Spot the difference: Zircon disparity tracks crustal evolution

M. Barham[1], C.L. Kirkland[1], and J. Hollis[2]

[1]Centre for Exploration and Targeting, School of Earth and Planetary Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

[2]Department of Geology, Ministry of Mineral Resources, Government of Greenland, P.O. Box 930, Nuuk, Greenland

ABSTRACT

We present a novel approach to examining the detrital zircon record, using similarity analysis of regionally defined populations to track crust production, preservation, and the efficacy of crustal recycling and homogenization. We compared temporally binned detrital zircon age data from geographically defined regions using Kolmogorov-Smirnov similarity measures, multidimensional scaling, and cluster analysis. This approach tracks disparity in the global detrital zircon record from 4 Ga to the present. Disparity values increase dramatically in the Neoarchean and are interpreted to reflect the emergence and preservation of isolated crustal fragments. Disparity values decrease through the early Paleoproterozoic, associated with the onset of plate tectonics and craton assembly. Oscillating disparity values through the remaining Proterozoic and Phanerozoic correlate (p = <0.01) with the supercontinent cycle, where regional detrital zircon populations are more similar during assembly and more distinct during dispersal. This link between the detrital zircon record and the supercontinent cycle necessitates well-coupled crustal recycling mechanisms that operate via both magmatic and sedimentary processes.

INTRODUCTION

Despite application of an increasing array of geochemical tools, facets of the evolution of Earth's continental crust remain enigmatic, most significantly because of denudation and subduction recycling of older crust (Condie, 2018; Hawkesworth et al., 2018). Zircon crystals grow in a range of magmatic rocks, are physicochemically robust, and accumulate as common accessory phases in sedimentary detritus. The stability of the $ZrSiO_4$ lattice and slow element diffusion enable primary age and geochemical data to be preserved in zircon grains over geological time scales, through weathering, erosion, diagenesis, and metamorphism, permitting the tracking of crustal evolution from at least 4.4 Ga (Hawkesworth and Kemp, 2006; Spencer et al., 2014). Despite source rock fertility influences and transport modification, investigation of detrital zircon populations captures snapshots of a drainage system's geological history and reduces preservation and sampling bias inherent in the available crystalline rock record (Hawkesworth et al., 2018).

While the age of "big data" is shedding new light on the development of continental crust (e.g., Voice et al., 2011), statistical tools are needed to resolve meaningful trends in data sets. Here, we demonstrate the potential of a new detrital zircon–based technique—temporally binned Kolmogorov-Smirnov distance-based multidimensional scaling (Vermeesch, 2013)—to assess geological relationships between discrete crustal regions across Earth history. We propose that this approach to global data provides novel insight into supercontinent development and fundamental tectonic processes that couple deep (magmatic-generational) and surface (sedimentary-preservational) systems.

METHODOLOGY

Detrital zircon analyses from a recently created Greenland geochronology database (Kirkland et al., 2016) were integrated with those extracted from the study of Voice et al. (2011) to yield 149,767 detrital zircon analyses spanning 4–0 Ga (Table DR1 in the GSA Data Repository[1]). Analyses were filtered to include only those within 10% of concordia. Analyses older than 4 Ga (298) are rare and geographically biased to Western Australia, and so they were omitted from global comparison. Data were divided geographically according to their sampling site and plotted as kernel density estimation age spectra (Fig. 1; Vermeesch, 2012). For grains older than 1500 Ma, $^{207}Pb/^{206}Pb$ ages were used, and $^{238}U/^{206}Pb$ ages were used for younger grains. Data from each geographic region were binned at 200 m.y. intervals to increase data per bin and thereby reduce the impact of local data significance, i.e., noise, while also resolving trends on a sub–500–300 m.y. supercontinent periodicity. Bins for any region with less than 30 analyses were deemed insufficient to meaningfully capture major peak age characteristics (Vermeesch, 2004).

