PHILOSOPHICAL TRANSACTIONS A

rsta.royalsocietypublishing.org

Research

Cite this article: Dhuime B, Hawkesworth CJ, Delavault H, Cawood PA. 2018 Rates of generation and destruction of the continental crust: implications for continental growth. *Phil. Trans. R. Soc. A* **376**: 20170403. http://dx.doi.org/10.1098/rsta.2017.0403

Accepted: 18 June 2018

One contribution of 14 to a discussion meeting issue 'Earth dynamics and the development of plate tectonics'.

Subject Areas:
plate tectonics, geochemistry

Keywords:
continental crust, continental growth, crustal evolution, plate tectonics

Author for correspondence:
Bruno Dhuime
e-mail: bruno.dhuime@gm.univ-montp2.fr

Electronic supplementary material is available online at https://dx.doi.org/10.6084/m9.figshare.c.4206266.

THE ROYAL SOCIETY
PUBLISHING

Rates of generation and destruction of the continental crust: implications for continental growth

Bruno Dhuime[1,2], Chris J. Hawkesworth[2,3], Hélène Delavault[2,4] and Peter A. Cawood[3,5]

[1]CNRS-UMR5243, Géosciences Montpellier, Université de Montpellier, 34095 Montpellier Cedex 05, France
[2]Bristol Isotope Group, School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK
[3]Department of Earth Sciences, University of St Andrews, North Street, St Andrews KY16 9AL, UK
[4]Thermo Fisher Scientific, 16 avenue du Québec, BP 30210, 91941 Villebon Courtaboeuf Cedex, France
[5]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria 3800, Australia

BD, 0000-0002-4146-4739; PAC, 0000-0003-1200-3826

Less than 25% of the volume of the juvenile continental crust preserved today is older than 3 Ga, there are no known rocks older than approximately 4 Ga, and yet a number of recent models of continental growth suggest that at least 60–80% of the present volume of the continental crust had been generated by 3 Ga. Such models require that large volumes of pre-3 Ga crust were destroyed and replaced by younger crust since the late Archaean. To address this issue, we evaluate the influence on the rock record of changing the rates of generation and destruction of the continental crust at different times in Earth's history. We adopted a box model approach in a numerical model constrained by the estimated volumes of continental crust at 3 Ga and the present day, and by the distribution of crust formation ages in the present-day crust. The data generated by the model suggest that new continental crust was generated continuously, but with a marked decrease in the net growth rate at approximately 3 Ga resulting in a temporary reduction in the volume of continental crust at that time. Destruction rates increased dramatically around 3 billion years ago, which may be linked to the widespread development of subduction zones. The volume of continental crust may have exceeded its present value by the mid/late Proterozoic. In this model, about 2.6–2.3 times of the present volume of continental crust has been generated since Earth's formation, and approximately 1.6–1.3 times of this volume has been destroyed and recycled back into the mantle.

This article is part of a discussion meeting issue 'Earth dynamics and the development of plate tectonics'.

1. The continental growth conundrum

The rates and timings of net addition of newly generated (or juvenile) crust to the continental landmass, commonly referred to as 'continental growth', have remained matters of considerable debate. This is, in part, because it is difficult to separate the process of crust generation from the processes of crustal destruction, reworking and preservation from the present rock record (e.g. [1–6]). Less than 25% of the volume of the continents contains rocks with Nd or Hf crust formation ages older than 3 Ga ([1,5,7–11], and light brown dashed curve in figure 1), less than 5% of the exposed surface of the continents is of juvenile rocks older than 3 Ga ([14,15], and dark brown dashed curve in figure 1) and there are no known rocks with crystallization ages older than 4.02 Ga [16]. Juvenile rocks preserved on Earth's surface show peaks and troughs in their age distributions [14,15] that translate into stepped-like curves when plotted as cumulative 'growth curves' (dark brown dashed curve in figure 1). These age peaks have been regarded as reflecting episodic pulses of new crust generation during mantle 'superplume' events [15,17–20], and/or as resulting from the better preservation potential of some rocks over others through time [3,21,22].

Continental growth curves depict how the volume of continental crust has changed with time. They therefore reflect the balance between the generation and destruction of crust at different times in Earth's history. Some curves are calculated from the cumulative proportion of crust formation ages in the present-day crust (figure 1, dashed curves). Such curves are based on the assumption that the relative proportion of juvenile magmatic rocks of different ages that are exposed on the continents surface [14,15], or the Nd isotope composition of continental sediments with a range of deposition ages [7,23], can be used to estimate the volumes of juvenile continental crust generated at different times in Earth's history. However, as recently discussed in Dhuime *et al*. [8] (and see also refs [1,24,25]), it seems unlikely that the relative proportions of rocks with Phanerozoic and Precambrian crust formation ages presently preserved in the rock record reflect the relative volumes of Phanerozoic and Precambrian crust that had been generated.

A number of approaches have therefore sought to evaluate the volumes of crust of different ages independent of the volumes preserved at the present day (figure 1, solid lines). These include 'mantle-derived' growth curves from Nb/U variations in basalts and komatiites [12,26] (black curve), 'atmosphere-derived' growth curves from Ar isotope variations in hydrothermal quartz [13,27] (blue envelope curve) and 'crust-derived' growth curves from both Nd isotopes in shales [7,8] (dark red curves) and Hf isotopes in zircon [1,2] (green curve). A key issue is the nature of the geochemical reservoirs sampled by the different approaches, and it is striking, for instance, that the worldwide variation in Nd isotopes in shales over the last 1 Ga does not follow the variation in Hf isotopes in zircon (figure 2), although both are records from the continental crust. It is widely accepted that shales (i.e. fine-grained continental sediments) sample the upper continental crust (e.g. [28,29]), and even though zircon is thought to crystallize preferentially from relatively high silica magmas (e.g. [10,30,31]), the distribution of the median zircon $\varepsilon_{\mathrm{Hf}}$ data around chondritic (CHUR) values indicates that the zircon record samples more of the bulk continental crust. The discrepancy between the shale and zircon records over the last billion years has, however, little influence on the shape of the continental growth curves modelled from these two records (figure 1, red curves and green curve), as recently demonstrated by Dhuime *et al*. [8].

