere and hydrosphere envelopes.

2 | ANTARCTIC DETRITAL ZIRCON RECORD

The cumulative dataset analysed in this study (ages < 15% discordant or <5% reverse discordant and culled of anomalous trace element values) shows a polymodal age distribution with about half of the detrital zircon age data (n = 2,781 of 5,755) from the studied sample suite yielding Archean to early Neoproterozoic ages (3.6–0.9 Ga; Figure 2). To assess the importance of changes in the average trace element ratios within this dataset through time, we conducted Monte Carlo bootstrap resampling (Efron, 1987) of compositional values of zircons in 0.1 Gyr brackets. The resampling was weighted inversely proportional to the temporal U-Pb age density to minimize the effect of sampling bias presented by peaks in detrital zircon abundance. The zircon dataset analysed here (Th/U > 0.1) may contain a small percentage of metamorphic grains (Rubatto, 2017). However, the majority of zircons in our dataset are expected to have igneous heritage associated with the generation of low temperature, high-silica hydrous melts along convergent margins, the primary zircon factory (Lee & Bachmann, 2014).

Trace elements in detrital zircons can be used both as a means to relate their formation to a general tectonic setting and as more specific proxies for changes in the characteristics of magmatic evolution (e.g. Barth et al., 2013). Garnet is a mineral found in crustal magmas that is stable during fractionation of magmas in the deep crust and incorporates heavy rare-earth elements (HREE)+Y relative to other trace elements. Therefore, Y/Gd and Yb/Gd ratios in zircon decrease with fractionation at increasing pressure associated with increases in crustal thickness (Barth et al., 2013).

The trace element record retained within the Pacific-Gondwana zircon dataset shows that lower Y/Gd and Yb/Gd ratios are generally associated with two principal periods (Figure 3). This pattern of depletion in HREE + Y suggests that crust was thicker in the source areas of the zircons formed during these intervals. The first suggests an increasing proportion of magmas formed along relatively thicker convergent margins after 3.1 Ga to a broad ~2.6 to 2.0 Ga high (considering younger and older age limits of the 0.1 Gyr age brackets), whereas the second suggests a peak in the proportion of magmas formed within thicker crust centred ~0.8 to 0.5 Ga. These peaks are separated by an intervening interval from ~1.9 to 0.9 Ga during a period of remarkable environmental stasis known as the 'boring' billion (Cawood & Hawkesworth, 2014; Holland, 2006; Roberts, 2013).

3 | LINKS TO GLOBAL PATTERNS

In terms of scale, the length of the palaeocontinental margin along which we have characterized relative palaeocrust thickness patterns is roughly equivalent to the Nazca-South American convergent plate margin along coastal Chile. The sources of the zircon

