GEOLOGY

Episodic growth of felsic continents in the past 3.7 Ga

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Continents form the most accessible parts of Earth, but their complex compositions make their origin difficult to investigate. A novel approach based on a comprehensive compilation of samarium-neodymium isotopic compositions of detrital sedimentary rocks is here used to unravel continental growth through time. This record reveals that continents were as felsic as today in the past 3.7 Ga (billion years) and that their growth was not continuous but episodic. Reworking of preexisting crust was a ubiquitous process during most of Earth history, but at least six periods of continental growth can be identified every 500 to 700 Ma (million years) in the past 3.7 Ga. This recurrence could be accounted for by changes in tectonic plate velocities favoring periods of rapid subduction and enhanced production of juvenile felsic crust.

INTRODUCTION

Understanding how continental crust forms is essential to unravelling the geodynamic forces that shaped Earth, the onset of plate tectonics, and the global geochemical cycles of elements such as oxygen and phosphorus that eventually contributed to the development of primitive life (*1*, *2*). Yet, our knowledge of the history of continents is far from complete. Modern continental crust is largely made of felsic rocks—rocks rich in silicon and aluminum—and is formed and destroyed in subduction zones via processes linked to plate tectonics (*3*). At present, the net growth rate of continental crust (i.e., the volume of new crust generated minus the volume of crust destroyed) is estimated to be close to zero, meaning that the total volume of continental crust has not changed significantly in the past 200 to 300 million years (Ma) (*4*). Whether plate tectonics operated during the first half of Earth history and was responsible for the early crustal growth is highly controversial (*5*–*8*). The debate crystallizes around two key questions: whether continental crust has grown by pulses or continuously (*9*–*12*) and whether the composition of continental crust has changed through time (*13*–*15*), in particular, at the end of the Archean 2.5 billion years (Ga) ago.

In this study, crustal composition and growth mechanisms are investigated using a compilation of published Sm-Nd isotopic analyses—$N = 2653$ including both the $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios—of fine- and coarse-grained detrital sedimentary rocks that formed in the past 3.7 Ga (data S1 and fig. S1). The great advantage of using bulk sediment composition is that a single analysis provides the average composition of a large continental area (*16*) and is therefore much more powerful in terms of representativity than in situ analyses of zircons on individual mineral grains (*5*, *17*). Provided that the effects of weathering and hydrodynamic sorting during sediment transport are properly treated (*18*, *19*), the Sm-Nd isotopic compositions of detrital sedimentary rock is a powerful tool capable of recording the full spectrum of rock compositions that were exposed at the surface of continents at different times through Earth history. In particular, it has proven to be quite sensitive to the presence of mafic rocks in modern (*18*, *19*) and Archean (*20*) catchment areas. On the basis of the well-defined correlation that exists between $^{147}Sm/^{144}Nd$ ratios and SiO_2 contents in igneous rocks (*20*), the $^{147}Sm/^{144}Nd$ ratios of the compiled sedimentary rocks are first used to estimate the average silica (SiO_2) content of the continents through time. Then, the compiled radiogenic $^{143}Nd/^{144}Nd$ ratios of sedimentary rocks are integrated into an isotopic model to trace the proportion of juvenile crust and discuss continental crust volumes through time. This approach assumes that the composition of the upper continental crust, as sampled by sedimentary rocks, does provide useful insights into the generation and evolution of the continental crust as a whole.

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RESULTS AND DISCUSSION

The silica content of continental crust through time

The silica content of continental crust is a key parameter for understanding how crustal rocks formed through time. Rocks making up modern continents are felsic with an average SiO_2 content of 66.6 weight % (wt %) (*21*). They are highly differentiated compared to rocks in the oceanic crust, which have mafic compositions and an average SiO_2 content of 50.5 wt % (*22*). Estimating the silica content of the continents through time is not straightforward because most of the rocks that outcropped in the past have since been eroded away. In addition, silica contents cannot be directly extrapolated from the composition of sedimentary rocks because quartz, the main mineral carrier of SiO_2, is hydrodynamically sorted during sediment transport, leading to strong variation of SiO_2 contents as a function of sediment grain size. In contrast, the $^{147}Sm/^{144}Nd$ ratio of sedimentary rocks has been shown to faithfully reflect the composition of the continents exposed to weathering because this ratio is not very fractioned by mineral sorting during sediment transport (*19*, *23*), and Sm and Nd are among the most insoluble elements. This means that fine- and coarse-grained sedimentary rocks share roughly the same $^{147}Sm/^{144}Nd$ ratios (fig. S2) as their source rocks. During the formation of igneous rocks, melting and crystallization generate a large range of $^{147}Sm/^{144}Nd$ ratios. This translates into a strong inverse correlation between the $^{147}Sm/^{144}Nd$ ratio of igneous rocks and their SiO_2 contents (Fig. 1B). Note that the correlations between $^{147}Sm/^{144}Nd$ ratios and SiO_2 contents are different for Archean and post-Archean igneous rocks (fig. S3) due to changes in mantle melting conditions through Earth's history (*24*). The secular evolution of igneous rock composition has important implications for crustal SiO_2 estimates through time (*25*, *26*) and is thoroughly discussed in the Supplementary Materials. In Fig. 1, a correlation combining all available SiO_2 and $^{147}Sm/^{144}Nd$ data for Archean and

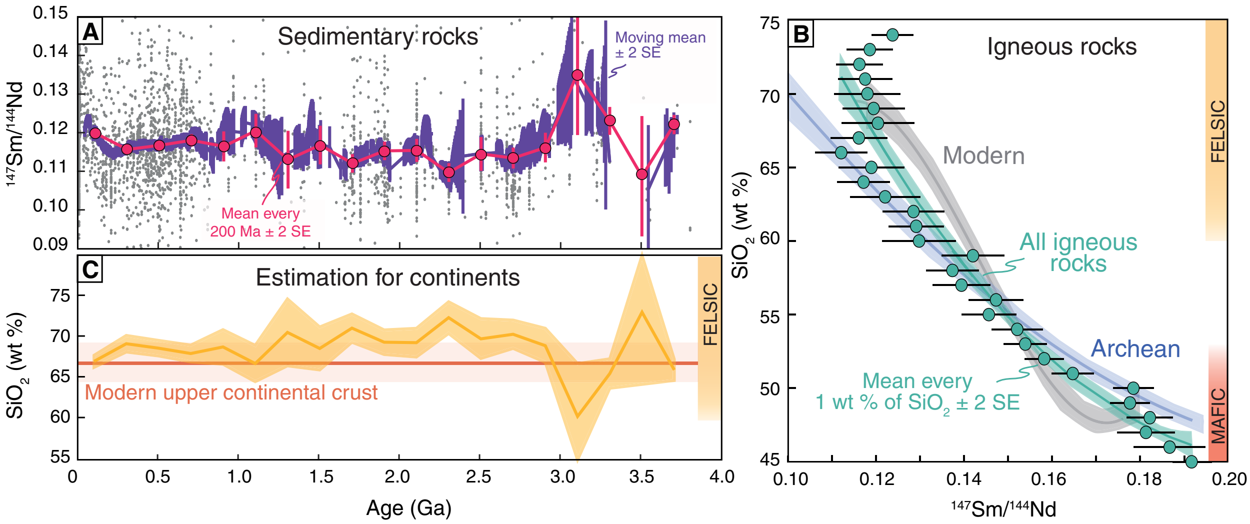

Fig. 1. Evolution of ^{147}Sm/^{144}Nd ratios and SiO_2 contents in rocks through time. (**A**) Compiled ^{147}Sm/^{144}Nd ratios of sedimentary rocks (gray points; data S1). Binned and moving means are shown in pink and purple with error bars. For the moving mean, the length of the sliding window is 200 Ma. The two types of means globally show the same variations through time. (**B**) Variation of SiO_2 contents as a function of ^{147}Sm/^{144}Nd ratios in Archean (blue), modern (gray), and all age (green) igneous rocks compiled from the GEOROC database. The best-fit regression lines are shown with 95% confidence interval (shaded areas). (**C**) Average SiO_2 contents of continents through time estimated using binned means in (A) and the correlation for all igneous rocks (green) in (B). Value for modern upper continental crust is from Rudnick and Gao (*21*).