The continental growth curves that are not based on the present-day age distribution of crust formation ages encouragingly yield similar results (figure 1, solid lines), suggesting that at least

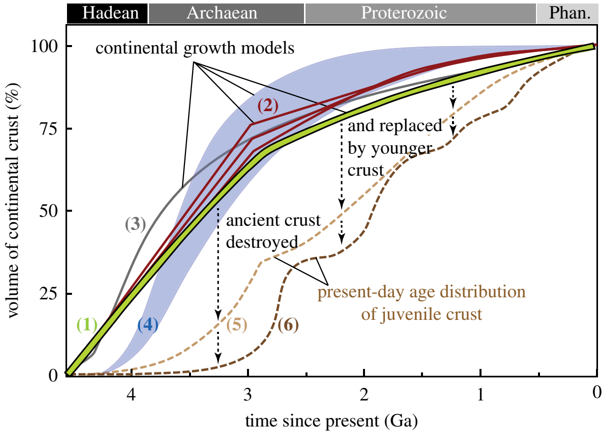

Figure 1. A selection of recent continental growth models (curves 1–4), which suggest that 60–80% of the present volume of continental crust was established by 3 Ga. These curves are in stark contrast with the cumulative distribution of crust formation ages in the crust preserved today (curves 5 and 6). The gap between curves 1–4 and curves 5–6 implies the destruction of large amounts of ancient continental crust (schematized by the dashed vertical arrows). The rates at which continental crust was destroyed and replaced by younger crust are explored in this contribution. References to curves: (1) Dhuime *et al*. [2], (2) Dhuime *et al*. [8], (3) Campbell [12], (4) Pujol *et al*. [13], (5) Condie & Aster [14], (6) Dhuime *et al*. [8].

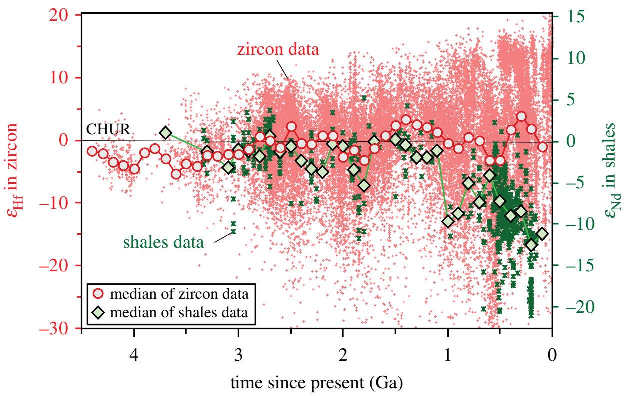

Figure 2. Variation in the ε_{Hf} in zircon (primary *Y*-axis) and in the ε_{Nd} in shales (secondary *Y*-axis) as a function of the crystallization age of the zircons (zircon data), or the deposition age of the sediments (shales data). The running median of the data calculated for every 100 Myr time slice is represented by the dots (zircon data) and diamonds (shales data). Zircon database (including zircons from both juvenile and reworked crust) from Roberts & Spencer [11] and shales database from Dhuime *et al*. [8].

60% of the present volume of the continental crust (PVCC) was established by 3 billion years ago. These curves are in contrast with those calculated from the cumulative proportion of crust formation ages in the present-day crust (figure 1, dashed lines), and this, in turn, implies that large volumes of pre-3 Ga crust must have been destroyed and replaced by younger crust since the late Archaean. The break in slope at around 3 Ga in many of the most recent growth models (figure 1, solid lines) marks the transition from relatively rapid (*ca* 3.4–2.9 $km^3\ yr^{-1}$ on average before 3 Ga) to slower (*ca* 0.9–0.6 $km^3\ yr^{-1}$ on average after 3 Ga) rates of continental growth. This is increasingly taken to reflect higher crustal destruction rates as plate tectonics and subduction zones developed [2,8].

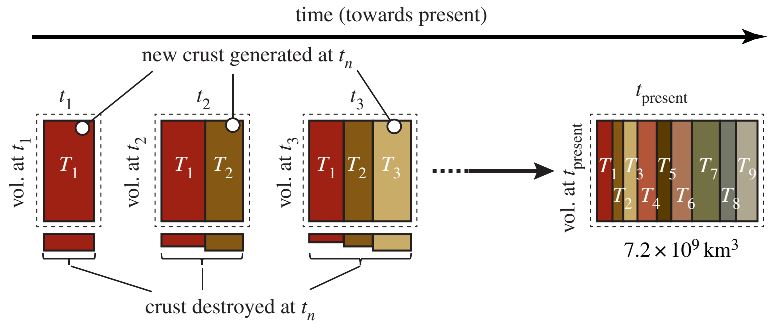

Figure 3. Schematic of the numerical box model used to evaluate the changes in the rates of crust generation and destruction through time. $t_1, t_2, \ldots, t_n$ are the times at which new crustal segments of ages $T_1, T_2, \ldots, T_n$ were generated. Vol. at t_n: volume of continental crust established at t_n. The present volume of continental crust targeted by the model is 7.2×10^9 km^3 [38,41].