We measured the similarity of detrital zircon spectra between different regions for each 200 m.y. time slice using the Kolmogorov-Smirnov distance statistic (Massey, 1951) expressed in multidimensional scaling (MDS) space (Vermeesch, 2013, 2018; see the Data Repository for a more detailed account of the methods). MDS diagrams graphically represent the similarity of samples by their proximity on a plot (Fig. 1B). We applied cluster analysis within MDS space to determine changes in the degree of similarity in detrital zircon populations through time. To avoid bias in measures of clustering, both average distance to a centroid (CD) and average nearest neighbor (NN) values were determined in MS Excel® and PAST (https://folk.uio.no/ohammer/past/), respectively (Fig. 1B; Hammer et al., 2001). The CD metric focuses on the proximity (similarity) of all regions relative to each other, while the NN metric is more sensitive to subclusters of regions (connections between some regions regardless of similarity to the total data set).

The detrital zircon time-disparity pattern was assessed for correlation with the supercontinent cycle via a point-biserial test in SPSS, using disparity measures as a continuous record against a simplified, binary
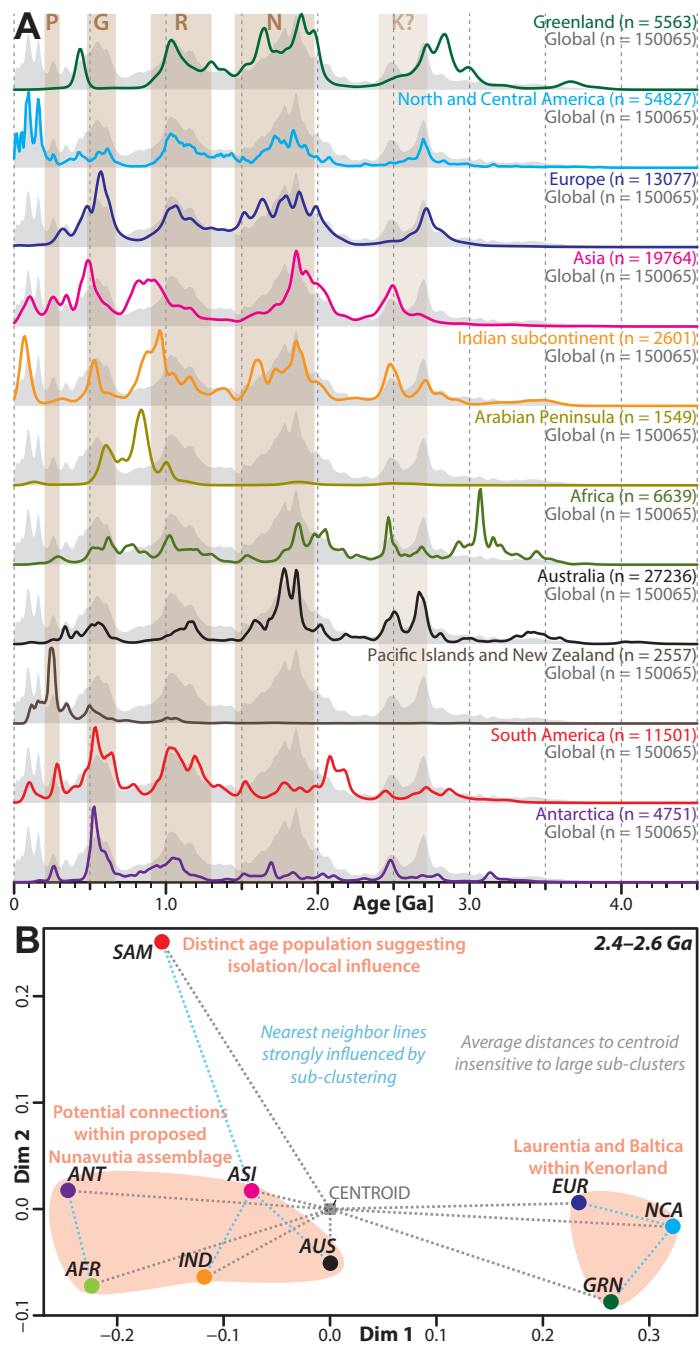