Table 1. Average Nd isotopic composition of the upper continental crust through time as estimated in this study. Values reported for ^{147}Sm/^{144}Nd, ^{143}Nd/^{144}Nd (T), ε_{Nd} (T), and Nd model ages correspond to mean compositions of sedimentary rocks (fine- and coarse-grained) every 200 Ma. The number of samples per bin is the number of sedimentary rocks averaged per bin after outlier rejection. SE stands for standard error. ^{143}Nd/^{144}Nd (T), ε_{Nd} (T), and model ages were calculated as described in Materials and Methods. Nd model ages correspond to $TDM_{4.5Ga}$ (model ages calculated relative to the depleted mantle linearly extrapolated back in time to the CHUR composition at 4.5 Ga from the present-day Nd isotopic composition of MORB).

Age bin (Ga)	Average age bin (Ga)	Number of samples per bin	^{147}Sm/^{144}Nd	2 SE	^{143}Nd/^{144}Nd (T)	2 SE	ε_{Nd} (T)	2 SE	Nd model age (Ga)	2 SE
0–0.2	0.1	659	0.1200	0.0010	0.512098	0.000032	−9.5	0.6	1.56	0.05
0.2–0.4	0.3	381	0.1157	0.0013	0.511770	0.000026	−9.2	0.5	1.71	0.04
0.4–0.6	0.5	456	0.1168	0.0013	0.511557	0.000022	−8.7	0.4	1.86	0.04
0.6–0.8	0.7	244	0.1181	0.0016	0.511365	0.000042	−8.1	0.8	1.95	0.06
0.8–1.0	0.9	60	0.1165	0.0039	0.511238	0.000070	−5.1	1.3	1.86	0.09
1.0–1.2	1.1	47	0.1206	0.0043	0.511009	0.000043	−3.7	1.0	2.01	0.11
1.2–1.4	1.3	22	0.1131	0.0075	0.510765	0.000120	−3.9	2.0	2.16	0.24
1.4–1.6	1.5	26	0.1168	0.0050	0.510735	0.000061	−1.1	1.0	2.01	0.08
1.6–1.8	1.7	126	0.1121	0.0024	0.510262	0.000046	−3.3	0.9	2.40	0.08
1.8–2.0	1.9	153	0.1153	0.0024	0.510011	0.000031	−3.7	0.6	2.60	0.05
2.0–2.2	2.1	70	0.1155	0.0030	0.509902	0.000034	−0.3	0.7	2.51	0.06
2.2–2.4	2.3	47	0.1097	0.0024	0.509544	0.000037	−3.1	0.6	2.84	0.06
2.4–2.6	2.5	51	0.1145	0.0044	0.509300	0.000042	−1.9	0.8	2.98	0.07
2.6–2.8	2.7	154	0.1135	0.0027	0.509151	0.000019	−0.4	0.4	2.99	0.03
2.8–3.0	2.9	55	0.1162	0.0038	0.508917	0.000041	−0.3	0.5	3.15	0.06
3.0–3.2	3.1	15	0.1354	0.0159	0.508589	0.000118	−1.5	2.5	3.46	0.24
3.2–3.4	3.3	44	0.1231	0.0036	0.508399	0.000033	−0.7	0.6	3.54	0.07
3.4–3.6	3.5	7	0.1088	0.0155	0.508023	0.000027	−0.4	0.7	3.72	0.05
3.6–3.8	3.7	7	0.1221	0.0025	0.507891	0.000009	1.7	0.2	3.721	0.003

post-Archean igneous rocks (Fig. 1B) is used to reconstruct the average SiO_2 content of continents through time (Fig. 1C) from the compiled $^{147}Sm/^{144}Nd$ ratios of detrital sedimentary rocks (Fig. 1A). The binning approach used in Fig. 1B is similar to a binary mixing calculation, taking into account the differences in Nd concentrations between felsic and mafic lithologies (fig. S4). The advantage of the binning approach over binary mixing calculations is that no assumption is made on the compositions of the felsic and mafic endmembers. The robustness of the model and its sensitivity to data binning, regression type, and sediment grain size are evaluated in the Supplementary Materials (figs. S2, S3, and S5).

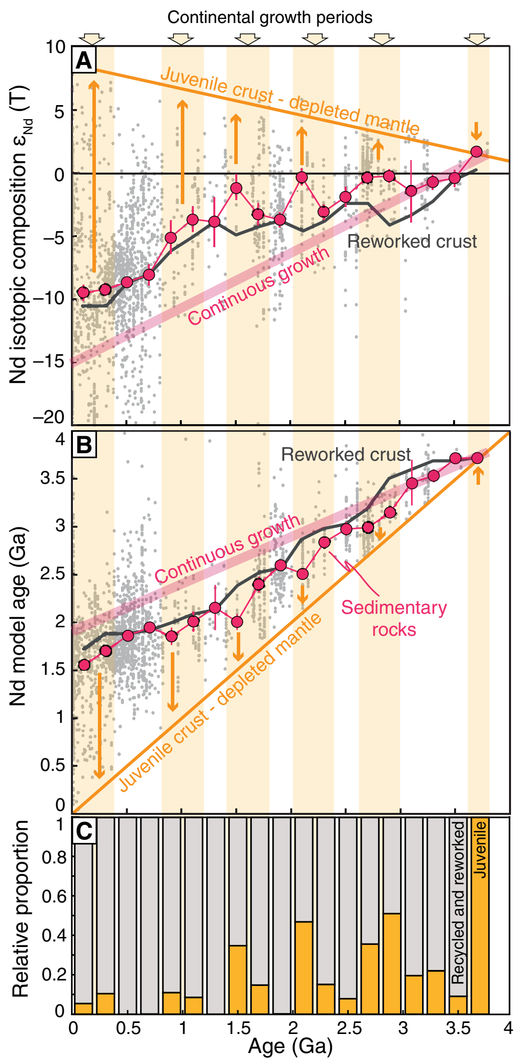

Fig. 2. Initial Nd isotopic composition and model age of sedimentary rocks as proxies to estimate the proportion of juvenile crust through time. (**A**) Nd isotopic compositions, expressed as ε_{Nd} (T), are recalculated at the stratigraphic age of the sedimentary rocks. (**B**) Nd model ages are calculated relative to the depleted mantle assuming a depletion event at 4.5 Ga. It is here assumed that juvenile crust formed from a mantle depleted at 4.5 Ga; hence, the composition of juvenile crust is similar to that of the depleted mantle at any time, *t* (yellow evolution line). Data compiled for sedimentary rocks are shown by gray points. Pink dots and error bars (+/- 2SE) correspond to the compiled means binned every 200 Ma as in Fig.1A. Vertical yellow arrows and bands indicate periods during which the contribution of juvenile crust is higher than expected from the modeled reworked crust (i.e., continental growth periods). The continuous growth line corresponds to the trend that sediments should have followed if they were derived from a continental crust made by the addition of a constant volume of juvenile crust every 100 Ma for the past 3.8 Ga (see Materials and Methods for more details). (**C**) Results of the model showing the relative proportions of juvenile crust through time deduced from Nd model ages of sedimentary rocks.

The important result emerging from this exercise is that the average SiO_2 content of continents did not vary significantly over the past 3.7 Ga. Since sediments only sample the part of continental crust that is above sea level, this means that the emerged part of continental crust has remained felsic (>60 wt % SiO_2) as far back as the preserved sedimentary record goes. No obvious transition from a mafic basaltic crust (45 to 52 wt % SiO_2) to a felsic upper crust is observed at the end of the Archean 2.5 Ga ago. Two periods of time—3.1 and 3.5 Ga—are subjected to large uncertainties due to the scarcity of sedimentary rock data older than 3 Ga ($N = 73$; Table 1) relative to the number and geographic extent of the sampled cratons (Pilbara, Kapvaal, Zimbabwe, North Atlantic, and Slave). While underconstrained, the estimated SiO_2 contents at 3.1 and 3.5 Ga are >60 wt % and overlap with modern upper continental crust values (Fig. 1C).