We have developed a numerical box model to explore new ways to reconcile models in which more than 60% of the PVCC was present by 3 Ga (e.g. [2,8,12,13,26,32–37]) with the scarcity of rocks older than 3 Ga and the age distributions of the present-day continental record (e.g. [5,7–11,14,15]). Two different end-member curves serve as proxies for the relative volumes of juvenile rocks of different ages preserved in today's crust: (i) *Model 1* is based on the surface age distribution curve of rocks with juvenile Nd isotope ratios at their age of crystallization [14]; (ii) *Model 2* uses the age distribution curve of juvenile crust modelled from the Nd isotope composition of continental sediments [8]. Unlike recent growth models in which the methodology and/or sampling approaches do not allow cumulative curves of crustal volume to decrease over time (e.g. [1,2,9,12,13,38]), the box model approach let us explore scenarios in which crust destruction exceeded rates of crust generation, i.e. in time frames in which net crustal growth rates were negative (see also [21,32]). We used crust generation rates that vary smoothly through time, in line with temporal changes in mantle temperature [39,40], to show that the present-day age distribution of the juvenile crust [14] can be modelled by a number of key changes in destruction rates at different times in Earth's history. Finally, we show that peaks and troughs in the age distribution of juvenile rocks preserved on the continents surface (*Model 1*) do not necessarily imply any dramatic change in the rates of crustal generation through time.

2. Methodology: the box model approach

A numerical box model illustrated schematically in figure 3 was used to address the effects, at each step t_n, of changing the rates of formation and destruction of the continental crust on both the volume and the age distribution of the juvenile continental crust through time. Each step t_n has a duration of 500 Myr. The model starts at $t_0 = 4.5$ Ga (0% crust), with its first step at $t_1 = 4$ Ga, its second step at $t_2 = 3.5$ Ga, and so on until its last step ends up at $t_{present} = 0$ Ga. For each step t_n, we have assumed that the continental crust at that time was made of (i) a segment of new crust formed at t_n; and (ii) the crustal segment(s) formed previously at t_{n-i} and still preserved at t_n. We also assumed that the volume of crust available at each step t_n was controlled by (i) the volume of crust that was present at t_{n-1}; (ii) the volume of new crust added at t_n and (iii) the volumes of both new crust (age t_n) and pre-existing crustal segments (ages t_{n-i}) destroyed at t_n. The model is constrained by a PVCC of 7.2×10^9 km^3 [38,41], 60 to 80% of the PVCC being present at 3 Ga [2,8,12,13,38], the distribution of crust formation ages in the present-day crust after Condie & Aster [14] (*Model 1*), or after Dhuime *et al.* [8] (*Model 2*), a present-day crustal generation rate (CGR) of 3.2 to 4.4 km^3 yr^{-1} [41–44], and a present-day crustal destruction rate (CDR) of 3.2 to 5.5 km^3 yr^{-1} [41–45]. In *Model 2*, we assumed a value of 6 for the erosion parameter K, following Dhuime *et al.* [8] (and see discussions on the significance of K and its impact on continental

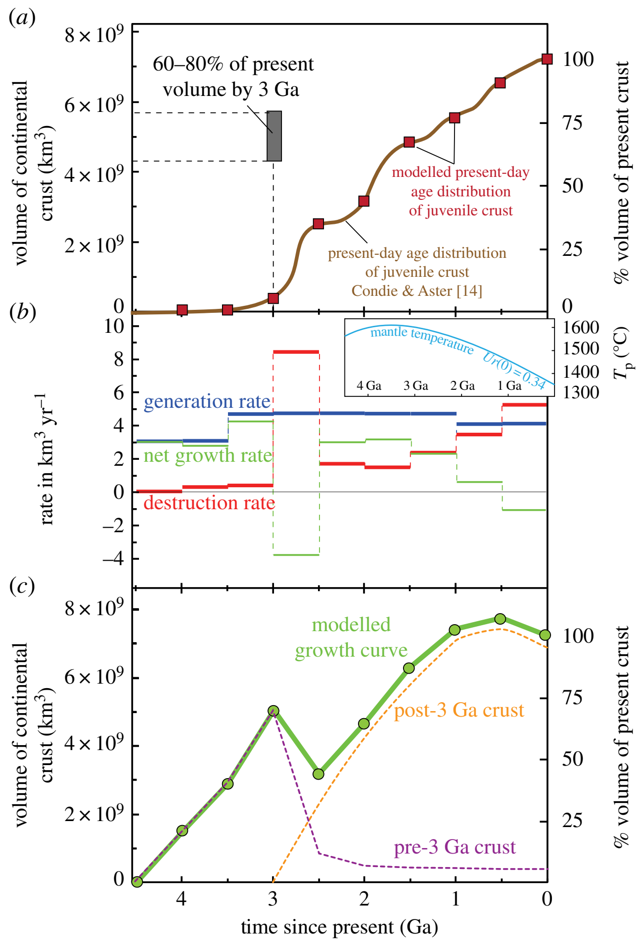

Figure 4. *Model 1* for the volume and rates of generation and destruction of the continental crust through time, estimated from the box model approach schematized in figure 3. (*a*) Cumulative curve for the present-day distribution of juvenile crust (brown curve, after [14]), which is the target of the model, and the modelled present age distribution (red squares). The grey box at 3 Ga represents the conditional starting parameter of the model, i.e. 60–80% of the present-day volume of continental crust established by 3 Ga [2,8,12,13]. (*b*) Rates of generation (blue curve), destruction (red curve) and net growth (green curve) of the continental crust, for every 500 Myr step of the model. The inset shows the smooth evolution of the mantle temperature through time, after Herzberg *et al*. [39] and Korenaga [40]. (*c*) Volumes of continental crust calculated for every 500 Myr step of the model (green curve), and estimated changes in the volumes of pre-3 Ga (purple curve) and post-3 Ga (orange curve) continental crust through time.