Figure 1. Global detrital zircon age data. A: Color-coded, geographically defined detrital zircon age spectra within 10% of concordia. Vertical bars correspond to intervals of proposed supercontinents: P—Pangea; G—Gondwana; R—Rodinia; N—Nuna; K—Kenorland (Table DR2 [see footnote 1]). Background gray spectra correspond to pooled global data. B: Multidimensional scaling plot of geographically distinguished detrital zircon populations for 2.4–2.6 Ga interval. AFR—Africa, ANT—Antarctica, ASI—Asia, AUS—Australia, EUR—Europe, GRN—Greenland, IND—India, NCA—North and Central America, SAM—South America.

supercontinent/no-supercontinent record (Kornbrot, 2014). There are no qualitative deep-time measures of the degree of supercontinentality. Instead, we adopted the definition of a "supercontinent" as a substantial grouping of formerly dispersed continents (Bradley, 2011). The most recent constraints on the timings of supercontinents were compiled for the Phanerozoic and Proterozoic (Table DR2), including relevant

constructive phases of the supercontinents. We calculated r and p values to establish the sense and statistical significance of any relationship between the variables (see the Data Repository for further explanation).

RESULTS

Detrital zircon age spectra exhibit broad similarities in age components and define global age peaks at ca. 0.5 Ga, ca. 1.0 Ga, ca. 1.8 Ga, ca. 2.5 Ga, and ca. 2.7 Ga, which correspond to intervals of supercontinentality (Fig. 1A; Hawkesworth et al., 2018). A distinct contribution of detrital zircon ages outside of a supercontinent episode from the North and Central American region provides a "Western Cordillera" (<0.25 Ga) sampling bias in the global data set from ongoing Pacific subduction. Disparity data vary by close to one order of magnitude, with values reflecting a relative metric within the time series being considered (Fig. 2; Table DR3). Overall, global detrital zircon disparity values are low through the Eoarchean to Mesoarchean, rise through the Neoarchean, and fall again through the first half of the Paleoproterozoic. Global detrital zircon disparity measures oscillate through the rest of the Proterozoic and Phanerozoic, with peaks in disparity centered at ca. 1.5 Ga, ca. 0.9 Ga, ca. 0.5 Ga, and 0.1 Ga (Fig. 2). Temporal variations in global detrital zircon disparity measure are broadly consistent regardless of the binning interval used (400, 200, or 100 m.y.), with reduced data per bin more likely to express noise from local signals in shorter intervals, while longer bins lack sufficient resolution for geologically significant processes such as the supercontinent cycle (Nance et al., 2014).

GEOLOGICAL IMPLICATIONS

Ideally, when interpreting global detrital zircon age data, consideration should be given to the potential of multicycle detritus, as well as renewed/enhanced erosion of preexisting, regionally specific, age-diagnostic crystalline rocks during later continent associations. Theoretically, interregional detrital zircon homogenization via exchange of preexisting diagnostic detrital zircon age signatures during supercontinent assembly has the potential to falsely indicate older, shared geological histories. However, Parman (2015) demonstrated that although distinctive age peaks in the global detrital zircon record are persistent through time, in general, diagnostic peaks are most prominent in preserved sediments laid down soonest after source crystallization. Furthermore, areas currently juxtaposed, or areas that were adjacent during recent supercontinent events (e.g., Antarctica, Australia, and India) show distinct total population detrital zircon spectra (Fig. 1). These observations support the dominantly intracrustal block erosion-preservation coupling that accounts for characteristic detrital zircon age peaks within geographically pooled data sets, rather than secondary exchange during later collisions. This, in turn, implies that the global detrital zircon database predominantly reflects fundamental tectono-magmatic production and preservation associations, and that detrital zircon global disparity patterns provide a tool that can track first-order crustal assemblages and processes through time.

Detrital zircon data were grouped according to present-day geographical sampling locations, reflecting one approach to areal pooling that mitigates limitations of insufficient data from smaller regions (impact of local/sampling bias), as well as complexities of tracking modern sampling back through complex geological histories for dissected or amalgamated crustal elements. While the geographic regions utilized do not necessarily reflect defined crustal blocks, many do contain discrete cratonic cores. Therefore, the approach provides a spatially unitized reference that can provide meaningful insights regarding geologically influenced disparity variations within the global detrital zircon population.