The average SiO_2 content of the upper continental crust can be interpreted in two ways. It could reflect the mean composition of the bimodal distribution of SiO_2 contents in continental igneous rocks (*27*), i.e., the result of a mixture between mafic, mostly volcanic rocks ($45 < SiO_2 < 55$ wt %) and felsic, mostly plutonic rocks ($65 < SiO_2 < 75$ wt %) as assumed by many others before (*13*, *14*, *26*, *28*). In this case, the proportion of felsic and mafic rocks exposed to weathering on continents could be estimated with mixing curves in the SiO_2 versus Sm/Nd space (fig. S4) but mixing proportions heavily depend on the chosen endmember compositions. Alternatively, the average SiO_2 of the upper crust may not result from a binary mixture between mafic and felsic rocks but could be indicative of deeper crustal processes and represent the average composition of evolved silicic melts produced by the differentiation of mafic magmas [e.g. (*29*)] or could be a combination of both processes.

The result of the $^{147}Sm/^{144}Nd$ model strongly contrasts with previous studies that suggested a major change in the composition of the continental crust, from dominantly mafic to felsic composition, about 2.5 to 3 Ga ago; a change that was often related to the onset of plate tectonics (*13*, *15*, *30*). More recently, Greber *et al.* (*14*) used the Ti isotopic composition of shales to infer an absence of significant variation in the SiO_2 content of the crust exposed to weathering in the past 3.5 Ga. Recent reevaluations of the trace and major element records of terrigenous sediments by Keller and Harrisson (*25*) and Ptáček *et al.* (*26*) further conclude that the Archean continental crust was dominantly felsic. Such a compositional stability supports the idea that the mechanism of formation of felsic continental crust did not significantly change through time and hence that subduction, and some form of plate tectonics, may have operated at least during the past 3.7 Ga. Felsic continental crust can however form in other geodynamic settings [e.g. (*31*)] that cannot be excluded on the basis of the secular evolution of crustal silica contents alone.

Continental growth

Thereafter, the compiled $^{143}Nd/^{144}Nd$ isotopic ratios of sedimentary rocks, expressed as ε_{Nd} (T) in Fig. 2A, are considered to be representative for the composition of the continents at the time of sediment deposition. ε_{Nd} (T) are then used to calculate Nd model ages of continents, i.e., the average age at which the continents were

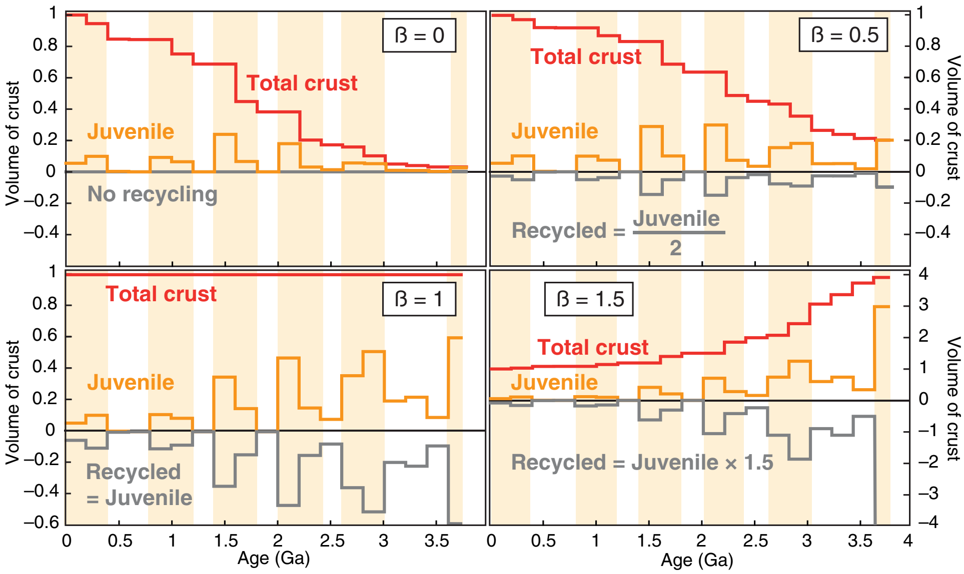

Fig. 3. Volume of continental crust through time. Four possible scenarios are presented depending on how continental crust was recycled in the past. The β value determines the relationship between the proportion x of recycled and juvenile crust such that $x_{recycled}(t) = \beta \times x_{juvenile}(t)$ at any time, t. The red curves show cumulative volume of continental crust through time normalized to present-day volume. The yellow and gray curves show the volume of juvenile and recycled crust for each age bin in the past 3.7 Ga. Vertical yellow bands indicate periods of continental growth as defined in Fig. 2.

extracted from the depleted mantle (Fig. 2B). By definition, if the isotopic system has remained closed since crystallization/deposition, model ages are always equal to or older than crystallization or stratigraphic ages. No significant bias is observed between the Nd isotopic record of fine- and coarse-grained sedimentary rocks (fig. S6). Following the reasoning of Allègre and Rousseau (*16*), the Nd model age of continental crust at any time, *t*, is decomposed into three contributions: juvenile, reworked, and recycled crust. Juvenile crust is the crust newly separated from the mantle. Juvenile crust formed at time, *t*, has, by definition, the same Nd isotopic composition as the depleted mantle and a Nd model age equal to the stratigraphic/crystallization age, *t* (1:1 juvenile crust line in Fig. 2B). Any addition of juvenile crust increases the total volume of continental crust. Juvenile crust has to be distinguished from "reworked crust," which has older Nd model age than crystallization or stratigraphic ages because it has been processed/remelted several times since its initial separation from the mantle. Reworked crust should not be taken into account when reconstructing the total volume of continental crust because it does not represent the separation of new crust from the mantle. Recycled crust is the crust destroyed by erosion and/or recycled back into the deep mantle by any means (e.g., subduction and delamination). Recycled crust is the portion of crust that is lost and contributes to the diminution of the total volume of continental crust. In this study, it is assumed that recycled crust has the same Nd model age as the reworked crust. At any time, *t*, the composition of the reworked crust is calculated as the weighted average composition of all crustal blocks formed up to that time. The gradient of the Nd model age curve defined by sedimentary rocks (Fig. 2B) is used to estimate the relative proportion of juvenile crust on continents for each age bin in the past 3.7 Ga (Fig. 2C). Periods during which Nd model ages of sedimentary rocks are shifted away from the modeled reworked crust evolution [vertical yellow arrows in Fig. 2 (A and B)] correspond to periods during which juvenile crust was present in excess on continents (peaks in Fig. 2C). The sensitivity of the model to Nd model age calculations, and the way juvenile crust is defined, is discussed in the Supplementary Materials and shown in fig. S7. Overall, the sensitivity tests indicate that the peaks and troughs of Fig. 2C are robust and independent of whether Nd model ages are calculated relative to the primitive mantle or with a younger mantle-depletion age.

While the relative proportion of juvenile crust can be determined for each age bin, this approach shows that Nd model ages of sedimentary rocks alone are not sufficient to determine how the absolute volume of crust changed through time (Fig. 3; Supplementary Materials). This is because the system is underconstrained, and the proportions of recycled and reworked crust cannot be determined separately. Different scenarios are possible depending on the recycling rate of the crust in the past, which is represented by the parameter β in Fig. 3. For the past 200 to 300 Ma, the recycling rate of the crust is estimated to be equal to the formation rate of juvenile crust (β = 1) (*4*), but it remains largely unknown for the rest of Earth history. If the recycling rate was higher than or similar to modern values (e.g., β = 1.5 or 1), the data suggest that higher volumes of juvenile crust were present in the Archean and that the total volume of continental crust has been stable or has decreased in the past 3.7 Ga. If the recycling rate was lower than today (e.g., β = 0 or 0.5), then the volumes of juvenile crust are more evenly distributed in the past 3.7 Ga, and the total volume of continental crust has increased through time. It is not possible to find a β value, even variable through time, for which the volume of juvenile crust would remain constant through time (see Materials and Methods for more details). This means that recycling alone cannot explain the variable proportions of juvenile crust calculated from Nd isotopic compositions of sedimentary rocks in Fig. 2C.

