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Igneous rock area and age in continental crust

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ABSTRACT

Rock quantity and age are fundamental features of Earth's crust that pertain to many problems in geoscience. Here we combine new estimates of igneous rock area in continental crust from the Macrostrat database (https://macrostrat.org/) with a compilation of detrital zircon ages in order to investigate rock cycling and crustal growth. We find that there is little or no decrease in igneous rock area with increasing rock age. Instead, igneous rock area in North America exhibits four distinct Precambrian peaks, remains low through the Neoproterozoic, and then increases only modestly toward the recent. Peaks in Precambrian detrital zircon age frequency distributions align broadly with peaks in igneous rock area, regardless of grain depositional age. However, detrital zircon ages do underrepresent a Neoarchean peak in igneous rock area; young grains and ca. 1.1 Ga grains are also overrepresented relative to igneous area. Together, these results suggest that detrital zircon age distributions contain signatures of continental denudation and sedimentary cycling that are decoupled from the cycling of igneous source rocks. Models of continental crustal evolution that incorporate significant early increase in volume and increased sedimentation in the Phanerozoic are well supported by these data.

INTRODUCTION

Quantitative constraints on the age-varying properties of rocks in Earth's crust are critical for generating and testing hypotheses about the long-term evolution of Earth systems. *A priori* expectations for the quantity-age distribution of some rock types can be formulated with assumptions about how geological processes operate. For example, a fundamental prediction of the sedimentary cycle is that surviving sediment quantity should decrease exponentially with increasing age (e.g., Mackenzie and Pigott, 1981). The same principles of rock cycling apply to igneous rocks in continental crust, but models are less firmly grounded in a steady-state world view. This is because it is accepted that while today continents occupy ~30% of Earth's surface, at some early point in Earth's history there cannot have been any continental crust. Between these two constraints, nearly all possible models have been proposed, each with different preferences for the relative importance of cycling versus time-varying production (Armstrong, 1981; Roberts and Spencer, 2015; Puetz et al., 2017; Condie et al., 2018; Dhuime et al., 2018; Condie and Aster, 2010). Resolving these models and calibrating rock cycling has implications for how we interpret deep-time records and for generating and testing hypotheses for drivers of long-term changes in Earth systems (e.g., Hayes and Waldbauer, 2006; Husson and Peters, 2018).

Several attempts have been made to estimate continent- or global-scale rock quantity so as to constrain rock cycling and crustal growth models with minimum estimates of original volume. Some are based on geological maps (e.g., Blatt and Jones, 1975; Goodwin, 1996; Wilkinson et al., 2009), the most widely produced models for the lithology and age of rocks in Earth's crust, albeit only explicitly for a surface. Studies that integrate both surface and subsurface data provide a more complete description of crustal age and composition, but most have emphasized sediments (Ronov et al., 1980; Husson and Peters, 2017). Recent advances in high-throughput zircon U-Pb geochronology and geochemistry provide a proxy for crustal growth and recycling (e.g., Cawood et al., 2013; Payne et al., 2016; Korenaga, 2018; Rosas and Korenaga, 2018; Puetz and Condie, 2020), but these methods rely on several key assumptions, including that the frequency of crystallization ages among compilations of detrital zircon (DZ) is proportional to the quantity of igneous rocks that sourced the sediment.

We leverage advances in geoinformatics in order to provide new constraints on the area-age relationship of igneous rocks in continental crust. Our study is focused on North America, where surface and subsurface data are available, but we consider this record in the context of global map data.

DATA AND METHODS

Geologic maps in the Macrostrat database (https://macrostrat.org/; Peters et al., 2018) are grouped into four scales that combine sources into coherent two-dimensional representations. Here, we use the two scales that are globally complete for continents: "tiny" (~1:20,000,000 scale) and "small" (~1:5,000,000 scale; Fig. 1). The tiny-scale map derives from Chorlton (2007), and the small-scale map was composited from this and other sources (see Table S1 in the Supplemental Material[1]). All bedrock maps in Macrostrat consist of polygons for unit boundaries, each of which minimally has chronostratigraphic age(s) and lithology descriptions linked to vocabularies (see https://macrostrat.org/api/defs/).

Two map scales are considered here to illustrate the effects of different temporal binning

[1]Supplemental Material. Supplemental Figures S1 and S2, and Table S1 (data used in this analysis). Please visit https://doi.org/10.1130/GEOL.S.14772795 to access the supplemental material, and contact editing@geosociety.org with any questions.