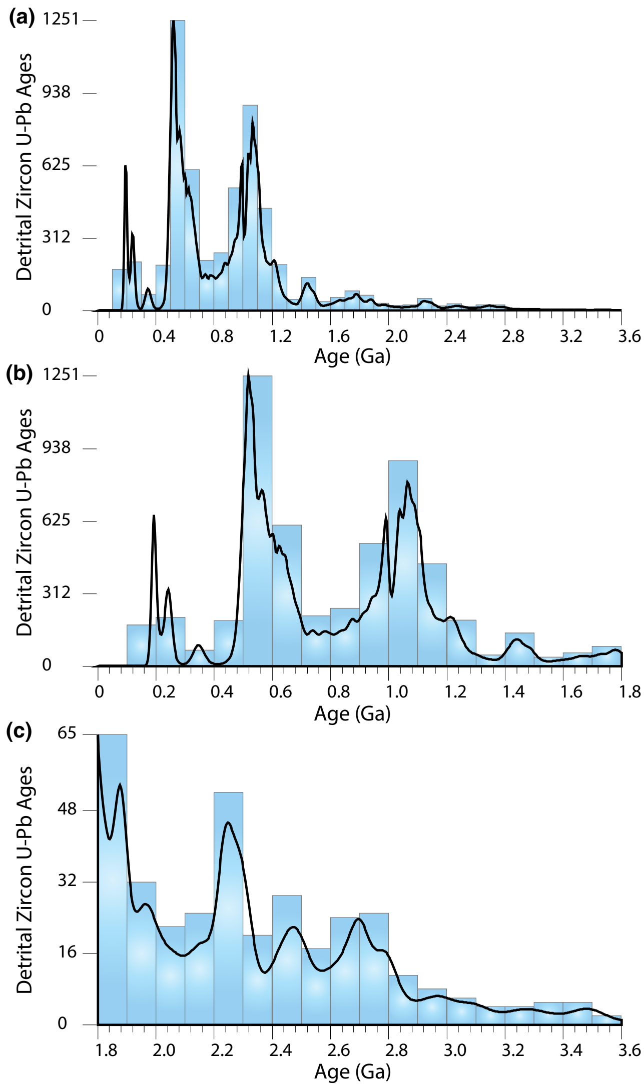

FIGURE 2 Kernel density estimate plots and histograms (Vermeesch, 2012) of cumulative U-Pb age data (*n* = 5,755) for the compilation of detrital zircons analyse in this study from the Transantarctic Mountains and Marie Byrd Land area of Antarctica. (a) 3.6 to 0 Ga (*n* = 5,755), (b) 1.8 to 0 Ga (*n* = 5,400) and (c) 3.6 to 1.8 Ga (*n* = 356). Data sources for compilation provided in text

populations in these samples may include exposed and ice-covered igneous provinces in Antarctica, for example the Ross and Gondwanide orogens (Goodge et al., 2004; Nelson & Cottle, 2017), as well as interior areas of Gondwana like the East African orogen (Squire et al., 2006). Regardless of their precise provenance, the large number of detrital zircon U-Pb age and trace element measurements within our dataset suggests that the crustal thickness proxies are likely representative of at least a significant portion of East Gondwana. Global detrital zircon trace element records (Balica et al., 2020) show overall average crustal thickness patterns similar to those yielded by the Pacific-Gondwana zircon suite (Figure 3), despite the sample suites possessing only minor overlap (2 samples). Differences in the thickness patterns are primarily seen in the older time intervals (the 3.2–3.1 Ga opposing peaks and troughs), which may reflect issues stemming from sampling bias and/or data treatment. Collectively, these results suggest that the two principal increases in average crustal thickness identified here and in Balica et al. (2020) may have global significance, a notion supported by other proxy data to which we now turn.

Shifts in $^{87}Sr/^{86}Sr$ within marine carbonates have previously been found to correlate with episodes of extensive felsic magmatism associated with an increase in assimilation of older radiogenic crust (Bataille et al., 2017), a process that is favoured along compressional advancing convergent margins and collisions (Collins, Belousova, Kemp, & Murphy, 2011; Condie & Aster, 2013), which, in turn, lead to increases in continental elevation and Sr runoff into the Earth's oceans (Shields, 2007). The $^{87}Sr/^{86}Sr$ isotope curve shown in Figure 4, which is normalized to the model $^{87}Sr/^{86}Sr$ of global river and mantle inputs, shows two primary peaks that post-date the peaks in crustal thickness, a delay that is expected as continental relief is reduced by weathering and erosion. The $^{87}Sr/^{86}Sr$ isotope peaks may in part reflect increased sediment input into the oceans due to exhumation associated with rifting (DeLucia, Guenthner, Marshak, Thomson, & Ault, 2018) and deglaciation that marked the end of two prominent periods of global glaciation referred to as 'snowball Earth' (Sobolev & Brown, 2019). However, our data indicate that significant continental relief along convergent margins may have played an important additional role in producing these $^{87}Sr/^{86}Sr$ isotopic excursions, as also suggested for the ~0.7–0.5 Ga time interval by Balica et al. (2020). A mix of these processes likely played a fundamental role in the generation of two of the most significant unconformities in the geological record, the Proterozoic-Phanerozoic Great Unconformity and its predecessor at the Archean-Proterozoic boundary (Keller et al., 2019; Peters & Gaines, 2012; Windley, 1984).