Whatever past recycling rates, Fig. 3 shows that the volume of juvenile crust is not constant through time. Instead, it describes a series of peaks and troughs that could be accounted for either (i) an episodic production of felsic crust or (ii) a bias in the Nd isotopic record of sedimentary rocks that would artificially generate the

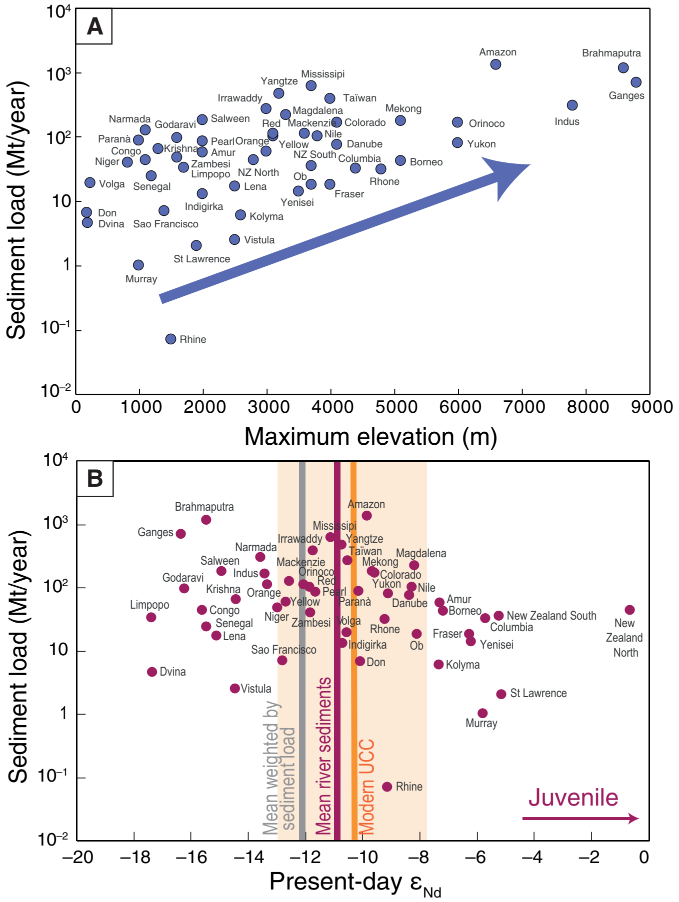

Fig. 4. Relief, sediment load, and present-day Nd isotopic composition (ε_{Nd}) of sediments delivered by major world rivers. Major world rivers are defined as those rivers for which the drained area is >0.2 × 10^6 km^2 or for which the sediment load is >30 Mt/year. Such thresholds are arbitrary but allow for the consideration of small mountainous and large basin rivers that both significantly contribute to the global sediment budget. The names of the rivers are shown next to the data point. Data and references can be found in data S2. (**A**) Relationship between sediment load and relief. Maximum elevation in the catchment area is taken here as a proxy for relief. (**B**) Relationship between sediment load and present-day Nd isotopic composition (ε_{Nd}) of sediments delivered by major world rivers. Average Nd isotopic composition ± 2 SE (vertical yellow band) for modern upper continental crust (UCC) is from (*43*). The mean Nd isotopic composition of major world river sediments, weighted or not by sediment load, is similar, within uncertainties, to the composition of the upper continental crust independently constrained from worldwide loess samples (*43*).

peak pattern. The second hypothesis—implicit in the model of, e.g., (*9*)—assumes that crustal growth was continuous through Earth history. While they are often confused in the literature, two distinct types of biases—hereinafter referred as selective preservation and sampling bias—may explain the peaks and troughs of Figs. 2 and 3. Selective preservation is reflected by the irregularity of the rock record available for sampling as defined by Hawkesworth *et al.* (*9*). Here, it cannot account for the peak pattern because the model does not rely on data frequency as is the case for the distribution of zircon crystallization ages (*9*, *11*, *12*). Furthermore, if the selective preservation of sedimentary rocks during certain periods of time was the explanation for the peak pattern of Figs. 2 and 3, we would expect a correlation between the relative proportion of juvenile crust and the number of available Sm-Nd data. This is clearly not the case (fig. S8).

Sampling bias, the second type of bias, differs from selective preservation as it refers not to the preservation potential of the sedimentary rock record but to the preferential erosion of juvenile crust, over reworked crust, in the source area. Sampling bias could perhaps be responsible for the peaks observed in Figs. 2 and 3 if the sedimentary rock record was biased toward a more juvenile provenance than the average source area during specific periods of time or in specific tectonic environments. This erosion effect was first considered by Allègre and Rousseau (*16*) who introduced the erosion coefficient K to correct for a presumable overrepresentation of juvenile crust in sediments due to the preferential exposition of juvenile crust in areas of high reliefs where erosion is maximal. Later, Dhuime *et al.* (*32*) quantified K values in a detailed study of the catchment area and erosion products of an Australian river, but this concept was never tested at the scale of the global sedimentary system.

Here, hydrological and orographic data of major world rivers were compiled together with Sm-Nd isotopic data of river sediments delivered to the modern ocean (Fig. 4 and data S3) to determine whether modern sediments are biased toward a more juvenile composition than that of the average present-day upper continental crust. As expected, river sediment loads are relatively well correlated to relief in the catchment area (Fig. 4A), indicating that erosion is maximal in areas of high topography (*33*). There is, however, no correlation between river sediment loads and sediment Nd isotopic compositions, and rivers with the highest sediment loads do not preferentially sample juvenile crust (Fig. 4B). This indicates that there is no obvious topography-related sampling bias in the Nd isotopic record of sedimentary rocks at the global scale. It follows that there is no need to use the erosion coefficient K to correct the proportions of juvenile crust deduced from Nd isotopic systematics of sediments.

If the above reasoning is correct, the peaks and troughs in Figs. 2 and 3 cannot be artifacts of selective preservation and sampling; instead, they must represent pulses in the production of juvenile felsic continental crust. The consequence is that the growth of continents was episodic and not continuous.

At least six pulses of continental growth can be identified in the past 3.7 Ga with a recurrence of about 500 to 700 Ma. The volume of juvenile felsic crust produced during each pulse is variable (Fig. 3); some pulses produce more growth than others. These peaks broadly correspond to those identified in previous zircon studies at 0.1 to 0.3, 1.0 to 1.2, 1.7 to 2.0, and 2.5 to 2.7 Ga (*17*), although the correlation is not evident due to the regionality of some zircon peaks and the 200-Ma binning used in this study (Fig. 5). The comparison is even more difficult that major differences exist between the available zircon records and depending on whether the whole dataset or only juvenile zircons are considered.