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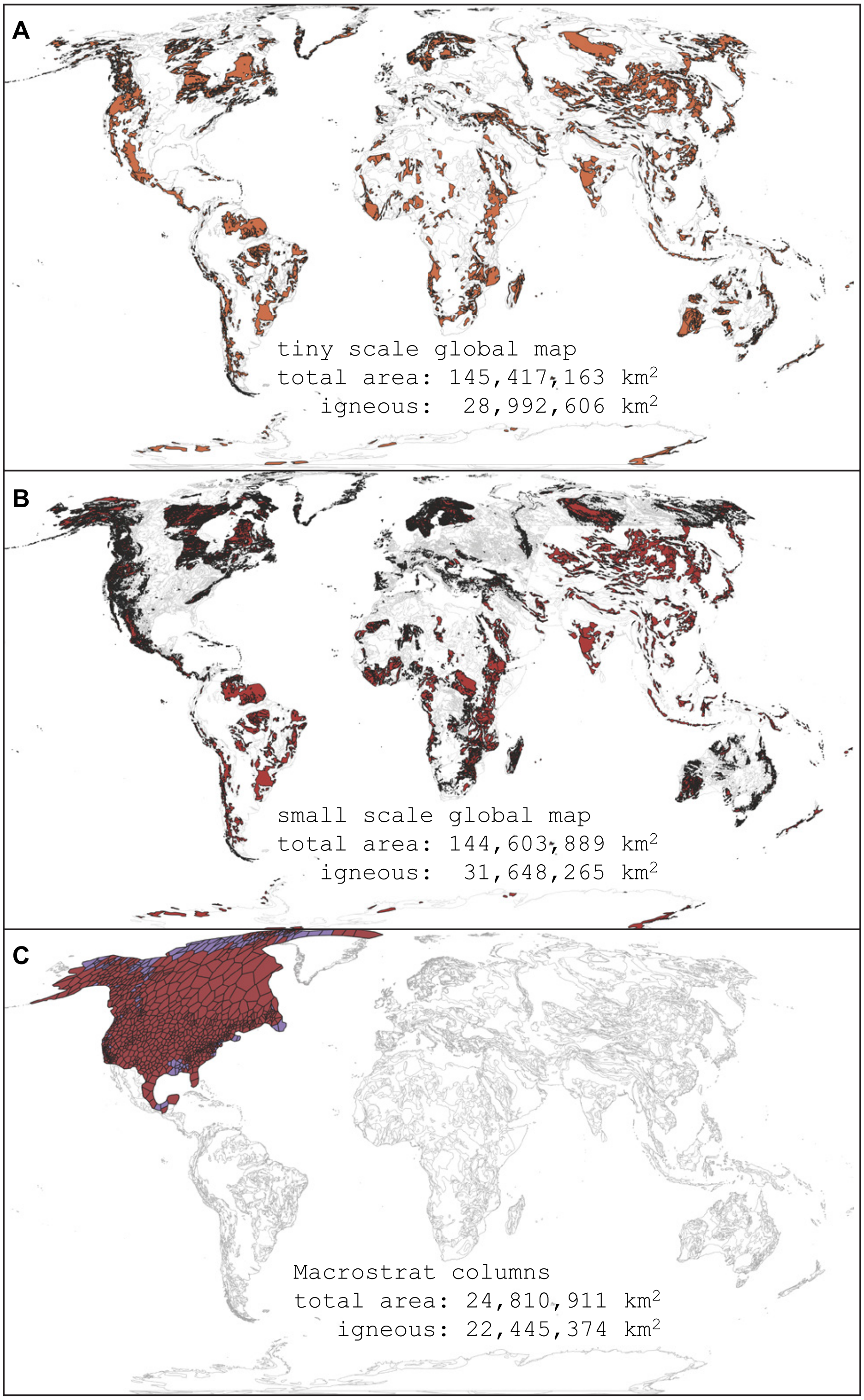

Figure 1. Geologic maps and columns. (A) "Tiny"-scale map, derived from ~1:20,000,000-scale map data. (B) "Small"-scale map, derived from ~1:5,000,000-scale map data. Dark polygons in A and B contain igneous rocks. (C) Locations of Macrostrat (https://macrostrat.org/) columns in North America. Red polygons contain igneous unit(s). Tiny-scale map from A is shown in gray in C.

schemes and rock unit definitions. To make the scales as comparable as possible, polygons were clipped to the outline of land today, and major oceanic islands were removed. Map polygons containing igneous or metaigneous rock are shown in Figure 1A and 1B, along with outlines for other rock types. For an online interactive version, see https://macrostrat.org/map/.