To test the hypothesis that these peaks in crustal thickness and subsequent increased Sr input into the Earth's oceans were associated with an increase in the reworking and assimilation of older radiogenic crust, we evaluated the Th/Yb ratio of the Pacific-Gondwana zircons based on the assumption that Th is enriched relative to the other elements as crust matures (Barth et al., 2013). Zircons with the highest Th/Yb ratios in our dataset correlate well with the thickness peaks (Figure 4). This pattern is confirmed on a global scale by the Hf isotope record (Cawood, Hawkesworth, & Dhuime, 2013), which shows two primary peaks in crustal input that correlate with the peaks in crustal thickness identified here (Figure 4). Our interpretation of these correlations is that they reflect an increase in the contribution of sediment from subducting slabs, as well as crustal assimilation associated with thermal maximums reached during peaks in crustal thickness. Crustal reworking associated with portions of the global Hf isotope trends may have been enhanced by magmatic recycling of sediment input into trenches following snowball Earth deglaciations (Keller et al., 2019; Sobolev & Brown, 2019). However, the correlation between crustal thickening and reworking indicated by our data suggests an additional strong orogenic signal in these datasets (Balica et al., 2020).

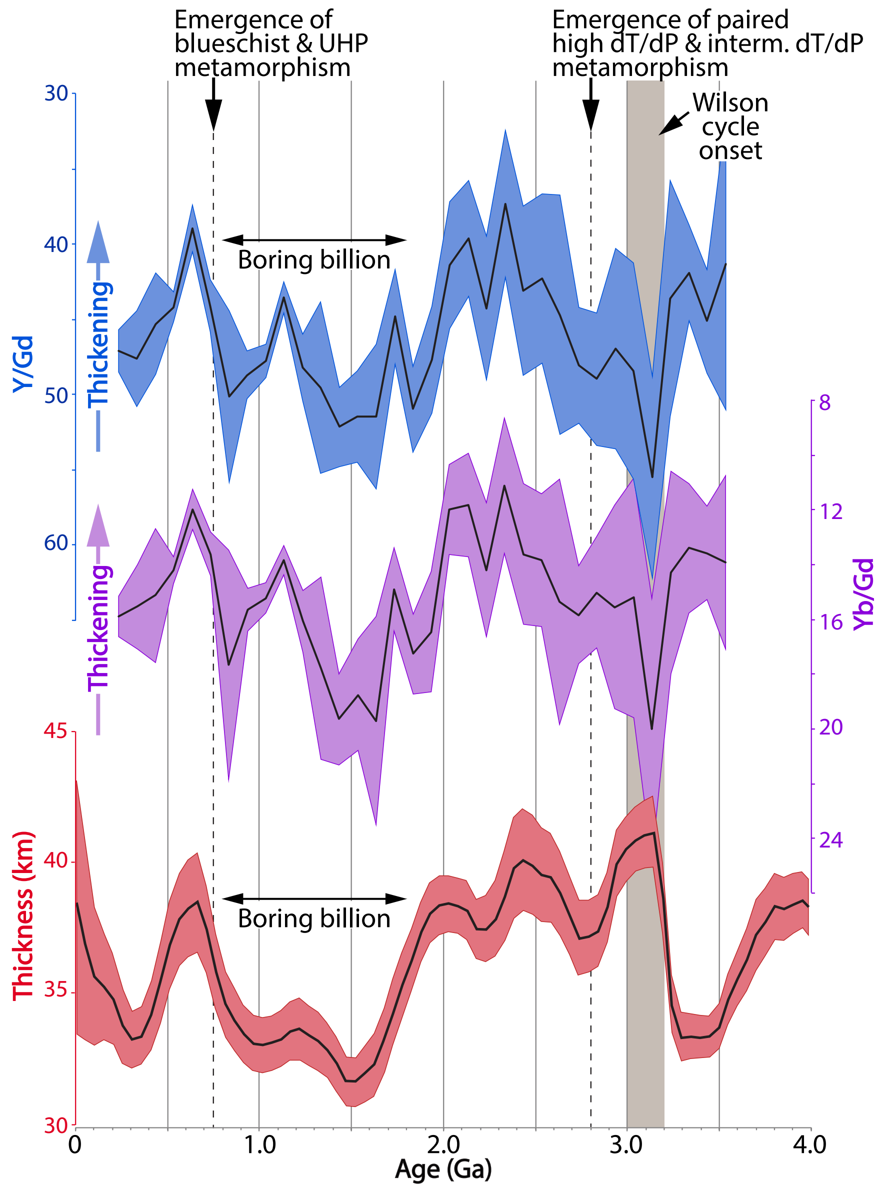

FIGURE 3 Average Y/Gd and Yb/Gd (crustal thickness proxies) with their 95% confidence envelopes determined by Monte Carlo bootstrap resampling of Antarctic detrital zircons in 0.1 Gyr time brackets, compared to crustal thickness derived from global average of La/Yb proxy from Balica et al. (2020). Ages of 'boring billion' from Holland (2006), emergence of paired high dT/dP-intermediate dT/dP metamorphism and widespread ultrahigh-pressure and blueschist metamorphism (cold subduction) marking onset of modern plate tectonic regime from Brown and Johnson (2018) and Wilson cycle onset from Shirey and Richardson (2011)