growth curves in refs [7,8,46]). Using a trial-and-error approach, the rates of crust generation and destruction for each crustal segment at each step t_n were adjusted until all the above-mentioned constraints (i.e. PVCC, volume of crust at 3 Ga, present-day age distribution of juvenile crust, present CGR and CDR) were satisfied. As a further constraint, crustal generation rates were assumed to vary smoothly through time, as does the mantle temperature evolution (e.g. [39,40]). Finally, in order to better account for the preferential destruction of younger high-relief crust through erosion processes (e.g. [7]), crustal destruction rates of the younger continental segments formed at t_{n-i} were, for each step t_n, not allowed to be lower than those of the oldest segments.

The key input and output parameters of the box model are summarized in figures 4 and 5, and in electronic supplementary material, table S1. The brown curves represent the distribution of crust formation ages in the present crust targeted by our models: *Model 1* targeted curve (figure 4*a*)

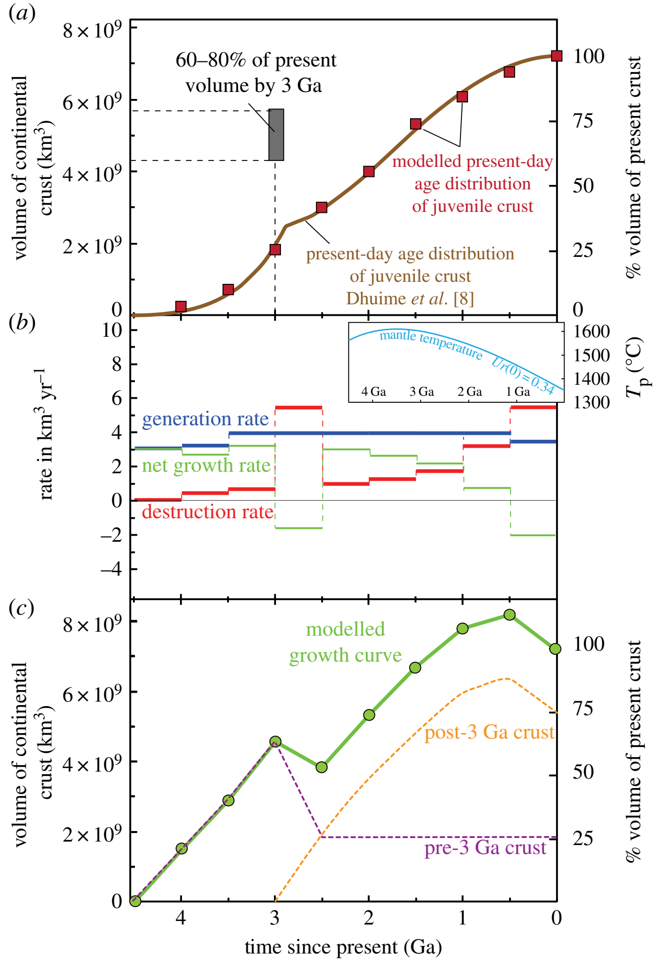

Figure 5. *Model 2* for the volume and rates of generation and destruction of the continental crust through time, estimated from the box model approach schematized in figure 3. The curves are as for figure 4, with one exception as the targeted present-day age distribution curve (brown curve) is after Dhuime *et al*. [8].

is from Condie & Aster [14], and *Model 2* targeted curve (figure 5*a*) is from Dhuime *et al*. [8]. The red squares represent the calculated present-day distribution of crust formation ages generated by the box model. Crust generation and destruction rates (figures 4*b* and 5*b*) were adjusted until the model distribution of today's crust formation ages matches the targeted age distributions within ± 2%. The green curve linking green dots in figures 4*c* and 5*c* is the continental growth curve generated by the model.

3. Rates of generation, destruction and growth of the continental crust through time

The crust generation and destruction rates calculated from the box model are represented by the blue and red curves respectively in figure 4*b* (*Model 1*) and 5*b* (*Model 2*). Rates of continental crust generation range 3.0–4.7 $km^3\ yr^{-1}$ (*Model 1*) and 3.1–4.0 $km^3\ yr^{-1}$ (*Model 2*). They broadly follow the evolution of mantle temperature (figures 4*b* and 5*b*, inset), increasing between Earth's formation and *ca* 3.5–3.0 Ga, and then decreasing to the present day. By contrast, crustal destruction rates show much greater variations. They range between 0.1–8.4 $km^3\ yr^{-1}$ (*Model 1*) and 0.1–5.5 $km^3 yr^{-1}$ (*Model 2*), with a marked peak in the period 3.0–2.5 Ga. This peak was generated by the numerical box model because (a) no restriction was applied for the minimum or the maximum crust destruction rates, and (b) 3.0–2.5 Ga is the period of the maximum difference between the crustal growth curve and the targeted present-day age distribution of the juvenile crust. This peak is followed by lower destruction rates after *ca* 2.5 Ga (1.7 $km^3 yr^{-1}$ in *Model 1* and 1.0 $km^3 yr^{-1}$ in *Model 2*), with a gradual increase in destruction rates during the Proterozoic. By the Phanerozoic crustal destruction rates (5.3 $km^3 yr^{-1}$ in *Model 1* and 5.5 $km^3 yr^{-1}$ in *Model 2*) exceeded crust formation rates (4.1 $km^3 yr^{-1}$ in *Model 1* and 3.5 $km^3 yr^{-1}$ in *Model 2*).