We also include geologic column data that summarize the lithologies and ages of rocks in the surface and subsurface regionally. Macrostrat columns are not yet global in coverage, and here we focus on 949 columns in North America (Fig. 1C). Column rock units acquire an age model that incorporates correlations to chronostratigraphic bins and relative age constraints between units within bins (Peters et al., 2018). Thus, the ages of rock units in columns are typically more finely resolved than in maps. Columns can also include igneous rocks of different ages and lithologies through a thickness of crust that is covered by sediment, a more volumetrically relevant representation of igneous rock quantity than that provided by maps (Fig. 1).

Area versus age was calculated for 1 m.y. increments by summing the Cartesian area in square kilometers (World Geodetic System 1984 [WGS84] spheroid) of all polygons (Fig. 1) containing igneous and/or metaigneous rocks with an intersecting age estimate. We also include concordant U-Pb "best ages" (Spencer et al., 2016) for 69,453 DZ from 746 samples matched to 392 Phanerozoic sedimentary units in North American columns. DZ measurements derive from multiple sources, most aggregated by Puetz (2018) and all of which are accessible via Macrostrat's application programming interface (API) and included in the Supplemental Material. DZ data were not used to construct Macrostrat age models.

RESULTS

Area-age results for igneous and metaigneous rocks in Macrostrat's global geological maps and North American columns (Fig. 1) share many similarities over 3.5 b.y. (Fig. 2). First, the absolute values of the area estimates are similar. This coincidence occurs because igneous rocks compose 19.8% and 21.9% of the total global area of the tiny- and small-scale maps, respectively, whereas columns occupy 17.1% of the total global map area. Thus, North America stripped of sediments to reveal all igneous rocks in the surface and subsurface has approximately the same total area as surface-exposed igneous rocks do globally; North America does have proportionally more igneous rock at the surface compared to globally (22.8% and 29.6% of the tiny- and small-scale map area in North America is igneous).

The more salient similarities between igneous rock area in global maps and North American columns involve temporal patterns (Fig. 2), including shared late Archean and late Paleoproterozoic peaks followed by a decrease into the Mesoproterozoic and then a smaller mid- to late Phanerozoic rise. The better temporal resolution of the small-scale map makes patterns more apparent, but results are consistent between map scales. Importantly, neither the global geological map nor North American column data exhibit a sustained increase in igneous area toward the present (Fig. 2A). To further assess this