Continents from 3.5 Ga onward contain only a small proportion of juvenile crust, indicating that reworking of older felsic crust was a ubiquitous process during most of Earth history. At 3.7 Ga, the compiled sedimentary data suggest that the continents were fully covered by juvenile crust (Fig. 2C). This result must be taken with great care because of the small number of sedimentary rocks available for this age bin (n = 7). This could be because the production of juvenile crust was more important at the beginning of the Archean than later on or because there were not a lot of continental rocks to rework by that time, or both. In any case, the model used in this

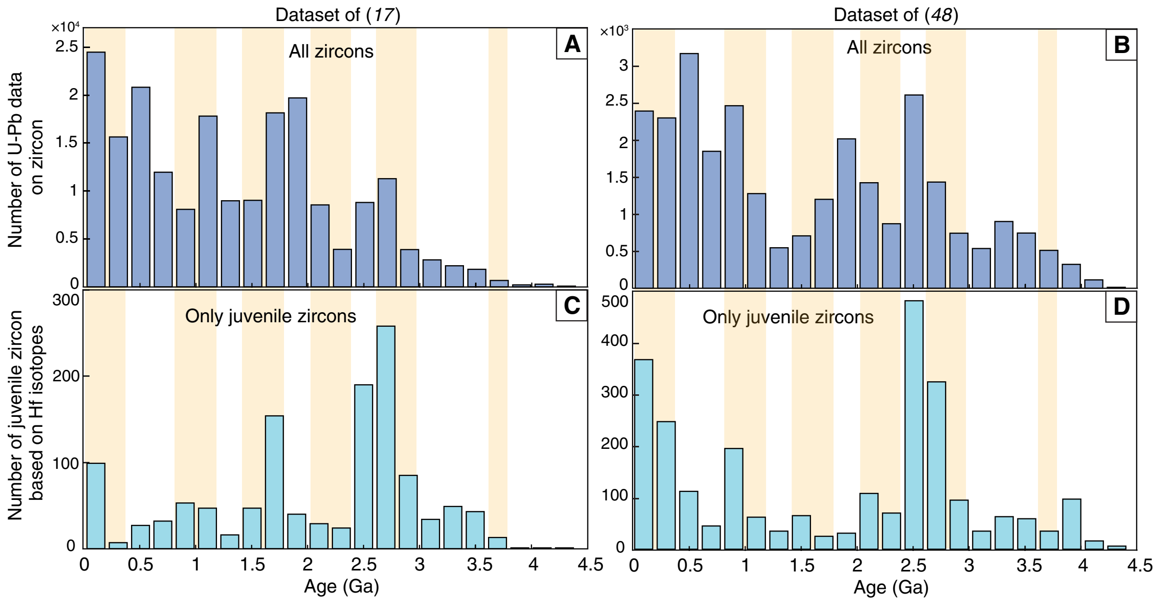

Fig. 5. Comparison between continental growth periods (this study) and previously published zircon records. Vertical yellow bars indicate peaks of continental growth as defined in this study (Figs. 2C and 3). All datasets are binned in a 200-Ma bin to be properly compared to the Sm-Nd dataset used in this study. (**A**) Distribution of available U-Pb data on zircon ($N = 197{,}583$) as compiled by Voice *et al.* (*17*). (**B**) Distribution of available U-Pb-Hf data on zircon ($N = 2573$) as compiled by Roberts and Spencer (*48*). (**C** and **D**) Distributions of juvenile zircons from the compilation of (*17*) ($N = 1250$) and (*48*) ($N = 2573$), respectively. Juvenile zircons are zircons with short crustal residence time, i.e., having a difference < 200 Ma between their Hf model age and their U-Pb crystallization age. Additional information about the definition of juvenile zircons and the calculation of two-stage Hf model ages can be found in the Supplementary Materials.

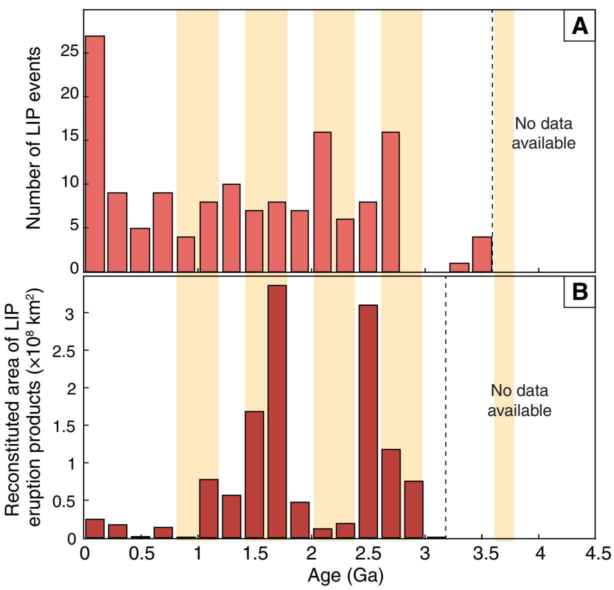

Fig. 6. Comparison between continental growth periods (this study) and previously published LIP records. Vertical yellow bars indicate peaks of continental growth as defined in this study (Figs. 2C and 3). All datasets are binned in a 200-Ma bin to be properly compared to the Sm-Nd dataset. (**A**) Number of LIP events through time after Prokoph *et al.* (*39*). (**B**) Reconstituted area of the eruption products of LIP events through time from Abbott and Isley (*38*).

study provides little information about the global extent of continental crust before 3.7 Ga or on the mechanisms responsible for the formation of the depleted mantle. Therefore, the crustal Big Bang scenario (*34*) cannot be formally excluded.

Contrary to the views expressed in some publications, episodic continental growth is not incompatible with a generation of continental crust through plate tectonic processes in a subduction setting (*11*, *35*–*37*). No net growth of continental crust occurs in modern subduction settings, suggesting that the six growth periods recorded in the past 3.7 Ga were triggered by major recurrent events. Several studies suggested that such recurrent events were linked to superplume activity and the generation of large igneous provinces (LIPs) (*11*, *12*, *36*). The periodicity (<50 to 100 Ma) and duration (often <10 Ma) of LIP activity (*38*, *39*) are, however, much shorter than those calculated here for continental growth. Although it is acknowledged that the LIP record may suffer from significant preservation issues, there is also no obvious correlation between the LIP and continental growth records except maybe at 1.5 to 1.7 and 2.5 to 2.7 Ga (Fig. 6). Instead, the periodicity of continental growth seems more in line with the recurrence of supercontinent cycles (≈500 Ma), but, here again, the existing uncertainties on the timing of supercontinent assembly and breakup through time (*40*) do not allow for a proper comparison of the two records. Numerical models (*41*) and paleomagnetic data (*37*) show that the aggregation and dispersal of continents are accompanied by changes in plate velocities. Such alternating periods of slow and fast continental motions may account for the episodic nature of continental growth through pulses of rapid subduction that would enhance both the production of juvenile continental crust and the recycling of existing crust. How the total volume of continental crust did vary through Earth history heavily depends on the balance between these two processes, which remains largely unknown.

MATERIALS AND METHODS

Sm-Nd database for detrital sedimentary rocks

The Sm-Nd database used to estimate the average SiO_2 contents of continents and the relative proportion of juvenile crust through time is available in data S1. The compilation includes 2653 data from 104 publications reporting $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios for fine- or coarse-grained sedimentary rocks of all ages. The compiled $^{147}Sm/^{144}Nd$ ratios were all analyzed by isotope dilution except in modern sediments (<100 Ma) for which they were calculated from Sm and Nd concentrations. Epsilon values were calculated relative to the chondritic uniform reservoir (CHUR) value of Bouvier *et al.* (*42*). Three types of Nd model ages are reported in data S1. They were all calculated with a decay constant of 6.54×10^{12} year^{-1} for ^{143}Nd. TDM values correspond to model ages calculated relative to the depleted mantle linearly extrapolated back in time to the CHUR value of Bouvier *et al.* (*42*) at 4.5 or 3.8 Ga from the present-day Nd isotopic composition of MORB [$^{143}Nd/^{144}Nd$ (t = 0) = 0.513073 ± 0.000191 (2 SD), which gives ε_{Nd} = +8.6]. The present-day MORB value was estimated by averaging 3297 Nd isotopic compositions of MORB from the PetdB database (compilation of igneous rocks from spreading center, off-axis spreading center, triple junction, aseismic ridge on 3 March 2020) after removing outliers above and below the mean ± 2 SD. TPM values correspond to model ages calculated relative to the primitive mantle [CHUR reservoir; (*42*)].