The changes in the rates of net continental growth through time, calculated from the variations in crust generation and destruction rates, are shown by the green curve in figures 4*b* (*Model 1*) and 5*b* (*Model 2*). Rates of continental growth are highly variable and range between −3.7 and 4.3 $km^3 yr^{-1}$ in *Model 1*, and between −2.0 and 3.3 $km^3 yr^{-1}$ in *Model 2*. From 4.5 to 3.0 Ga, they range from 2.8 to 4.3 $km^3 yr^{-1}$ (*Model 1*) and 2.8 to 3.3 $km^3 yr^{-1}$ (*Model 2*). There is a marked reduction in crustal growth rates between 3.0 and 2.5 Ga, with a negative value of −3.7 $km^3 yr^{-1}$ in *Model 1* and −1.5 $km^3 yr^{-1}$ in *Model 2*. From 2.5 Ga until the present day, net growth rates gradually decrease from 3.0–3.2 $km^3 yr^{-1}$ to −1.1 $km^3 yr^{-1}$ (*Model 1*), and from 3.0 $km^3 yr^{-1}$ to −2.0 $km^3 yr^{-1}$ (*Model 2*). The cumulative growth curve calculated from the net growth rates generated by the box model is represented by the green curve in figures 4*c* (*Model 1*) and 5*b* (*Model 2*). This curve differs from recent continental growth models (figure 1) because our box model allows the incorporation of negative crustal growth rates when building a cumulative growth curve.

While the models presented here are not unique (e.g. as evidenced by small differences between *Model 1* and *Model 2*), the approach offers the opportunity of developing more realistic growth curves for the evolution of the continental crust through time. This evolution can be summarized in four main stages: a first stage of rapid growth in the volume of continental crust between *ca* 4.5 Ga and 3 Ga (70% of the PVCC at 3 Ga in *Model 1*, and 63% in *Model 2*); a second stage of crustal destruction and continental shrinking between *ca* 3 Ga and 2.5 Ga (44% of PVCC at 2.5 Ga in *Model 1*, and 53% in *Model 2*); a third stage of crustal growth with gradually decreasing rates of growth between *ca* 2.5 Ga and 0.5 Ga, at the end of which the volume of continental crust may have exceeded its present volume (108% of the PVCC at 0.5 Ga in *Model 1*, and 114% in *Model 2*); a fourth stage between *ca* 0.5 Ga and present, during which the volume of continental crust has slightly decreased as crustal destruction rates exceeded crustal formation rates (e.g. [44,45]).

4. Geological implications

The processes involved in the development of the peaks and troughs in the age distributions of juvenile rocks, and more generally in the age distribution of zircons, have remained controversial for a number of decades (e.g. see recent reviews in [4,38,47]). Dramatic, episodic variations in crustal growth rates in relation to changes in mantle convection and the formation of 'superplumes' have been invoked to account for age peaks widely observed in the preserved rock record. Although our model does not rule out an episodic Earth evolution (e.g. [18]), it offers new insights into alternative models in which continental crust was continuously extracted from the mantle, and the age distribution of today's juvenile rock record is at least partly explained by changes in the rates of destruction of continental crust. This, in turn, relates to the development of subduction zones in a planet evolving from a 'single/stagnant lid' to a regime in which plate tectonics dominates (Cawood *et al*. [48] and references therein).

Recent studies have suggested that *ca* 3 Ga marked the transition between two different types of continental crust. New continental crust generated before 3 Ga was on average mafic, dense and relatively thin (less than 20 km) [49], and the upper crust preserved from that time was also relatively mafic [50]. By contrast, continental crust that formed after 3 Ga gradually became more intermediate in composition, increasingly buoyant and thicker [49]. The volumes of pre-3 Ga and post-3 Ga continental crust available through time calculated with our box model are shown in figures 4*c* (*Model 1*) and 5*c* (*Model 2*), and these volumes are represented by the purple dashed curve and red dashed curve, respectively. These highlight that the reduction in estimated crustal volumes at the end of the Archaean reflects the destruction of largely mafic continental crust, and the initiation of the generation of continental crust with more immediate compositions.

In the context of the inferred onset of widespread subduction at around 3 Ga (e.g. [2,8,24,51]), the high peak of destruction rate predicted by the box model for this period is strikingly consistent with the rapid recycling of mafic/dense pre-3 Ga crust back into the mantle through subduction. Dense, predominantly mafic and relatively thin pre-3 Ga continental crust reached a volume of 60–70% of the PVCC at 3 Ga (figures 4*c* and 5*c*), but has been almost completely destroyed since then. Only small amounts of that crust preferentially survived after a billion years (i.e. after 2 Ga) of crustal evolution and recycling (figures 4*a* and 5*a*, brown curve). High 3.0–2.5 Ga destruction rates are also consistent with the age distributions of zircons from sediments with a range of deposition ages, because ages greater than 3 Ga are poorly preserved in sediments younger than 2.5 Ga [52,53]. The gradual increase in destruction rates from the Archaean–Proterozoic transition predicted by the model can be accommodated by a change in subduction dynamics as the Earth became cooler [54–57] and/or by the emergence of a thicker, buoyant, higher relief and therefore more prone to erosion, new continental crust [31,49,50,58–60].