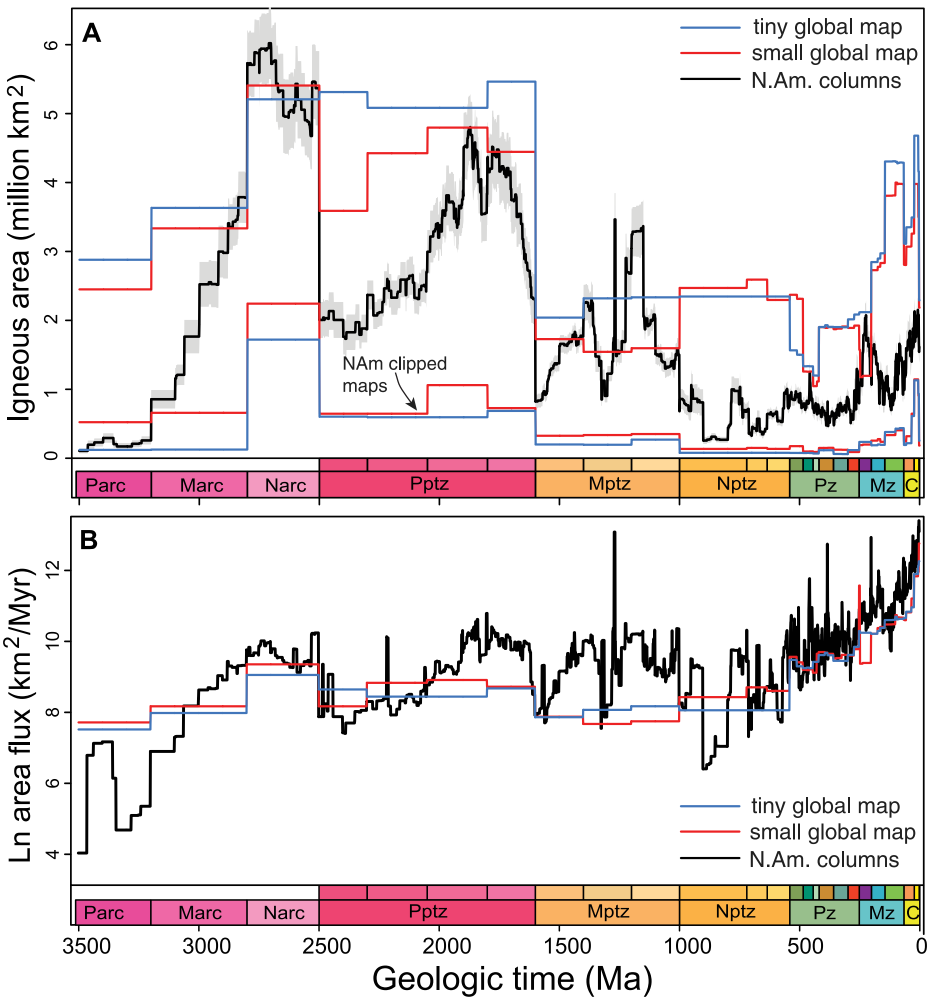

Figure 2. Time series of igneous rock area in global maps and North American (NAm) columns. (A) Total igneous area. Gray shading shows ±1 standard deviation of 100 bootstrap samples of rock units from North American columns. "North American clipped maps" shows igneous map area in North America. (B) Same as in A, but with area normalized by unit duration and plotted on natural log *y*-axis. Parc, Marc, Narc—Paleo-, Meso-, and Neoarchean; Pptz, Mptz, Nptz—Paleo-, Meso-, and Neoproterozoic; Pz, Mz, Cz—Paleo-, Meso-, and Cenozoic.

long-term trend and to address potential overweighting of poorly time-resolved rock units, we normalized the area of each igneous polygon by its estimated duration in millions of years. Such normalization does impact the temporal trajectory (Fig. 2B). Notably, the Archean and Paleoproterozoic peaks are lower and there is a large increase in area toward the recent during the Phanerozoic. Normalization by duration may, however, introduce bias by increasing the area per million years of units from extant igneous systems that will range into the future while decreasing that of igneous units that formed over an area for a long duration. Despite such distortions, and regardless of which estimate is used, there is little or no long-term decrease in igneous rock area with increasing age for most of the past 3.5 b.y. (Fig. 2).

Detrital zircon age frequencies in North America share many similarities with igneous rock area estimated from columns in the same region (Fig. 3A). This is true for combined DZ ages and for Precambrian-aged grains when they are subdivided by the depositional age of their host sediments. Notably, both igneous area and DZ ages exhibit Neoarchean and late Paleoproterozoic peaks, but their relative magnitudes are different. DZ age frequency also aligns broadly with a peak in column area at ca. 1.4 Ga, and there is a shared late Mesoproterozoic peak, albeit one that is larger and somewhat younger in DZ. Both igneous area and DZ age frequencies are low through the Neoproterozoic and Paleozoic and then increase in the Mesozoic–Cenozoic, with DZ becoming richer in grains relative to igneous rock area toward the recent (Fig. 3B).

DISCUSSION

Data on igneous-metaigneous rock area in the continental surface and subsurface combined with DZ age distributions have several implications. The simplest is that North America is sufficiently large and tectonically diverse to capture a signal of igneous rock quantity with parallels seen globally (Fig. 2). This result is consistent with the finding that the sedimentary record of North America contains a global signal (Ronov et al., 1980; Peters and Husson, 2017) and probably reflects the fact that "global tectonics" is quantitatively expressed in all such syntheses of rocks from large samples of continental crust. Nevertheless, there are clear differences between the global and regional data. For example, the small-scale global map shows a Neoproterozoic increase in igneous area whereas igneous area declines to a minimum in North America (Fig. 2), a likely signal of the Gondwanan Pan-African orogeny.

Another useful result is that both igneous rock area in North America and DZ age frequencies in the same region have similar temporal variation (Fig. 3A). Thus, both records are likely detecting the same quantity-age property of the crust. More interesting, however, are the differences in these records. Notably, Archean igneous rocks are more abundant in direct measures of quantity (Fig. 2) than suggested by DZ age frequencies. Indeed, there is an overall decrease in grain frequency relative to igneous area with increasing age (Fig. 3B). One hypothesis for this discrepancy is that zircon fertility is lower in older igneous rocks because they are more mafic on average (Moecher and Samson, 2006; Lee et al., 2016). However, the mean felsic-to-mafic ratio of igneous rocks in Macrostrat columns is not markedly different in the Archean (Fig. S1 in the Supplemental Material), and major elemental data from sediments also indicate that Archean crust had a compositional diversity similar to that of modern continents (Lipp et al., 2021). Correcting DZ abundance for changes in the zircon saturation of magmas (Keller et al., 2017) does significantly increase DZ density estimates in the Archean (Fig. S2), but not enough to account for the discrepancy (Fig. 3B).