Disparity measures of geographically distinct detrital zircon age populations, based on both NN and CD metrics, largely trace the same
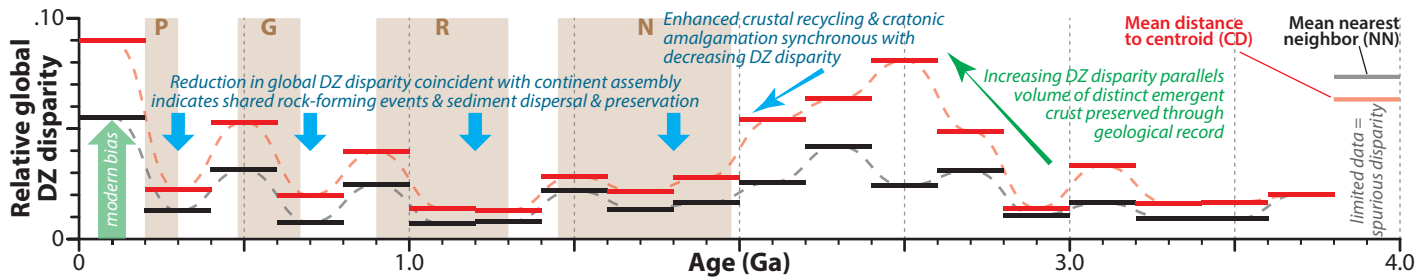
Figure 2. Detrital zircon (DZ) disparity measure of global rock record. Supercontinent intervals are indicated with vertical colored bars after Figure 1.

patterns of similarity through geological time (*r* value = 0.8, *p* value << 0.000), except during the 2.6–2.4 Ga interval. During this period, the NN metric tracks two relatively distinct subclusters of regional detrital zircon similarity and consequently indicates lower disparity, while the CD value is insensitive to subclusters and indicates higher disparity (Fig. 1B). The components of the two clusters identified by NN analysis within the 2.6–2.4 Ga interval broadly correspond with proposals for Kenorland and Nunavutia (Pehrsson et al., 2013), during one of the earliest known intervals of craton assembly (Evans, 2013). These observations, and the coherence of detrital zircon disparity patterns through time across different temporal bin widths, strongly support the interpretation of a real geological signal within global detrital zircon disparity measures.

Supercontinent Cycle

Myriad studies have previously identified patterns in the relative abundance of zircon crystallization ages, as well as the Hf- and O-isotope records preserved in the same grains, to help constrain crustal evolution during supercontinent assembly and breakup (Fig. 3). Broad temporal agreement across independent isotopic systems (e.g., O, Hf, Sm-Nd; Condie, 2014; Gardiner et al., 2016), crustal geochronology, and paleomagnetism (Veikkolainen et al., 2017) has improved confidence on the timing of Earth's supercontinent cycle. Whether some of these proxies track fundamental changes in crust generation and destruction (Condie, 2005) or preservational bias (Hawkesworth et al., 2009) associated with continental assembly and breakup continues to be debated. Regardless of which model is correct, here we demonstrate the excellent correlation between detrital zircon disparity measures and the perceived supercontinent cycle (*p* values 0.009–0.003; Table DR2). Sensitivity analysis of the disparity measure indicates the metric is robust to spurious signals (see the Data Repository).

Supercontinents involve shared orogenic belts and enhanced sediment dispersal and ultimate preservation from these same uplifted crystalline source regions. Conversely, separated continental fragments are characterized by unique magmatic events and independent sediment systems. Thus, overall, global detrital zircon age spectra are more similar (lower disparity) during supercontinent assembly and less similar (higher disparity), and regionally unique, during separation (Figs. 3 and 4).