The suggestion that increased crustal reworking relates to changes in processes involving subduction warrants an examination of the U/Yb ratio in zircon, which has been used as a proxy for subducting slab fluid addition because the fluids are enriched in U relative to HREE such as Yb (Barth et al., 2013). The Pacific-Gondwana zircon suite shows U/Yb increases that correlate with the two primary peaks in crustal thickness we have identified (Figure 4). Igneous zircon U contents are also influenced by the composition of source rocks involved in the generation of melts and the presence of other minerals that compete to incorporate U during crystallization (Kirkland, Smithies, Taylor, Evans, & McDonald, 2015). However, the onset of increased crustal thickness associated with the first episode (Archean-Proterozoic) correlates with the ~3.0 Ga appearance of eclogite-bearing diamonds, marking the inception of widespread subduction associated with the onset of the Wilson cycle (Figure 4) (Shirey & Richardson, 2011). Subsequent increases in fluid flux from subducting oceanic slabs have, in turn, been postulated to have driven voluminous 3.0–2.5 Ga felsic magmatism associated with remelting of previously formed mafic crust (Tang, Chen, & Rudnick, 2016); a time period that is here also characterized by increased crustal input into magmas.

To investigate the relationship between crustal thickness and the record of metamorphism along convergent margins, we compared thickness patterns to the in situ high-grade metamorphic rock record shown in Figure 5a. The increase in crustal thickness during the Archean-Proterozoic time interval correlates with the ~2.8 Ga emergence of high dT/dP and intermediate dT/dP metamorphism thought to mark widespread coupling of paired metamorphic belts, the hallmark signature of subduction (Brown & Johnson, 2018). Decreased crustal thickness during the boring billion in turn correlates with a period dominated by high dT/dP metamorphism with higher thermal gradients (Brown & Johnson, 2018). This could relate to supercontinent insulation of the mantle (Figure 5; Brown & Johnson, 2018) and associated development of hot back-arc environments (Hyndman,