In the absence of a compositional shift in igneous source rocks, another explanation for the observed change in DZ abundance relative to igneous rock area is that DZ grains undergo attrition in a way that is much faster than that of their igneous source rocks. This is expected if older grains are more likely to have undergone metamictization and Pb loss as well as physical destruction during transport (e.g., Markwitz et al., 2017; Andersen et al., 2019). The DZ record may also be inherently overprinted by its sedimentary origin (e.g., Andersen et al., 2016), with igneous rocks yielding fewer grains per unit area as they age due to increasing isolation from active orogens and lowering of their mean elevation (Spencer et al., 2018).

On shorter time scales, a notable difference between DZ age frequency and igneous area occurs at ca. 1.1 Ga, where the well-known peak in DZ ages associated with the assembly

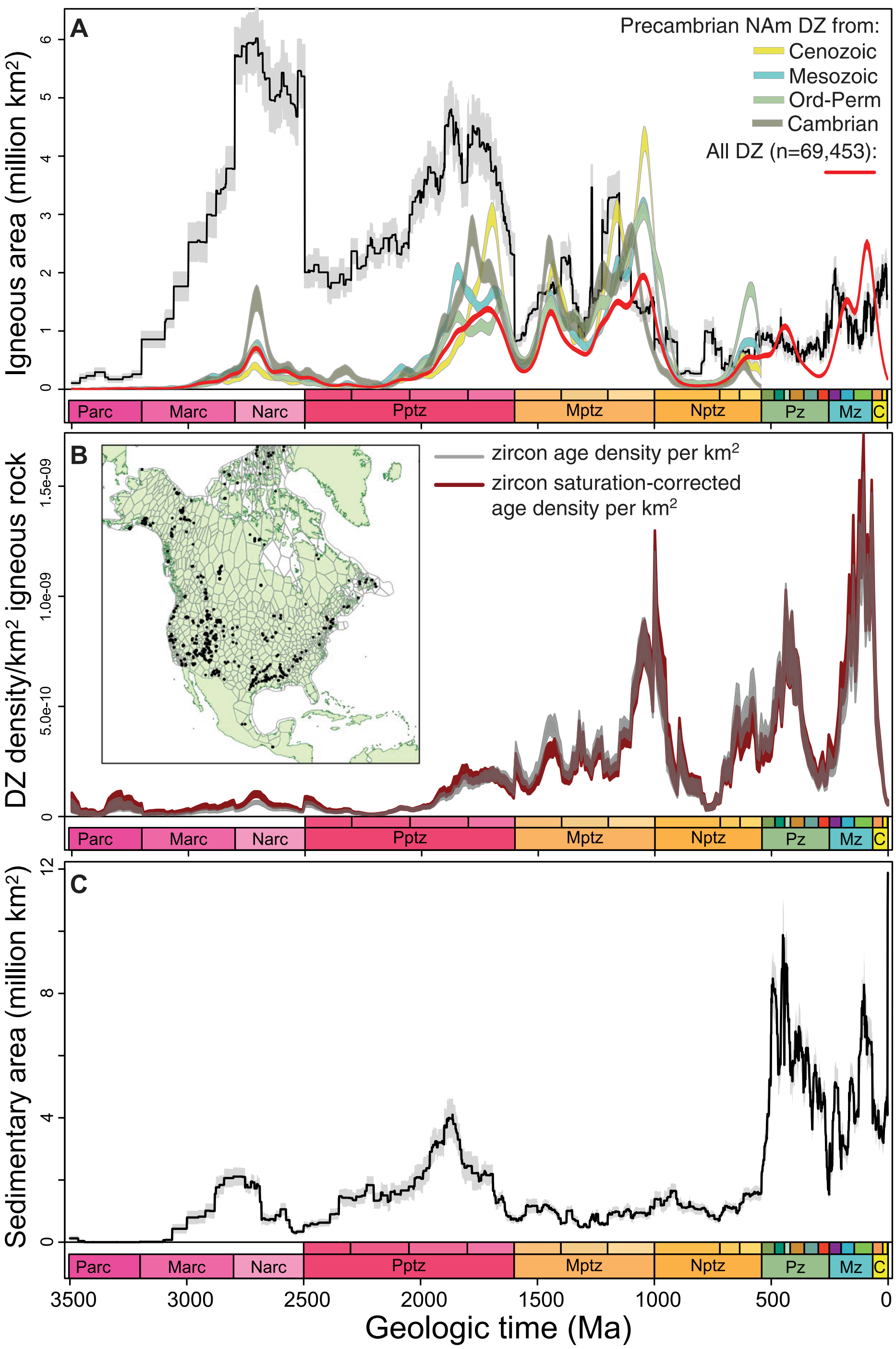

Figure 3. Rock area and detrital zircon (DZ) age kernel density (KD) in North America (NAm) versus geologic time. (A) Igneous area (from Fig. 2A) and KD for Precambrian-aged concordant DZ, subdivided by depositional age: Cambrian (*n* = 4368), Ordovician–Permian (*n* = 10,554), Mesozoic (*n* = 13,225), and Cenozoic (*n* = 11,196). KD for all concordant grains is also shown. KD scaling is identical between groups but arbitrary relative to rock area. KD lines encompass 95% confidence limits from 100 bootstrap replicate samples of grains. (B) Ratio of DZ KD and saturation-corrected KD (DZ density) to North American igneous rock area; envelopes incorporate bootstrap confidence limits for KD and igneous area (from A). Inset map shows location of all DZ samples (black dots), columns (Fig. 1C), and land area today. (C) Sedimentary rock area from columns (as in A). Geologic time abbreviations are as in Figure 2.

of Rodinia (Condie and Aster, 2010) is larger and younger than the peak in igneous area. It is possible that this offset reflects error in the column age model or overweighting by columns of small but widespread intrusive rocks, such as the Mackenzie dike swarm (western Canada) spike at ca. 1260 Ma (Fig. 2). Indeed, the ca. 1.2 Ga peak in igneous area is driven primarily by mafic rocks (Fig. S1), which may account for some of the difference with DZ ages. It is also possible that the offset reflects the unroofing of zircon-rich igneous rocks from a narrow, active stretch of the eastern North American margin (Park et al., 2010) or input of grains from outside of North America.