In the following models, the Sm-Nd database was screened for outliers to remove sediment data with extreme or aberrant values such as 0.05 > $^{147}Sm/^{144}Nd$ > 0.4, 0 > TDM (or TPM) > 4.56 Ga, and TDM (or TPM) < stratigraphic age ± 0.1 Ga. TDM values outside the ranges specified above could reflect a reopening of the Sm-Nd isotopic system after sediment deposition. In the preferred model using $TDM_{4.5Ga}$ (depleted mantle extrapolated back in time to the CHUR value at 4.5 Ga), the outlier rules lead to a removal of 26 outliers from the initial database. The width of the bins to be used in the models was determined using Scott's and Freedman-Diaconis' rules, which are two statistically independent rules used to select the best width of the bins to be used in a histogram. Both rules suggest that a 200-Ma binning is the most appropriate way to group the Sm-Nd data given their distribution. The distribution of fine- and coarse-grained sedimentary rocks per bin is shown in fig. S1.

Description of the model used to determine average SiO_2 contents of continents using $^{147}Sm/^{144}Nd$ ratios of detrital sedimentary rocks

Relationship between SiO2 contents and $^{147}Sm/^{144}Nd$ ratios in igneous rocks

The first step of this model is to determine the equation of the regression line that expresses the best relationship between the SiO_2 contents and the $^{147}Sm/^{144}Nd$ ratios of igneous rocks (Fig. 1B). For this purpose, I compiled $^{147}Sm/^{144}Nd$ ratios and SiO_2 contents of volcanic and plutonic rocks from Archean cratons, convergent margins, and oceanic plateaus from the GEOROC database on 27 January 2020 (N = 3864). The dataset was screened for outliers to remove data 0.05 > $^{147}Sm/^{144}Nd$ > 0.4 and 45 wt % > SiO_2 > 75 wt %. This step led to the rejection of 636 data out of the initial dataset. The $^{147}Sm/^{144}Nd$ ratios were averaged every 1 wt % of SiO_2 and screened for outlier above and below the mean ± 2 SD for each bin. The regression was performed using a third-order polynomial fit by residual resampling bootstrap (N = 10,000) to obtain both the best-fit line and the 95% confidence interval. With this method, the equation of the regression line is

$$SiO_2(\text{wt}\,\%) = -1054 \times \left(\frac{^{147}Sm}{^{144}Nd}\right)^3 + 3256 \times \left(\frac{^{147}Sm}{^{144}Nd}\right)^2 - 1228 \times \left(\frac{^{147}Sm}{^{144}Nd}\right) + 169 \quad (1)$$

Note that fitting a linear regression on a more restricted range of SiO_2 contents (55 to 70 wt %) with the same bootstrap method provides similar results (cf. fig. S5).

Variation of $^{147}Sm/^{144}Nd$ ratios of sedimentary rocks through time

The variation of $^{147}Sm/^{144}Nd$ ratios of sedimentary rocks through time was estimated by averaging $^{147}Sm/^{144}Nd$ ratios of fine- and coarse-grained sedimentary rocks every 200 Ma and by removing outliers below and above the mean ± 2 SD for each bin (Fig. 1A). Using the median value of each bin, a moving average with a sliding window of 200 Ma or a moving average with a lag of 100 points does not change the trendlines through time (Fig. 1A).

The mean $^{147}Sm/^{144}Nd$ ratio of the first bin (0 to 200 Ma), represented at 0.1 Ga in Fig 1A, yields a value of 0.1200 ± 0.0010 (2 SE) (cf. Table 1), which is in good agreement with the average $^{147}Sm/^{144}Nd$ ratio of 0.1193 ± 0.0052 (2 s) independently constrained from loess by Chauvel *et al.* (*43*) for modern upper continental crust.

Estimation of the average SiO2 content of continents through time

The average SiO_2 content of continents was calculated every 200 Ma (Fig. 1C) using the mean $^{147}Sm/^{144}Nd$ ratio of sedimentary rocks and Eq. 1. The error bar shown in Fig. 1C (±2 SE) corresponds to the propagation of the uncertainties of both the mean $^{147}Sm/^{144}Nd$ ratio of sedimentary rocks binned every 200 Ma and the 95% confidence interval of the best-fit line between SiO_2 and $^{147}Sm/^{144}Nd$ ratios of igneous rocks.

This estimation yields a SiO_2 content of 66.7 ± 0.7 (2 SE) wt % for the first bin (0 to 200 Ma), which is in good agreement with the average SiO_2 content of 66.6 ± 2.4 (2 s) wt % estimated for modern upper continental crust by Rudnick and Gao (*21*).

Description of the model used to estimate relative proportions of juvenile crust through time using Nd model ages of sedimentary rocks

At any time t, the total volume of continental crust can be written as the volume of existing/reworked crust at (t − 1) plus the volume of new juvenile crust extracted from the mantle at t minus the volume of crust recycled into the mantle at t such that

$$V_{CC}(t) = V_{Juv}(t) + V_{Rew}(t) - V_{Recy}(t) \text{ with } V_{Rew}(t) = V_{CC}(t-1) \quad (2)$$

where V_{CC} (t), V_{Juv} (t), V_{Rew} (t), and V_{Recy} (t) correspond, respectively, to the total volume of continental crust, the volume of juvenile crust, the volume of existing/reworked crust, and the volume of recycled crust at any time t.

Note that volume can be replaced by mass in Eq. 2 because it is assumed that, at the first order, juvenile, recycled, and reworked crust share the same felsic composition through time (cf. Fig. 1) and hence share similar densities.

The relative proportions of juvenile, reworked, and recycled crust can be linked to the volume of crust and expressed as follows

$$X_{\mathrm{Juv}}(t)=\frac{V_{\mathrm{Juv}}\,(t)}{V_{\mathrm{CC}}\,(t)};\ X_{\mathrm{Rew}}(t)=\frac{V_{\mathrm{Rew}}\,(t)}{V_{\mathrm{CC}}\,(t)};\ X_{\mathrm{Recy}}(t)=\frac{V_{\mathrm{Recy}}\,(t)}{V_{\mathrm{CC}}\,(t)} \quad (3)$$

where $X_{\mathrm{Juv}}(t)$, $X_{\mathrm{Rew}}(t)$, and $X_{\mathrm{Recy}}(t)$ correspond, respectively, to the proportion of juvenile, reworked, and recycled crust at time t.

Similarly to Eq. 2, at any time t, the average Nd isotopic composition of the continents or its average Nd model age, $\mathrm{TDM_{CC}}$, can be decomposed into three contributions such that

$$\mathrm{TDM_{CC}}\,(t)=X_{\mathrm{Juv}}(t)\times\mathrm{TDM_{Juv}}\,(t)+X_{\mathrm{Rew}}(t)\times\mathrm{TDM_{Rew}}\,(t)-X_{\mathrm{Recy}}\,(t)\times\mathrm{TDM_{Recy}}\,(t) \quad (4)$$

$$\text{with } X_{\mathrm{Juv}}(t)+X_{\mathrm{Rew}}(t)-X_{\mathrm{Recy}}(t)=1$$

$$\text{and } \mathrm{TDM_{Rew}}\,(t)=\mathrm{TDM_{CC}}\,(t-1)$$

where $\mathrm{TDM_{Juv}}\,(t)$, $\mathrm{TDM_{Rew}}\,(t)$, and $\mathrm{TDM_{Recy}}\,(t)$ correspond, respectively, to the Nd model age of juvenile, reworked, and recycled crust, at time t. Note that this equation is not pondered by concentrations as it is assumed that juvenile, reworked, and recycled crusts share similar Nd concentrations, as in previous models (*16*, *44*).

Determining the volume of total continental crust at any time t requires the knowledge of three parameters: $X_{\mathrm{Juv}}(t)$, $X_{\mathrm{Rew}}(t)$, and $X_{\mathrm{Recy}}(t)$, but there are several unknowns in the above equation, particularly regarding the way the crust was recycled through time.