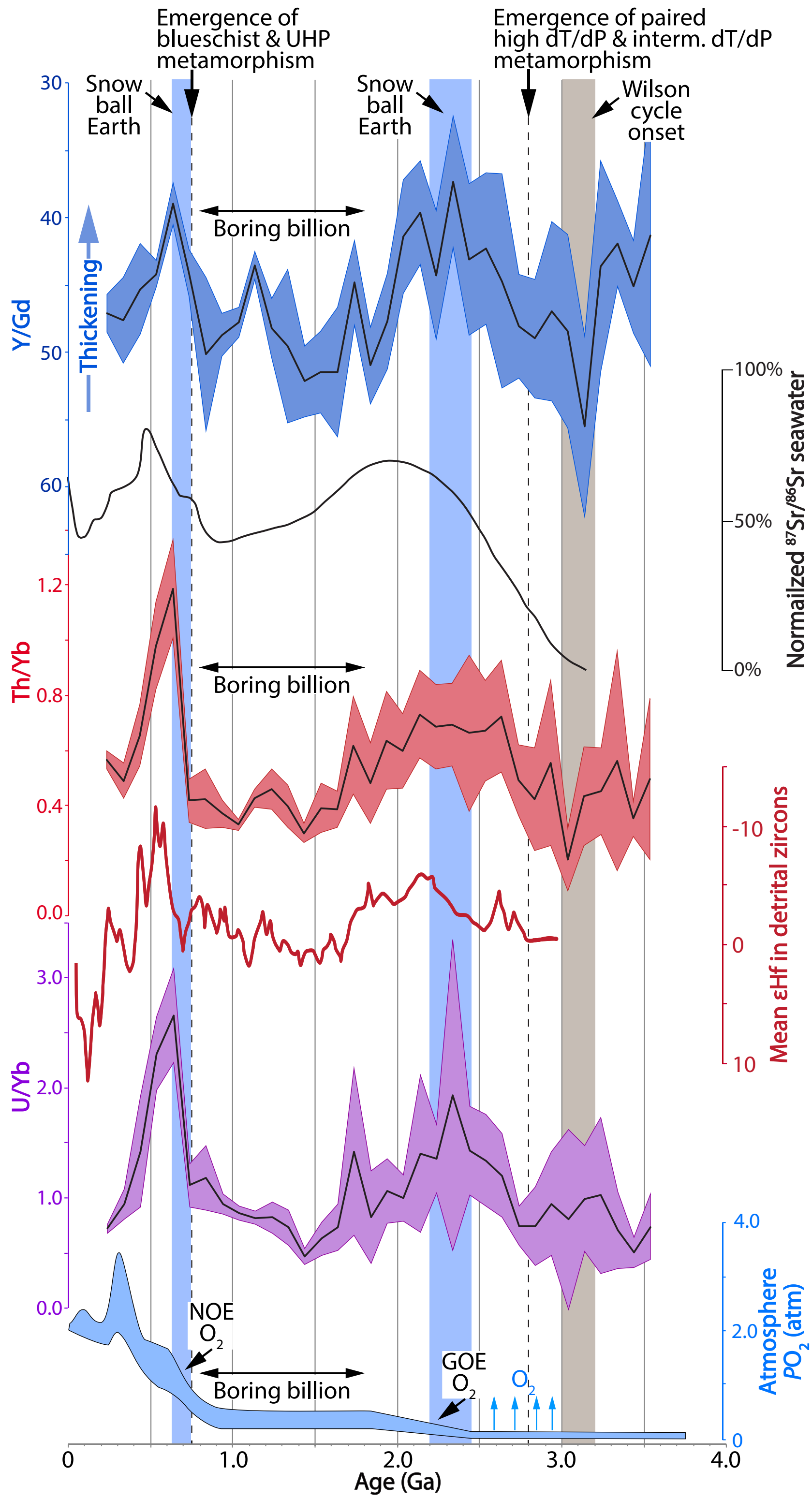

FIGURE 4 Average Y/Gd (crustal thickness proxy), Th/Yb (crustal input proxy) and U/Yb (subducting slab fluid proxy) with their 95% confidence envelopes determined by Monte Carlo bootstrap resampling of Antarctic detrital zircons in 0.1 Gyr time brackets, compared to global average zircon εHf values from Cawood et al. (2013), normalized marine $^{87}Sr/^{86}Sr$ evolution from Shields (2007), increases in atmospheric oxygen, early 'whiffs' of oxygen (blue arrows) and intervening boring billion from Holland (2006) and Lyons, Reinhard, and Planavsky (2014). Ages of the emergence of paired high dT/dP-intermediate dT/dP metamorphism and widespread ultrahigh-pressure and blueschist metamorphism (cold subduction) marking onset of modern plate tectonic regime from Brown and Johnson (2018), Wilson cycle onset from Shirey and Richardson (2011), and snowball Earth glaciations adapted from Sobolev & Brown (2019). GOE, Great oxygenation event; NOE, Neoproterozoic oxygenation event

Currie, & Mazzotti, 2005) with a greater proportion of convergent margins in retreating states in outboard localities on thinner crust (Roberts, 2013).