The growth of 'modern', increasingly thicker, more differentiated and buoyant post-3 Ga continental crust is represented by the orange dashed curve in figures 4*c* (*Model 1*) and 5*c* (*Model 2*). The generation of that crust, dominantly through subduction [49], is likely to be associated with the emergence of the continents from 3 Ga [49,50,58,59,61]. The shape of the growth curve of the post-3 Ga crust is similar to that of the juvenile crust thickness curve of Dhuime *et al*. [49], as both curves show a gradual increase from the Mesoarchaean to the Meso/Neoproterozoic followed by a decrease towards the present. This latter feature in the crustal thickness curve was interpreted by Dhuime *et al*. [49] as crustal destruction exceeding crustal generation rates, consistent with Phanerozoic rates [41–45], and it is independently validated by both *Model 1* and *Model 2* (figures 4*b* and 5*b*).

Finally, the data generated by our box model imply that about 2.6 times (*Model 1*), or 2.3 times (*Model 2*), of the PVCC has been generated since Earth's formation, and thus *ca* 1.6 times (*Model 1*), or 1.3 times (*Model 2*), of the PVCC has been destroyed and recycled back into the mantle since the onset of plate tectonics. This opens new perspectives for models of mantle evolution and mantle–crust interaction through time, including testing the scenarios offered by our box model by modelling of radiogenic isotope systematics in the mantle–crust system.

Data accessibility. This article has no additional data.

Authors' contributions. B.D. and C.J.H. designed the study and wrote the paper. B.D. and H.D. processed the data and designed the figures, and P.A.C. contributed to linking the box model approach with geodynamical processes.

Competing interests. We declare we have no competing interests.

Funding. This work was supported by the Natural Environment Research Council (NERC grant NE/K008862/1 to B.D.), the Leverhulme Trust (grant RPG-2015-422 to B.D. and C.J.H., and Emeritus Fellowship EM-2017-047\4 to C.J.H.), and by the Australian Research Council (grant FL160100168 to P.A.C.).

Acknowledgements. Discussions with James Wookey, the comments of Nick Arndt on an earlier draft, and the thorough reviews of Jan Kramers and an anonymous referee, were greatly appreciated.

References

1. Belousova EA, Kostitsyn YA, Griffin WL, Begg GC, O'Reilly SY, Pearson NJ. 2010 The growth of the continental crust: constraints from zircon Hf-isotope data. *Lithos* **119**, 457–466. (doi:10.1016/j.lithos.2010.07.024)
2. Dhuime B, Hawkesworth CJ, Cawood PA, Storey CD. 2012 A Change in the geodynamics of continental growth 3 Billion years ago. *Science* **335**, 1334–1336. (doi:10.1126/science.1216066)
3. Hawkesworth CJ, Cawood PA, Kemp AIS, Storey CD, Dhuime B. 2009 A matter of preservation. *Science* **323**, 49–50. (doi:10.1126/science.1168549)