Importantly, Precambrian-aged DZ age densities are similar relative to each other and to igneous area, no matter the depositional age of their host sediment (Fig. 3A). Post-Cambrian Paleozoic sediments do contain more Ediacaran grains, a signature that reflects the docking of Ediacaran-aged arcs and terranes along the eastern margin of Laurentia (Park et al., 2010), and Cambrian sediments are richer in Archean grains, but the overall differences are small.

The similarities in Precambrian DZ age frequencies among depositional cohorts, combined with clear evidence of early Paleozoic reburial of most if not all of the igneous source rocks in North America (Fig. 3; Peters and Gaines, 2012; Keller et al., 2019), raises the possibility that much of the Precambrian DZ grain population was introduced *en masse* to the surface environment during late Precambrian continental denudation. Under this model, Precambrian-aged DZ grains in post-Cambrian Phanerozoic sedimentary rocks did not come predominantly from exposed igneous rocks, but rather from sediments that were recycled from the margins of a largely denuded continent. This pool of DZ was then spread back over the continent during progressive Phanerozoic reburial of the Great Unconformity, beginning with a thin blanket of predominately marine sediments that covered essentially all of Laurentia by the end-Ordovician. The possibility that a similar episode of continental denudation followed by reburial occurred during the Paleoproterozoic (Husson and Peters, 2018; Keller et al., 2019) provides an intriguing, if speculative, hypothesis for the low abundance of Archean DZ. In this scenario, Archean grains in post-Cambrian sediments would have undergone two such major cycles of continental exhumation and reburial.

Finally, regardless of sampling approach or geographic scale (Fig. 2), igneous rock quantity does not decrease exponentially with increasing age, as predicted by most basic models of rock cycling. Scaling igneous area by unit duration (Fig. 2B) does produce a decrease, but only over the recent to mid-Paleozoic. This is the same time scale over which there is a large decrease in nonmarine sediment (Peters and Husson, 2017), a higher elevation, faster-cycling component of the sedimentary system that does include igneous rocks. Thus, the rock age distributions reported here provide minimum bounds on net continental crustal quantities that account for rocks in the subsurface and in more rapidly cycling geomorphic systems. Covariance in old igneous and sedimentary rock quantity and the shifting abundance of sediment in continental crust (Fig. 3C) reinforces crustal evolution as a critical driver of long-term changes in Earth systems. Critical tests of this hypothesis and many new insights will be gained by expanding the geographic footprint and temporal acuity of surface-subsurface column data globally.