The increase in crustal thickness during the Proterozoic-Phanerozoic time interval in turn correlates with a decrease in thermal gradients of high dT/dP metamorphism, as well as the ~0.75 Ga widespread appearance of blueschist (Tsujimori & Ernst, 2014) and ultrahigh-pressure (Liou, Tsujimori, Yang, Zhang, & Ernst, 2014) metamorphism (Figure 5a; Brown & Johnson, 2018). Blueschist metamorphism is a hallmark of a cooler subduction environment, which fostered deeper subduction of crust and ultrahigh-pressure metamorphism (Brown, 2007). The decrease in thermal gradients

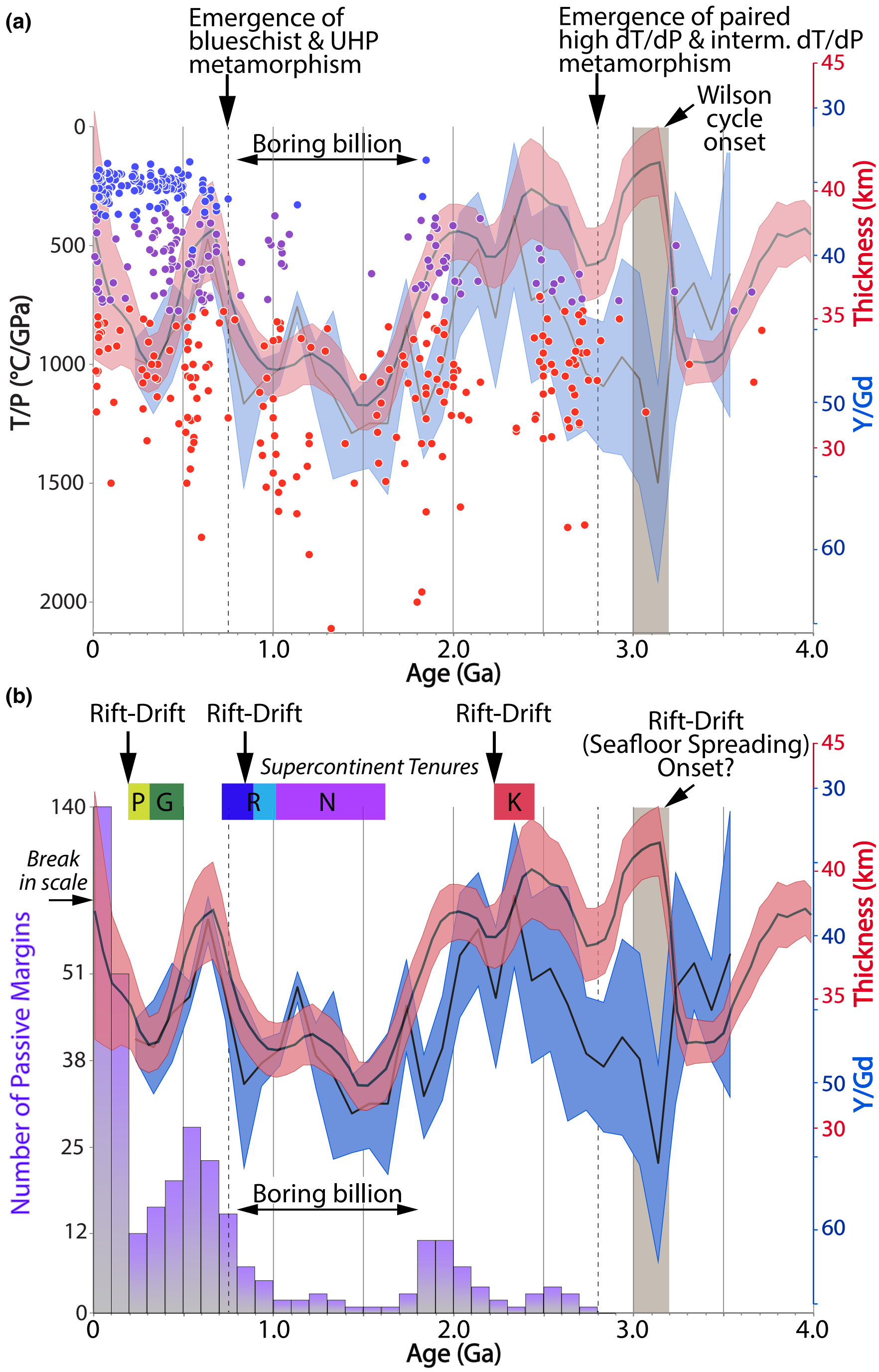

FIGURE 5 (a) Average crustal thickness proxies with their 95% confidence envelopes compared to global compilation of ages versus T/P (°C/GPa) of high dT/dP (granulite – ultrahigh temperature) (red), intermediate dT/dP (eclogite – high-pressure granulite) (purple) and low dT/dP (high-pressure – ultrahigh-pressure) metamorphism (blue). (b) Average crustal thickness proxies with their 95% confidence envelopes compared to the tenure of supercontinent/cratons and a global compilation of passive margin abundance binned in 0.1 Gyr time brackets; passive margins contribute to each bin over which their lifespan overlaps. Increased crustal thickness tends to correlate with increased passive margin abundance suggesting a convergent margin response to continental rift-drift phases. Onset of widespread rift-drift ~3.2–3.0 Ga is implied assuming the appearance of mantle eclogites marking widespread subduction is balanced by construction of new crust associated with the onset of the Wilson cycle. Supercontinent/craton abbreviations: G, Gondwana; K, Kenor; N, Nuna; P, Pangea; R, Rodinia. Data for metamorphic rock compilation from Brown and Johnson (2018) and passive margin abundance from Bradley (2008). Age ranges of the tenure of supercontinents/cratons from Bradley (2011), emergence of paired high dT/dP-intermediate dT/dP metamorphism and widespread ultrahigh-pressure and blueschist metamorphism (cold subduction) marking onset of modern plate tectonic regime from Brown and Johnson (2018) and Wilson cycle onset from Shirey and Richardson (2011)

of high dT/dP metamorphism has in turn been associated with supercontinent breakup (Brown & Johnson, 2018), which may throw convergent margins into compressional advancing states associated with thicker crust (Lee et al., 2013; Lenardic, 2016; Lenardic et al., 2011). Indeed, the increase in crustal thickness during this time interval correlates well with an increase in passive margin abundance marking supercontinent rifting and the onset of continental drift (Figure 5b; Bradley, 2008). Similar correlations over Earth history (Figure 5b) suggest that increased crustal thickness recorded along greater proportions of convergent margins is primarily driven by the processes governing the rift-drift of the continents (Li et al., 2019).