4. Arndt NT. 2013 Formation and evolution of the continental crust. *Geochem. Perspect.* **2**, 405–533. (doi:10.7185/geochempersp.2.3)
5. Voice PJ, Kowalewski M, Eriksson KA. 2011 Quantifying the timing and rate of crustal evolution: global compilation of radiometrically dated detrital zircon grains. *J. Geol.* **119**, 109–126. (doi:10.1086/658295)
6. Vervoort JD, Kemp AIS. 2016 Clarifying the zircon Hf isotope record of crust-mantle evolution. *Chem. Geol.* **425**, 65–75. (doi:10.1016/j.chemgeo.2016.01.023)
7. Allègre CJ, Rousseau D. 1984 The growth of the continent through geological time studied by Nd isotope analysis of shales. *Earth Planet. Sci. Lett.* **67**, 19–34. (doi:10.1016/0012-821X(84)90035-9)
8. Dhuime B, Hawkesworth CJ, Delavault H, Cawood PA. 2017 Continental growth seen through the sedimentary record. *Sediment. Geol.* **357**, 16–32. (doi:10.1016/j.sedgeo.2017.06.001)
9. Iizuka T, Yamaguchi T, Itano K, Hibiya Y, Suzuki K. 2017 What Hf isotopes in zircon tell us about crust-mantle evolution. *Lithos* **274**, 304–327. (doi:10.1016/j.lithos.2017.01.006)
10. Korenaga J. 2018 Estimating the formation age distribution of continental crust by unmixing zircon ages. *Earth Planet. Sci. Lett.* **482**, 388–395. (doi:10.1016/j.epsl.2017.11.039)
11. Roberts NMW, Spencer CJ. 2015 The zircon archive of continent formation through time. In *Continent formation through time* (eds NMW Roberts, M Van Kranendonk, S Parman, S Shirey, PD Clift), pp. 197–225. London, UK: The Geological Society of London Special Publication.
12. Campbell IH. 2003 Constraints on continental growth models from Nb/U ratios in the 3.5 Ga barberton and other Archaean basalt-komatiite suites. *Am. J. Sci.* **303**, 319–351. (doi:10.2475/ajs.303.4.319)
13. Pujol M, Marty B, Burgess R, Turner G, Philippot P. 2013 Argon isotopic composition of Archaean atmosphere probes early Earth geodynamics. *Nature* **498**, 87–90. (doi:10.1038/nature12152)
14. Condie KC, Aster RC. 2010 Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and continental growth. *Precambrian Res.* **180**, 227–236. (doi:10.1016/j.precamres.2010.03.008)
15. Condie KC. 1998 Episodic continental growth and supercontinents: a mantle avalanche connection? *Earth Planet. Sci. Lett.* **163**, 97–108. (doi:10.1016/S0012-821X(98)00178-2)
16. Reimink JR, Davies JHFL, Chacko T, Stern RA, Heaman LM, Sarkar C, Schaltegger U, Creaser RA, Pearson DG. 2016 No evidence for Hadean continental crust within Earth's oldest evolved rock unit. *Nat. Geosci.* **9**, 777–780. (doi:10.1038/ngeo2786)
17. Albarède F. 1998 The growth of continental crust. *Tectonophysics* **296**, 1–14. (doi:10.1016/S0040-1951(98)00133-4)
18. Arndt N, Davaille A. 2013 Episodic earth evolution. *Tectonophysics* **609**, 661–674. (doi:10.1016/j.tecto.2013.07.002)
19. Stein M, Hofmann AW. 1994 Mantle plumes and episodic crustal growth. *Nature* **372**, 63–68. (doi:10.1038/372063a0)
20. Condie KC, Puetz SJ, Davaille A. 2018 Episodic crustal production before 2.7 Ga. *Precambrian Res.* **312**, 16–22. (doi:10.1016/j.precamres.2018.05.005)
21. Gurnis M, Davies GF. 1986 Apparent episodic crustal growth arising from a smoothly evolving mantle. *Geology* **14**, 396–399. (doi:10.1130/0091-7613(1986)14<396:AECGAF>2.0.CO;2)
22. Condie KC, Bickford ME, Aster RC, Belousova E, Scholl DW. 2011 Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust. *Geol. Soc. Am. Bull.* **123**, 951–957. (doi:10.1130/b30344.1)
23. Dia A, Allegre CJ, Erlank AJ. 1990 The development of continental crust through geological time: the South African case. *Earth Planet. Sci. Lett.* **98**, 74–89. (doi:10.1016/0012-821x(90)90089-g)
24. Hawkesworth CJ, Cawood PA, Dhuime B. In press. Rates of generation and growth of the continental crust. *Geosci. Front.* (doi: 10.1016/j.gsf.2018.1002.1004).
25. DePaolo DJ, Linn AM, Schubert G. 1991 The continental crustal age distribution: methods of determining mantle separation ages from Sm-Nd isotopic data and application to the southwestern United-States. *J. Geophys. Res. Solid Earth Planets* **96**, 2071–2088. (doi:10.1029/90JB02219)

26. Hofmann AW, Puchtel I. 2017 Nb/U in komatiites: perspective on Archean crustal volume. *Goldschmidt Abstracts* **2017**, 1658.
27. Stuart FM, Mark DF, Gandanger P, McConville P. 2016 Earth-atmosphere evolution based on new determination of Devonian atmosphere Ar isotopic composition. *Earth Planet. Sci. Lett.* **446**, 21–26. (doi:10.1016/j.epsl.2016.04.012)
28. Rudnick RL, Gao S. 2003 Composition of the continental crust. In *Treatise on geochemistry, Vol. 3, The crust* (ed. RL Rudnick), pp. 1–64. Amsterdam, The Netherlands: Elsevier.
29. Nance WB, Taylor SR. 1976 Rare earth element patterns and crustal evolution-I. Australian post-Archean sedimentary rocks. *Geochim. Cosmochim. Acta* **40**, 1539–1551. (doi:10.1016/0016-7037(76)90093-4)
30. Keller CB, Boehnke P, Schoene B. 2017 Temporal variation in relative zircon abundance throughout Earth history. *Geochem. Perspect. Lett.* **3**, 179–189. (doi:10.7185/geochemlet.1721)
31. Lee CTA, Yeung LY, McKenzie NR, Yokoyama Y, Ozaki K, Lenardic A. 2016 Two-step rise of atmospheric oxygen linked to the growth of continents. *Nat. Geosci.* **9**, 417–424. (doi:10.1038/ngeo2707)
32. Fyfe WS. 1978 Evolution of Earth's crust - modern plate tectonics to ancient hot spot tectonics. *Chem. Geol.* **23**, 89–114. (doi:10.1016/0009-2541(78)90068-2)
33. Hawkesworth CJ, Cawood PA, Dhuime B. 2016 Tectonics and crustal evolution. *GSA Today* **26**, 4–11. (doi:10.1130/GSATG272A.1)
34. Brown GC. 1979 The changing pattern of batholith emplacement during Earth history. In *Origin of granite batholiths* (eds MP Atherton, J Tarney), pp. 106–115. Boston, MA: Birkhäuser.
35. Armstrong RL. 1981 Radiogenic isotopes: the case for crustal recycling on a near-steady-state no-continental-growth Earth. *Phil. Trans. R. Soc. Lond. A* **301**, 443–472. (doi:10.1098/rsta.1981.0122)
36. Dewey JF, Windley BF. 1981 Growth and differentiation of the continental crust. *Phil. Trans. R. Soc. Lond. A* **301**, 189–206. (doi:10.1098/rsta.1981.0105)
37. Reymer A, Schubert G. 1984 Phanerozoic addition rates to the continental crust and crustal growth. *Tectonics* **3**, 63–77. (doi:10.1029/TC003i001p00063)
38. Cawood PA, Hawkesworth CJ, Dhuime B. 2013 The continental record and the generation of the continental crust. *Geol. Soc. Am. Bull.* **125**, 14–32. (doi:10.1130/B30722.1)
39. Herzberg C, Condie K, Korenaga J. 2010 Thermal history of the Earth and its petrological expression. *Earth Planet. Sci. Lett.* **292**, 79–88. (doi:10.1016/j.epsl.2010.01.022)
40. Korenaga J. 2013 Initiation and evolution of plate tectonics on Earth: Theories and observations. *Ann. Rev. Earth Planet. Sci.* **41**, 117–151. (doi:10.1146/annurev-earth-050212-124208)
41. Scholl DW, von Huene R. 2007 Crustal recycling at modern subduction zones applied to the past-issues of growth and preservation of continental basement crust, mantle geochemistry, and supercontinent reconstruction. In *4–D framework of continental crust* (eds RD Hatcher, MP Carlson, JH McBride, JRM Catalán), pp. 9–32. London, UK: Geological Society of America Memoir.
42. Scholl DW, von Huene R. 2009 Implications of estimated magmatic additions and recycling losses at the subduction zones of accretionary (non-collisional) and collisional (suturing) orogens. In *Earth accretionary systems in space and time* (eds PA Cawood, A Kröner), pp. 105–125. London, UK: Geological Society, Special Publications.
43. Stern RJ, Scholl DW. 2010 Yin and yang of continental crust creation and destruction by plate tectonic processes. *Int. Geol. Rev.* **52**, 1–31. (doi:10.1080/00206810903332322)
44. Stern CR. 2011 Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. *Gondwana Res.* **20**, 284–308. (doi:10.1016/j.gr.2011.03.006)
45. Clift PD, Vannucchi P, Morgan JP. 2009 Crustal redistribution, crust-mantle recycling and Phanerozoic evolution of the continental crust. *Earth Sci. Rev.* **97**, 80–104. (doi:10.1016/j.earscirev.2009.10.003)
46. Dhuime B, Hawkesworth CJ, Storey CD, Cawood PA. 2011 From sediments to their source rocks: Hf and Nd isotopes in recent river sediments. *Geology* **39**, 407–410. (doi:10.1130/G31785.1)