We can simplify Eq. 4 by expressing the model age of the recycling crust, $\mathrm{TDM_{Recy}}\,(t)$ as a function of the Nd model age of the existing and juvenile crust, $\mathrm{TDM_{Rew}}\,(t)$ and $\mathrm{TDM_{Juv}}\,(t)$,such that

$$\mathrm{TDM_{Recy}}\,(t)=\alpha\times\mathrm{TDM_{Rew}}\,(t)+(1-\alpha)\times\mathrm{TDM_{Juv}}\,(t)\ \text{with}\ \alpha\ \geq\ 0 \quad (5)$$

$\alpha = 0$ means that the material recycled at time t is juvenile.

$\alpha = 1$ means that the material recycled at time t has the same model age as the average existing crust; hence, the material recycled is similar to the average continental crust at time t.

$0 < \alpha < 1$ means that the material recycled at time t has younger model ages than the average existing crust; hence, juvenile material is preferentially recycled.

$\alpha > 1$ means that the material recycled at time t has older model ages than the average existing crust; hence, older crust is preferentially recycled.

Similarly, we can express the proportion of recycled crust, $X_{\mathrm{Recy}}(t)$, as a function of the proportion of juvenile crust such that

$$X_{\mathrm{Recy}}(t)=\beta\times X_{\mathrm{Juv}}(t)\ \text{with}\ \beta\ \geq\ 0 \quad (6)$$

$\beta = 0$ means that the crust is not recycled at time t (volume of recycled crust = 0).

$\beta = 1$ means that the volume of crust recycled and produced from the mantle (i.e., juvenile crust) are equal at time t.

$0 < \beta < 1$ means that there is less crust recycled than what is produced from the mantle at time t.

$\beta > 1$ means that there is more crust recycled than what is produced from the mantle at time t.

With these new expressions, we can rewrite Eq. 4 as

$$\mathrm{TDM_{CC}}\,(t)=X_{\mathrm{Juv}}(t)\times\mathrm{TDM_{Juv}}\,(t)+X_{\mathrm{Rew}}(t)\times\mathrm{TDM_{CC}}\,(t-1)-\beta\times X_{\mathrm{Juv}}(t)\times[\,\alpha\times\mathrm{TDM_{CC}}\,(t-1)+(1-\alpha)\times\mathrm{TDM_{Juv}}\,(t)]$$

$$\text{Since } X_{\mathrm{Rew}}(t)=1-X_{\mathrm{Juv}}(t)+X_{\mathrm{Recy}}(t)=1-(1-\beta)\times X_{\mathrm{Juv}}(t) \quad (7)$$

We can express $X_{\mathrm{Juv}}(t)$ as

$$X_{\mathrm{Juv}}(t)=\frac{\mathrm{TDM_{CC}}\,(t)-\mathrm{TDM_{CC}}\,(t-1)}{(1+\beta\times(1-\alpha))\times\mathrm{TDM_{Juv}}\,(t)+(\beta\times(1-\alpha)-1)\times\mathrm{TDM_{CC}}\,(t-1)}$$

At the time of its formation, juvenile crust has, by definition, an age of 0.

Therefore, $\mathrm{TDM_{Juv}}\,(t)=t$, and we can write

$$X_{\mathrm{Juv}}(t)=\frac{\mathrm{TDM_{CC}}\,(t)-\mathrm{TDM_{CC}}\,(t-1)}{(1+\beta\times(1-\alpha))\times t+(\beta\times(1-\alpha)-1)\times\mathrm{TDM_{CC}}\,(t-1)} \quad (8)$$

Considering that Sm-Nd isotopic systematics of sediments faithfully reflect those of their source rocks (cf. discussion in the above section), Nd model ages of sedimentary rocks can be used as a proxy to estimate Nd model ages of continents (i.e., $\mathrm{TDM_{CC}}$) through time. Such consideration is supported by the mean Nd isotopic composition and Nd model age of sedimentary rocks formed in the past 200 Ma [first bin: $\varepsilon_{\mathrm{Nd}} = -9.5 \pm 0.6$ (2 SE), $\mathrm{TDM_{4.5\,Ga}} = 1.56 \pm 0.05$ (2 SE) Ga; Table 1 and Fig. 2], which are in good agreement with the average Nd isotopic composition [$\varepsilon_{\mathrm{Nd}} = -10.3 \pm 2.4$ (2 s)] and Nd model age reported in (*43*) for modern upper continental crust ($\mathrm{TDM_{4.5Ga}} = 1.62$ Ga using the same depleted mantle values as for the sediment database).

In summary, the calculation of the relative proportions of juvenile crust through time with Eq. 8 is conditioned by the knowledge of parameters α and β at any time t in Earth history. Such parameters, in particular β, are needed to calculate the proportions of recycled and reworked crust (see Eqs. 6 and 7), and ultimately the volumes of total, juvenile, recycled, and reworked crusts through time (see Eqs. 2 and 3). In substance, this equation resumes the conclusion of Iizuka *et al.* (*45*) in their review paper on the use of Hf-U-Pb isotopic systematics of zircons to constrain continental growth through time.

Today, most of the recycled crust is reinjected back into the mantle by delamination and sediment subduction (*4*). There is no constraint on the potential model age of the material delaminated below the continents. However, modern subducting sediments [GLOSS II; (*46*)] have a mean Nd model age of 1.65 Ga (calculated with the Sm-Nd concentrations and Nd isotopic composition of GLOSS II using the same depleted mantle values as for the sediment database), which is similar to that of modern upper continental crust [cf. (*43*) and Table 1]. At the first order, it is thus reasonable to assume that $\alpha = 1$, i.e., that the crust recycled at any time t shares similar Nd model ages with the average existing crust. With $\alpha = 1$, Eq. 8 becomes much simple. It becomes similar to the equation of Allègre and Rousseau (*16*) in which they had neglected the contribution of recycled crust.

$$X_{\mathrm{Juv}}(t) = \frac{\mathrm{TDM_{CC}}\,(t) - \mathrm{TDM_{CC}}\,(t-1)}{t + \mathrm{TDM_{CC}}\,(t-1)} \tag{9}$$

Assuming α = 1 does not help for the calculation of $X_{\mathrm{Rew}}(t)$ and $X_{\mathrm{Recy}}(t)$, as these proportions are a function of β (see Eqs. 6 and 7). It is therefore impossible to calculate the absolute volume of juvenile crust produced through time or the volume of total continental crust through time with the latter equation. One would need to assign a value to β and hence define a rate of recycling (as in Fig. 3) to reconstruct continental growth through Earth history.

In Fig. 2C, the proportions of juvenile crust, $X_{\mathrm{Juv}}(t)$, are determined with Eq. 9 using the Nd model ages of detrital sedimentary rocks ($\mathrm{TDM_{4.5Ga}}$; data S1 and Table 1) as a proxy for $\mathrm{TDM_{CC}}(t)$. The calculation of $X_{\mathrm{Juv}}(t)$ is started at 3.7 Ga assuming that $\mathrm{TDM_{CC}}(t-1)$ = 4.4 Ga and then calculated every 200 Ma back to present day. For three age bins (0.7, 1.3, and 1.9 Ga), the calculated $X_{\mathrm{Juv}}(t)$ were negative (−0.09, −0.10, and −0.17, respectively) and were forced to zero as it likely reflects the limits of the model in using sediment means as representative estimates of continent compositions. Forcing the proportions to zero does, however, not change the peak pattern and the timing of the six continental growth periods. The initial parameter $\mathrm{TDM_{CC}}(t-1)$ = 4.4 Ga corresponds to the age of the oldest zircons on Earth [Jack Hills zircons; (*47*)], minerals that constitute the first evidence for the presence of felsic crust at 4.4 Ga. It is important to note that the choice of this initial age has no impact on the calculated proportion of juvenile crust at 3.7 Ga and for the other age bins. The mean Nd model age of sedimentary rocks in the 3.7 Ga age bin is almost equal to the stratigraphic age, meaning that most of the crust was juvenile at 3.7 Ga and that the proportion of reworked and recycled crusts will be, in any case, almost negligible. Assuming an initial $\mathrm{TDM_{CC}}(t-1)$ = 3.8 Ga, instead of 4.4 Ga, would change the proportion of juvenile crust at 3.7 Ga from 99.8 to 98.4%, which has no impact on the rest of the calculations.