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REFERENCES CITED

Andersen, T., Kristoffersen, M., and Elburg, M.A., 2016, How far can we trust provenance and crustal evolution information from detrital zircons? A South African case study: Gondwana Research, v. 34, p. 129–148, https://doi.org/10.1016/j.gr.2016.03.003.

Andersen, T., Elburg, M.A., and Magawaza, B.N., 2019, Sources of bias in detrital zircon geochronology discordance, concealed lead loss and common lead correction: Earth-Science Reviews, v. 197, 102899, https://doi.org/10.1016/j.earscirev.2019.102899.

Armstrong, R.L., 1981, Radiogenic isotopes: The case for crustal recycling on a near-steady-state no-continental-growth Earth: Philosophical Transactions of the Royal Society: Series A, Mathematical and Physical Sciences, v. 301, p. 443–472, https://doi.org/10.1098/rsta.1981.0122.

Blatt, H., and Jones, R.L., 1975, Proportions of exposed igneous, metamorphic, and sedimentary rocks: Geological Society of America Bulletin, v. 86, p. 1085–1088, https://doi.org/10.1130/0016-7606(1975)86<1085:POEIMA>2.0.CO;2.

Cawood, P.A., Hawkesworth, C.J., and Dhuime, B., 2013, The continental record and the generation of continental crust: Geological Society of America Bulletin, v. 125, p. 14–32, https://doi.org/10.1130/B30722.1.

Chorlton, L.B., 2007, Generalized geology of the world: Geological Survey of Canada Open-File 5529, 48 p., https://doi.org/10.4095/223767.

Condie, K.C., and Aster, R.C., 2010, Episodic zircon age spectra of orogenic granitoids: The supercontinent connection and continental growth: Precambrian Research, v. 180, p. 227–236, https://10.1016/j.precamres.2010.03.008.

Condie, K.C., Puetz, S.J., and Davaille, A., 2018, Episodic crustal production before 2.7 Ga: Precambrian Research, v. 312, p. 16–22, https://doi.org/10.1016/j.precamres.2018.05.005.

Dhuime, B., Hawkesworth, C.J., Delavault, H., and Cawood, P.A., 2018, Rates of generation and destruction of the continental crust: Implications for continental growth: Philosophical Transactions of the Royal Society A, v. 376, 20170403, https://doi.org/10.1098/rsta.2017.0403.

Goodwin, A.M., 1996, Principles of Precambrian Geology: San Diego, California, Academic Press, 327 p.

Hayes, J.M., and Waldbauer, J.R., 2006, The carbon cycle and associated redox processes through time: Philosophical Transactions of the Royal Society, B, v. 361, p. 931–950, https://doi.org/10.1098/rstb.2006.1840.

Husson, J.M., and Peters, S.E., 2017, Atmospheric oxygenation driven by unsteady growth of the continental sedimentary reservoir: Earth and Planetary Science Letters, v. 460, p. 68–75, https://doi.org/10.1016/j.epsl.2016.12.012.

Husson, J.M., and Peters, S.E., 2018, Nature of the sedimentary rock record and its implications for Earth system evolution: Emerging Topics in Life Sciences, v. 2, p. 125–136, https://doi.org/10.1042/ETLS20170152.

Keller, C.B., Boehnke, P., and Schoene, B., 2017, Temporal variation in relative zircon abundance throughout Earth history: Geochemical Perspectives Letters, v. 3, p. 179–189, https://doi.org/10.7185/geochemlet.1721.

Keller, C.B., Husson, J.M., Mitchell, R.N., Bottke, W.F., Gernon, T.M., Boehnke, P., Bell, E.A., Swanson-Hysell, N.L., and Peters, S.E., 2019, Neoproterozoic glacial origin of the Great Unconformity: Proceedings of the National Academy of Sciences of the United States of America, v. 116, p. 1136–1145, https://doi.org/10.1073/pnas.1804350116.

Korenaga, J., 2018, Estimating the formation age distribution of continental crust by unmixing zircon ages: Earth and Planetary Science Letters, v. 482, p. 388–395, https://doi.org/10.1016/j.epsl.2017.11.039.

Lee, C.-T.A., Yeung, L.Y., McKenzie, N.R., Yokoyama, Y., Ozaki, K., and Lenardic, A., 2016, Two-step rise of atmospheric oxygen linked to the growth of continents: Nature Geoscience, v. 9, p. 417–424, https://doi.org/10.1038/ngeo2707.

Lipp, A.G., et al., 2021, The composition and weathering of the continents over geologic time: Geochemical Perspectives Letters, v. 17, p. 21–26, https://doi.org/10.7185/geochemlet.2109.