Crustal Processes at the Archean-Proterozoic Boundary

An increase in global detrital zircon disparity occurs in the latest Neoarchean, before returning to low values during the 2.0–1.6 Ga interval, correlated with Nuna formation (Figs. 2 and 3). This pronounced excursion is interpreted to represent significant changes in crustal preservation and recycling during the transition from the early Earth's relatively hot crust and mantle conditions (Fig. 4).

Increases in measured detrital zircon disparity from ca. 2.8 Ga are interpreted to reflect increasingly emergent, isolated crustal components being progressively incorporated into the preserved rock record (Figs. 2–4;

Flament et al., 2008). Increased zircon abundance is recognized globally, along with an interpreted change from dominantly destructive crustal processes to production processes (Parman, 2015). These interpretations are supported by the appearance of passive continental margins in the geological record (Bradley, 2011), and geochemical evidence for significant pulses
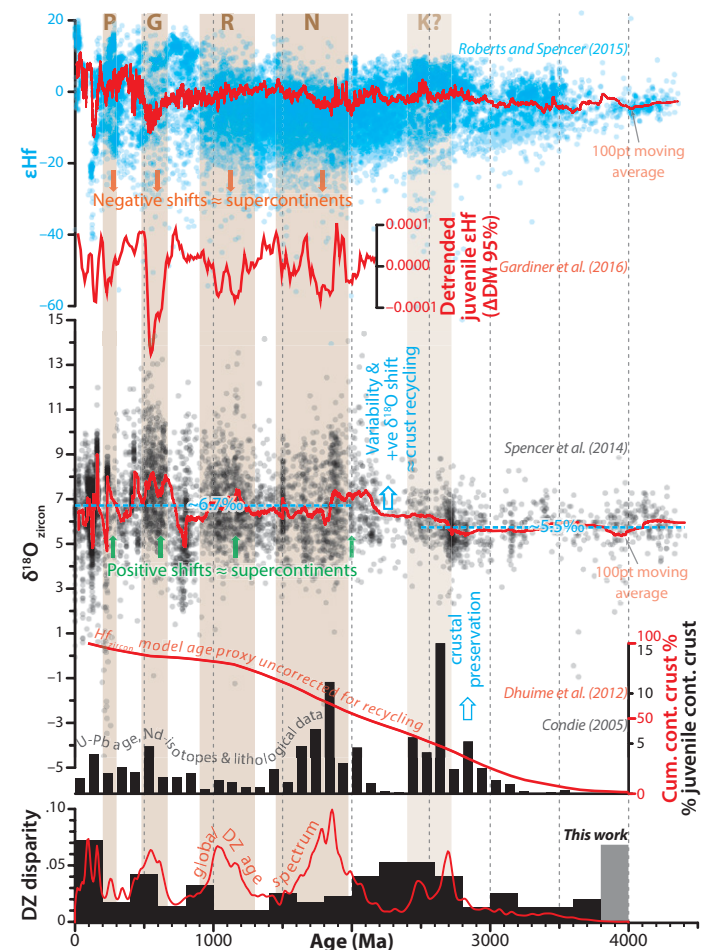