Error propagations with Monte Carlo simulations indicate that the relative proportions of juvenile crust estimated in this study are significantly different from zero for several periods of time, i.e., at 0.1 to 0.3, 1.5 to 1.7, 2.1 to 2.3, 2.7 to 2.9, and 3.7 Ga (see table S1).

Continuous growth model [pink trend in Fig. 2 (A and B)]

The evolution of Nd isotopic composition and Nd model age of a putative continental crust formed by the addition of a constant volume of juvenile crust every 100 Ma since 3.8 Ga was calculated for comparison [see Fig. 2 (A and B)]. In this model, it is assumed that juvenile crust formed from a mantle depleted at 4.5 Ga (same depleted mantle composition as used for the calculation of model ages all throughout the manuscript). The $^{147}\mathrm{Sm}/^{144}\mathrm{Nd}$ of the continental crust is assumed to be 0.1193 as estimated in (*43*) for modern upper continental crust and in agreement with the compiled sedimentary data through time (Fig. 1A). At any time *t*, the Nd isotopic composition and model age of the continental crust produced through continuous growth is calculated as the average composition of all the crustal blocks produced up to that time.

Estimation of the volume of continental crust through time

Quantifying the volume of continental crust present at any time *t* in Earth history requires knowing how the crust was recycled through time, which is represented by the parameter β (Eq. 6) in this study. In Fig. 3, the volume of continental crust potentially present on Earth in the past 3.7 Ga is calculated for different β values.

1) Assuming that there was no recycling in the past 3.7 Ga (β = 0):

From Eq. 6, $X_{\mathrm{Recy}}(t) = 0$ implies that $V_{\mathrm{Recy}}(t) = 0$

Therefore, $V_{\mathrm{CC}}(t) = V_{\mathrm{Juv}}(t) + V_{\mathrm{Rew}}(t)$

$$\Leftrightarrow\ V_{\mathrm{CC}}\,(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t) + V_{\mathrm{CC}}\,(t-1)$$

$$\Leftrightarrow\ V_{\mathrm{CC}}\,(t) = \frac{V_{\mathrm{CC}}\,(t-1)}{(1 - X_{\mathrm{Juv}}(t))}$$

From Eq. 9, we know that $X_{\mathrm{Juv}}(t) = \frac{\mathrm{TDM_{CC}}(t) - \mathrm{TDM_{CC}}(t-1)}{t + \mathrm{TDM_{CC}}(t-1)}$ and can calculate the volume of total continental crust, $V_{\mathrm{CC}}\,(t)$, at any time *t*, assuming that $V_{\mathrm{CC}}\,(t-1) = 1$ at 3.7 Ga to start the calculation. Then, we can calculate $V_{\mathrm{CC}}\,(t)$ backward until present day and renormalize all volumes to those of present-day continental crust as shown in Fig. 2B.

From $V_{\mathrm{CC}}\,(t)$, we can calculate $V_{\mathrm{Juv}}(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t)$, and $V_{\mathrm{Recy}}\,(t) = 0$ at any time *t*.

2) Assuming that, at any time *t*, half of the volume of newly produced crust is recycled (β = 0.5):

From Eq. 6, $X_{\mathrm{Recy}}(t) = \frac{X_{\mathrm{Juv}}(t)}{2}$

Therefore, $V_{\mathrm{CC}}(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}(t) + V_{\mathrm{CC}}(t-1) - \frac{X_{\mathrm{Juv}}(t)}{2} \times V_{\mathrm{CC}}(t)$

$$\Leftrightarrow\ V_{\mathrm{CC}}(t) = \frac{V_{\mathrm{CC}}(t-1)}{\left(1 - \frac{X_{\mathrm{Juv}}(t)}{2}\right)}$$

As above, $V_{\mathrm{Juv}}(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t)$,
and $V_{\mathrm{Recy}}\,(t) = X_{\mathrm{Recy}}(t) \times V_{\mathrm{CC}}\,(t) = \frac{X_{\mathrm{Juv}}(t)}{2} \times V_{\mathrm{CC}}\,(t)$

3) Assuming that, at any time *t*, the volume of newly produced crust is equal to the volume of recycled crust (β = 1):

From Eq. 6, $X_{\mathrm{Recy}}(t) = X_{\mathrm{Juv}}(t)$

Therefore, $V_{\mathrm{CC}}\,(t) = V_{\mathrm{CC}}\,(t-1)$, i.e., the volume of total crust is constant at any time *t*,
and $V_{\mathrm{Juv}}(t) = V_{\mathrm{Recy}}(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}(t)$

4) Assuming that, at any time *t*, the volume of recycled crust is 50% higher than the volume of newly produced crust (β = 1.5):

From Eq. 6, $X_{\mathrm{Recy}}(t) = 1.5 \times X_{\mathrm{Juv}}(t)$

Therefore,

$$V_{\mathrm{CC}}\,(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t) + V_{\mathrm{CC}}\,(t-1) - 1.5 \times X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t)$$

$$\Leftrightarrow\ V_{\mathrm{CC}}\,(t) = \frac{V_{\mathrm{CC}}\,(t-1)}{\left(1 + \frac{X_{\mathrm{Juv}}(t)}{2}\right)}$$

As above, $V_{\mathrm{Juv}}(t) = X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t)$,
and $V_{\mathrm{Recy}}\,(t) = X_{\mathrm{Recy}}(t) \times V_{\mathrm{CC}}\,(t) = 1.5 \times X_{\mathrm{Juv}}(t) \times V_{\mathrm{CC}}\,(t)$

Variable β through time

Taking the inverse problem and trying to solve the equations such that, at any time *t*, the volume of juvenile crust remains constant yields no solution for β. This means that the relative proportions of juvenile crust cannot be accounted for a variable recycling rate at a constant juvenile crust production [i.e., variable $V_{\mathrm{Recy}}\,(t)$ and constant $V_{\mathrm{juv}}\,(t)$] in the past 3.7 Ga. Whatever the β value, some periods of time require zero production of juvenile crust (i.e., *t* = 0.7, 1.3, and 1.9 Ga; cf. Fig. 2C), while other periods (i.e., $t = 3.7$ Ga; cf. Fig. 2C) are clearly buffered by a lot of juvenile material.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abj1807

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Acknowledgments: I acknowledge R. W. Carlson, N. T. Arndt, D. Andrault, M. Boyet, B. Dhuime, J. Monteux, E. Bruand, and L. Sauzéat for comments on an earlier version of the manuscript and B. Schoene, C. B. Keller, and an anonymous reviewer for helpful and insightful reviews. **Funding:** This work was funded by the European Research Council (ERC) under the European Union's Horizon H2020 research and innovation programme (Starting Grant GOforISOBIF, grant agreement no. 852239), the Swiss National Science Foundation (SNSF) - Ambizione Grant (no. PZ00P2_161218), the French Government Laboratory of

Excellence initiative n° ANR-10-LABX-0006, and the Region Auvergne and the European Regional Development Fund. This is Laboratory of Excellence ClerVolc contribution number 493. **Author contributions:** M.G. compiled the data, conceived the study and models, and wrote the manuscript**. Competing interests:** The author declares that she has no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Matlab codes used to process the compiled data are available here: https://doi.org/10.5281/zenodo.5121664.

Submitted 26 April 2021
Accepted 2 August 2021
Published 22 September 2021
10.1126/sciadv.abj1807

Citation: M. Garçon, Episodic growth of felsic continents in the past 3.7 Ga. *Sci. Adv.* **7**, eabj1807 (2021).

Science Advances

Episodic growth of felsic continents in the past 3.7 Ga

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Sci. Adv., 7 (39), eabj1807. • DOI: 10.1126/sciadv.abj1807

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