Mackenzie, F.T., and Pigott, J.D., 1981, Tectonic controls of Phanerozoic sedimentary rock cycling: Journal of the Geological Society, v. 138, p. 183–196, https://doi.org/10.1144/gsjgs.138.2.0183.

Markwitz, V., Kirkland, C.L., Mehnert, A., Gessner, K., and Shaw, J., 2017, 3-D characterization of detrital zircon grains and its implications for fluvial transport, mixing, and preservation bias: Geochemistry Geophysics Geosystems, v. 18, p. 4655–4673, https://doi.org/10.1002/2017GC007278.

Moecher, D.P., and Samson, S.D., 2006, Differential zircon fertility of source terranes and natural bias in the detrital zircon record: Implications for sedimentary provenance analysis: Earth and Planetary Science Letters, v. 247, p. 252–266, https://doi.org/10.1016/j.epsl.2006.04.035.

Park, H., Barbeau, D.L., Jr., Rickenbacker, A., Bachmann-Krug, D., and Gehrels, G., 2010, Application of foreland basin detrital-zircon geochronology to the reconstruction of the southern and central Appalachian orogen: The Journal of Geology, v. 118, p. 23–44, https://doi.org/10.1086/648400.

Payne, J.L., McInerney, D.J., Barovich, K.M., Kirkland, C.L., Pearson, N.J., and Hand, M., 2016, Strengths and limitations of zircon Lu-Hf and O isotopes in modelling crustal growth: Lithos, v. 248, p. 175–192, https://doi.org/10.1016/j.lithos.2015.12.015.

Peters, S.E., and Gaines, R.R., 2012, Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion: Nature, v. 484, p. 363–366, https://doi.org/10.1038/nature10969.

Peters, S.E., and Husson, J.M., 2017, Sediment cycling on continental and oceanic crust: Geology, v. 45, p. 323–326, https://doi.org/10.1130/G38861.1.

Peters, S.E., Husson, J.M., and Czaplewski, J., 2018, Macrostrat: A platform for geological data integration and deep-time Earth crust research: Geochemistry Geophysics Geosystems, v. 19, p. 1393–1409, https://doi.org/10.1029/2018GC007467.

Puetz, S.J., 2018, A relational database of global U-Pb ages: Geoscience Frontiers, v. 9, p. 877–891, https://doi.org/10.1016/j.gsf.2017.12.004.

Puetz, S.J., and Condie, K.C., 2020, Applying Popperian falsifiability to geodynamic hypotheses: Empirical testing of the episodic crustal/zircon production hypothesis and selective preservation hypothesis: International Geology Review, https://doi.org/10.1080/00206814.2020.1818143 (in press).

Puetz, S.J., Condie, K.C., Pisarevsky, S., Davaille, A., Schwarz, C.J., and Ganade, C.E., 2017, Quantifying the evolution of the continental and oceanic crust: Earth-Science Reviews, v. 164, p. 63–83, https://doi.org/10.1016/j.earscirev.2016.10.011.

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 [London] Special Publication 389, p. 197–225, https://doi.org/10.1144/SP389.14.

Ronov, A.B., Khain, V.E., Balukhovsky, A.N., and Seslavinsky, K.B., 1980, Quantitative analysis of Phanerozoic sedimentation: Sedimentary Geology, v. 25, p. 311–325, https://doi.org/10.1016/0037-0738(80)90067-6.

Rosas, J.C., and Korenaga, J., 2018, Rapid crustal growth and efficient crustal recycling in the early Earth: Implications for Hadean and Archean geodynamics: Earth and Planetary Science Letters, v. 494, p. 42–49, https://doi.org/10.1016/j.epsl.2018.04.051.

Spencer, C.J., Kirkland, C.L., and Taylor, R.J.M., 2016, Strategies towards statistically robust interpretations of in situ U-Pb zircon geochronology: Geoscience Frontiers, v. 7, p. 581–589, https://doi.org/10.1016/j.gsf.2015.11.006.

Spencer, C.J., Kirkland, C.L., and Roberts, N.M.W., 2018, Implications of erosion and bedrock composition on zircon fertility: Examples from South America and Western Australia: Terra Nova, v. 30, p. 289–295, https://doi.org/10.1111/ter.12338.

Wilkinson, B.H., McElroy, B.J., Kesler, S.E., Peters, S.E., and Rothman, E.D., 2009, Global geologic maps are tectonic speedometers—Rates of rock cycling from area-age frequencies: Geological Society of America Bulletin, v. 121, p. 760–779, https://doi.org/10.1130/B26457.1.

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