Figure 3. Compilation of geochemical proxies used to interpret aspects of geological evolution of Earth's crust. Multiple proxies demonstrate an increasing influence of continental crust preservation and onset of crustal processes (subduction, reworking, and assembly) that distinguishes Archean from Proterozoic intervals. Proterozoic record of Earth crustal processes is punctuated by supercontinent episodes, indicated by vertical colored bars after Figure 1. Detrital zircon (DZ) disparity values represent simplified average of nearest neighbor and distance to centroid measures. ΔDM95% represents the de-trended difference between depleted mantle and the Hf signal of the 95th-percentile most juvenile data per 10 m.y.
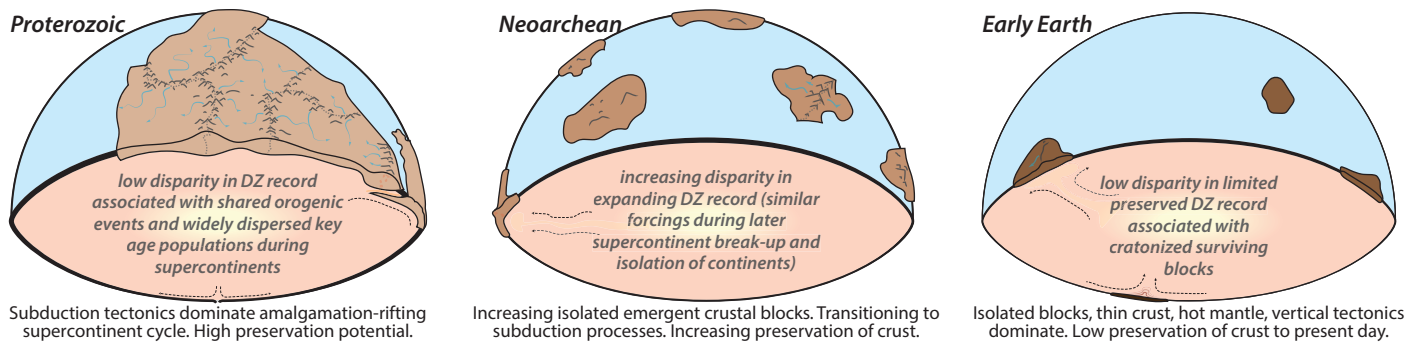
Proterozoic

low disparity in DZ record associated with shared orogenic events and widely dispersed key age populations during supercontinents

Subduction tectonics dominate amalgamation-rifting supercontinent cycle. High preservation potential.

Neoarchean

increasing disparity in expanding DZ record (similar forcings during later supercontinent break-up and isolation of continents)

Increasing isolated emergent crustal blocks. Transitioning to subduction processes. Increasing preservation of crust.

Early Earth

low disparity in limited preserved DZ record associated with cratonized surviving blocks

Isolated blocks, thin crust, hot mantle, vertical tectonics dominate. Low preservation of crust to present day.

Figure 4. Schematic model demonstrating connection between geographically defined detrital zircon (DZ) disparity and crustal evolution processes.

of juvenile continental crust growth between 3.0 and 2.6 Ga (Cawood et al., 2009), as well as increasing preservation and abundance of discrete continental crust fragments that formed in the Neoarchean.

Although geochemical evidence for juvenile crust addition and subduction processes has been identified in rocks from ca. 3.2 Ga (Van Kranendonk and Kirkland, 2016), it is likely that the transition to a world dominated by plate tectonics was gradual (Condie, 2018). The establishment of widespread subduction was associated with stiffening, thickening, and strengthening of the continental lithosphere from 2.6 to 2.4 Ga (Van Kranendonk and Kirkland, 2016), as also evidenced by the geochemistry of mafic rocks that reflect cooler mantle from the introduction of cold slabs (Condie, 2018). Coupling of zircon O- and Hf-isotope curves becomes apparent from approximately the Neoarchean, when isotope records become synchronized and more variable in response to increasing crust-mantle differentiation and later crustal reworking during the supercontinent cycle (Fig. 3). Zircon O-isotopes exhibit more positive values (with a distinctly different mean oscillation level after the Archean), corresponding to an increasing degree of crustal reworking (Fig. 3; Valley et al., 2005). This transition to widespread subduction and crustal recycling (Spencer et al., 2014; Roberts and Spencer, 2015), and consequent assembly of crustal fragments, is supported by a number of independent indicators of orogenesis, such as metamorphism (Brown, 2014) and orogenic gold mineralization (Goldfarb et al., 2010). Thus, reduced global detrital zircon disparity in the early Paleoproterozoic tracks increasing crustal recycling and orogenesis, and reflects the fundamental shift to a world with supercontinents, coincident with an increasing influence of collisional tectonics (Fig. 4).