47. Hawkesworth CJ, Cawood PA, Dhuime B, Kemp TIS. 2017 Earth's continental lithosphere through time. In *Annual review of earth and planetary sciences*, Vol. 45 (eds R Jeanloz, KH Freeman), pp. 169–198.
48. Cawood PA, Hawkesworth CJ, Pisarevsky SA, Dhuime B, Capitanio FA, Nebel O. 2018 Geological archive of the onset of plate tectonics. *Phil. Trans. R. Soc. B* **376**, 20170405. (doi:10.1098/rsta.2017.0405)
49. Dhuime B, Wuestefeld A, Hawkesworth CJ. 2015 Emergence of modern continental crust about 3 billion years ago. *Nat. Geosci.* **8**, 552–555. (doi:10.1038/ngeo2466)
50. Tang M, Chen K, Rudnick RL. 2016 Archean upper crust transition from mafic to felsic marks the onset of plate tectonics. *Science* **351**, 372–375. (doi:10.1126/science.aad5513)
51. Shirey SB, Richardson SH. 2011 Start of the Wilson cycle at 3 Ga shown by diamonds from subcontinental mantle. *Science* **333**, 434–436. (doi:10.1126/science.1206275)
52. Hawkesworth CJ, Dhuime B, Pietranik AB, Cawood PA, Kemp AI. S, Storey CD. 2010 The generation and evolution of the continental crust. *J. Geol. Soc. Lond.* **167**, 229–248. (doi:10.1144/0016-76492009-072)
53. Parman SW. 2015 Time-lapse zirconography: imaging punctuated continental evolution. *Geochem. Perspect. Lett.* **1**, 43–52. (doi:10.7185/geochemlet.1505)
54. Korenaga J. 2011 Thermal evolution with a hydrating mantle and the initiation of plate tectonics in the early Earth. *J. Geophys. Res. Solid Earth* **116**. (doi:10.1029/2011jb008410)
55. Sizova E, Gerya T, Brown M, Perchuk LL. 2010 Subduction styles in the Precambrian: insight from numerical experiments. *Lithos* **116**, 209–229. (doi:10.1016/j.lithos.2009.05.028)
56. van Hunen J, Moyen JF. 2012 Archean subduction: fact or fiction? *Ann. Rev. Earth Planet. Sci.* **40**, 195–219. (doi:10.1146/annurev-earth-04271-105255)
57. Gerya T. 2014 Precambrian geodynamics: concepts and models. *Gondwana Res.* **25**, 442–463. (doi:10.1016/j.gr.2012.11.008)
58. Flament N, Coltice N, Rey PF. 2008 A case for late-Archaean continental emergence from thermal evolution models and hypsometry. *Earth Planet. Sci. Lett.* **275**, 326–336. (doi:10.1016/j.epsl.2008.08.029)
59. Pons ML, Fujii T, Rosing M, Quitte G, Telouk P, Albarede F. 2013 A Zn isotope perspective on the rise of continents. *Geobiology* **11**, 201–214. (doi:10.1111/gbi.12030)
60. Rey PF, Coltice N. 2008 Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs. *Geology* **36**, 635–638. (doi:10.1130/g25031a.1)
61. Bindeman IN, Zakharov DO, Palandri J, Greber ND, Dauphas N, Retallack GJ, Hofmann A, Lackey JS, Bekker A. 2018 Rapid emergence of subaerial landmasses and onset of a modern hydrologic cycle 2.5 billion years ago. *Nature* **557**, 545–548. (doi:10.1038/s41586-018-0131-1)