Spot the difference: Zircon disparity tracks crustal evolution

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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 Neoproterozoic, associated with the onset of plate tectonics and craton assembly. Oscillating disparity values through the remaining Proterozoic and Phanerzoic 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 ZrSiO₄ lattice and slow element diffusion enable primary age and geochemical data to be preserved in zircon grains over geologic 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 geologic 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 Repository¹). 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, ²³⁸U/²³⁵⁸⁷Pb ages were used, and ²⁰⁷⁶Pb/²⁰⁶Pb 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 characteristic (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...
Instead, we adopted the definition of a “supercontinent” as a substantial no qualitative deep-time measures of the degree of supercontinentality. There are SAM—South America, ANT—Antarctica, ASI—Asia, AUS—Australia, EUR—Europe, P—Pangea; G—Gondwana; R—Rodinia; N—Nuna; K—Kenorland. Vertical bars correspond to intervals of proposed supercontinents: 2.4–2.6 Ga. Diagnostics of geographically distinct detrital zircon age 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.

**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 supercontinentiality (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. 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
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 pat-
terns through time across different temporal bin widths, strongly sup-
port the interpretation of a real geological signal within global detrital
zircon disparity measures.

**Supercontinent Cycle**

Myriad studies have previously identified patterns in the relative abun-
dance 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 paleo-
magnetism (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 preservation 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 superconti-
nent 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 charac-
terized 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 dispa-
ry), 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 Neo-
archean, before returning to low values during the 2.0–1.6 Ga interval,
correlated with Nuna formation (Figs. 2 and 3). This pronounced excur-
sion 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 pro-
cesses to production processes (Parman, 2015). These interpretations are
supported by the appearance of passive continental margins in the geologi-
cal record (Bradley, 2011), and geochemical evidence for significant pulses

![Figure 2. Detrital zircon (DZ) disparity measure of global rock record. Supercontinent intervals are indicated with vertical colored bars after Figure 1.](image)

![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.](image)
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 orogeny, 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–PanArchean). 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–PanArchean). 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.

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REFERENCES CITED