CONCLUSIONS

Time-series disparity measures of global detrital zircon age spectra provide a new technique with which to investigate a number of geologically significant lithospheric to surface processes. Fundamentally, higher global detrital zircon disparity correlates with regionally unique age records driven by (1) more widespread crustal preservation of discrete crustal fragments (Neoarchean), or (2) separate evolution of disconnected continental areas (Proterozoic–Phanerozoic). Conversely, lower global detrital zircon disparity correlates with matching age records dictated by (1) global signatures on limited crustal blocks (Archean), and (2) increasing amalgamation of continental areas via subduction, and the similarity of preserved detritus from shared tectono-magmatic events during continent assembly (Proterozoic–Phanerozoic). Zircon disparity data are sensitive to crust generation and destruction both prior to plate tectonics and through the supercontinent cycle, and they illustrate a fundamental coupling of magmatic crust-formation and sedimentation processes. Furthermore, disparity time-series analysis holds significant promise for more spatially or temporally focused applications to assess evolving catchment-basin-craton relationships.

REFERENCES CITED

Bradley, D.C., 2011, Secular trends in the geologic record and the supercontinent cycle: Earth-Science Reviews, v. 108, p. 16–33, https://doi.org/10.1016/j.earscirev.2011.05.003.

Brown, M., 2014, The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics: Geoscience Frontiers, v. 5, p. 553–569, https://doi.org/10.1016/j.gsf.2014.02.005.

Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., and Windley, B.F., 2009, Accretionary orogens through Earth history, in Cawood, P.A., and Kröner, A., Earth Accretionary Systems in Space and Time: Geological Society of London Special Publications, v. 318, p. 1–36, https://doi.org/10.1144/SP318.1.

Condie, K.C., 2005, Crustal and mantle evolution, in Condie, K.C., ed., Earth as an Evolving Planetary System: Amsterdam, Elsevier, p. 265–313.

Condie, K.C., 2014, Growth of continental crust: A balance between preservation and recycling: Mineralogical Magazine, v. 78, p. 623–637, https://doi.org/10.1180/minmag.2014.078.3.11.

Condie, K.C., 2018, A planet in transition: The onset of plate tectonics on Earth between 3 and 2 Ga?: Geoscience Frontiers, v. 9, p. 51–60, https://doi.org/10.1016/j.gsf.2016.09.001.

Dhuime, B., Hawkesworth, C.J., Cawood, P.A., and Storey, C.D., 2012, A change in the geodynamics of continental growth 3 billion years ago: Science, v. 335, p. 1334–1336, https://doi.org/10.1126/science.1216066.

Evans, D.A.D., 2013, Reconstructing pre-Pangean supercontinents: Geological Society of America Bulletin, v. 125, p. 1735–1751, https://doi.org/10.1130/B30950.1.

Flament, N., Coltice, N., and Rey, P.F., 2008, A case for late-Archaean continental emergence from thermal evolution models and hypsometry: Earth and Planetary Science Letters, v. 275, p. 326–336, https://doi.org/10.1016/j.epsl.2008.08.029.

Gardiner, N.J., Kirkland, C.L., and Van Kranendonk, M.J., 2016, The juvenile hafnium isotope signal as a record of supercontinent cycles: Scientific Reports, v. 6, p. 38503, https://doi.org/10.1038/srep38503.

Goldfarb, R.J., Bradley, D., and Leach, D.L., 2010, Secular variation in economic geology: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 105, p. 459–465, https://doi.org/10.2113/gsecongeo.105.3.459.

Hammer, Ø., Harper, D.A.T., and Ryan, P.D., 2001, PAST: Paleontological statistics software package for education and data analysis: Palaeontologia Electronica, v. 4, p. 1–9.

Hawkesworth, C.J., and Kemp, A.I.S., 2006, Using hafnium and oxygen isotopes in zircons to unravel the record of crustal evolution: Chemical Geology, v. 226, p. 144–162, https://doi.org/10.1016/j.chemgeo.2005.09.018.

Hawkesworth, C., Cawood, P., Kemp, T., Storey, C., and Dhuime, B., 2009, A matter of preservation: Science, v. 323, p. 49–50, https://doi.org/10.1126/science.1168549.

Hawkesworth, C., Cawood, P.A., and Dhuime, B., 2018, Rates of generation and growth of the continental crust: Geoscience Frontiers, v. 10, p. 165–173, https://doi.org/10.1016/j.gsf.2018.02.004.