4 | CONCLUSION AND IMPLICATIONS

Our results suggest two prominent increases in crustal thickness occurred as the lithosphere responded to major tectonic milestones as the mantle cooled through time. The cause of planetary cooling that induced two principal periods of global glaciation is controversial, but some models attribute these changes to steps in atmospheric oxygenation (Figure 4) that caused significant decreases in atmospheric methane, a potent greenhouse gas (Fakhraee, Hancisse, Canfield, Crowe, & Katsev, 2019). If the two prominent increases in crustal thickness identified here are representative of a global pattern, their temporal correlation with global glaciations raise the important question of whether or not increased crustal elevations provided essential cooler, higher elevation nurseries for initial ice sheet growth (Eyles & Januszczak, 2004), as was the case for the growth of Cenozoic continental glaciers in Antarctica (Deconto & Pollard, 2003). These correlations also highlight the possibility that greater amounts of crust were available for silicate weathering, a process that fostered global Cenozoic cooling through the drawdown of atmospheric CO_2 (Raymo & Ruddiman, 1992) and that may have also played a role in the snowball Earth glaciations (Donnadieu, Goddéris, Ramstein, Nédélec, & Meert, 2004; Hoffman & Schrag, 2002). The Palaeoproterozoic and Neoproterozoic steps in oxygenation of Earth's atmosphere have been previously postulated to in turn correlate with increases in continental elevation and consequent nutrient influx into the Earth's oceans (Campbell & Allen, 2008; Ganade De Araujo et al., 2014). While increases in crustal thickness likely played a significant role in these important milestones in Earth's evolution, the ultimate drivers were likely dependent on a complex set of variables and associated feedbacks that are inextricably linked (Lee et al., 2016). Indeed, widespread volcanism and exhumation associated with rifting, which we argue is linked to geodynamic changes in convergent margin networks, likely played a role in these processes during the Neoproterozoic time interval (Cox et al., 2016; DeLucia et al., 2018). Collectively, the intriguing correlations outlined above add increasing evidence for important potential links between the solid Earth and the evolution of its atmospheric and oceanic envelopes (Galvez & Pubellier, 2019), emphasizing the critical need to expand the collection of robust sample suites and further develop strategies to assess crustal thickness and exhumation through time.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available Paulsen et al. (2016a, 2016b), Nelson and Cottle (2017) and Paulsen et al. (2017).

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