Kirkland, C.L., Hollis, J., and Gardiner, N.J., 2016, Greenland U-Pb Geochronology Database: http://www.greenmin.gl (accessed March 2019).

Kornbrot, D., 2014, Point biserial correlation, in Balakrishnan, N., et al., eds., Wiley StatsRef: Statistics Reference Online: New York, Wiley, https://doi.org/10.1002/9781118445112.stat06227.

Massey, F.J., 1951, The Kolmogorov-Smirnov test for goodness of fit: Journal of the American Statistical Association, v. 46, p. 68–78, https://doi.org/10.1080/01621459.1951.10500769.

Nance, R.D., Murphy, J.B., and Santosh, M., 2014, The supercontinent cycle: A retrospective essay: Gondwana Research, v. 25, p. 4–29, https://doi.org/10.1016/j.gr.2012.12.026.

Parman, S.W., 2015, Time-lapse zirconography: Imaging punctuated continental evolution: Geochemical Perspectives Letters, v. 1, p. 43–52, https://doi.org/10.7185/geochemlet.1505.

Pehrsson, S.J., Berman, R.G., Eglington, B., and Rainbird, R., 2013, Two Neoarchean supercontinents revisited: The case for a Rae family of cratons: Precambrian Research, v. 232, p. 27–43, https://doi.org/10.1016/j.precamres.2013.02.005.

Roberts, N.M.W., and Spencer, C.J., 2015, The zircon archive of continent formation through time, *in* Roberts, N.M.W., et al., eds., Continent Formation Through Time: Geological Society of London Special Publications, v. 389, p. 197–225, https://doi.org/10.1144/SP389.14.

Spencer, C.J., Cawood, P.A., Hawkesworth, C.J., Raub, T.D., Prave, A.R., and Roberts, N.M.W., 2014, Proterozoic onset of crustal reworking and collisional tectonics: Reappraisal of the zircon oxygen isotope record: Geology, v. 42, p. 451–454, https://doi.org/10.1130/G35363.1.

Valley, J.W., et al., 2005, 4.4 billion years of crustal maturation: Oxygen isotope ratios of magmatic zircon: Contributions to Mineralogy and Petrology, v. 150, p. 561–580, https://doi.org/10.1007/s00410-005-0025-8.

Van Kranendonk, M.J., and Kirkland, C.L., 2016, Conditioned duality of the Earth system: Geochemical tracing of the supercontinent cycle through Earth history: Earth-Science Reviews, v. 160, p. 171–187, https://doi.org/10.1016/j.earscirev.2016.05.009.

Veikkolainen, T.H., Biggin, A.J., Pesonen, L.J., Evans, D.A., and Jarboe, N.A., 2017, Advancing Precambrian palaeomagnetism with the PALEOMAGIA and PINT(QPI) databases: Scientific Data, v. 4, p. 170068, https://doi.org/10.1038/sdata.2017.68.

Vermeesch, P., 2004, How many grains are needed for a provenance study?: Earth and Planetary Science Letters, v. 224, p. 441–451, https://doi.org/10.1016/j.epsl.2004.05.037.

Vermeesch, P., 2012, On the visualisation of detrital age distributions: Chemical Geology, v. 312–313, p. 190–194, https://doi.org/10.1016/j.chemgeo.2012.04.021.

Vermeesch, P., 2013, Multi-sample comparison of detrital age distributions: Chemical Geology, v. 341, Supplement C, p. 140–146.

Vermeesch, P., 2018, Dissimilarity measures in detrital geochronology: Earth-Science Reviews, v. 178, p. 310–321, https://doi.org/10.1016/j.earscirev.2017.11.027.

Voice, P.J., Kowalewski, M., and Eriksson, K.A., 2011, Quantifying the timing and rate of crustal evolution: Global compilation of radiometrically dated detrital zircon grains: The Journal of Geology, v. 119, p. 109–126, https://doi.org/10.1086/658295.

Printed in USA