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LETTERS

Microbial habitability of the Hadean Earth during the late heavy bombardment

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Lunar rocks[1,2] and impact melts[3], lunar[4] and asteroidal meteorites[5], and an ancient martian meteorite[6] record thermal metamorphic events with ages that group around and/or do not exceed 3.9 Gyr. That such a diverse suite of solar system materials share this feature is interpreted to be the result of a post-primary-accretion cataclysmic spike in the number of impacts commonly referred to as the late heavy bombardment (LHB)[1–7]. Despite its obvious significance to the preservation of crust and the survivability of an emergent biosphere, the thermal effects of this bombardment on the young Earth remain poorly constrained. Here we report numerical models constructed to probe the degree of thermal metamorphism in the crust in the effort to recreate the effect of the LHB on the Earth as a whole; outputs were used to assess habitable volumes of crust for a possible near-surface and subsurface primordial microbial biosphere. Our analysis shows that there is no plausible situation in which the habitable zone was fully sterilized on Earth, at least since the termination of primary accretion of the planets and the postulated impact origin of the Moon. Our results explain the root location of hyperthermophilic bacteria in the phylogenetic tree for 16S small-subunit ribosomal RNA[8], and bode well for the persistence of microbial biospheres even on planetary bodies strongly reworked by impacts.

Analyses of lunar crust samples[1,2] and impact melts[3] returned by the Apollo and Luna missions, as well as from lunar meteorites[4], indicate thermal metamorphism by events that typically group around and/or do not exceed 3.9 Gyr in age. This has been interpreted to be the consequence of a pronounced increase in the number of impacts ~3.9 Gyr ago within a period of 20 to 200 Myr (refs 2, 7), in what has been termed the lunar cataclysm[2] or, more commonly, the late heavy bombardment[7]. Shock ages suggestive of the LHB have also been documented in asteroidal meteorites[5], and the only known sample of the martian crust dating from earlier than 4.0 Gyr ago, meteorite ALH 84001[6]. However, evidence of the LHB on the Earth has apparently been all but erased[9] by crustal recycling processes.

Habitats at the immediate surface of the early Earth were almost certainly repeatedly destroyed by the LHB. At the same time, however, new subsurface habitats would have formed from impact-induced hydrothermal systems[10], which perhaps provided sanctuary to existing life or may even have been the crucible of its origin[11]. The cessation of the LHB coincides very well with the earliest evidence for marine sediments[12,13] and proxy stable isotopic evidence for life existing on the Earth ~3.83 Gyr ago[14,15]. Molecular phylogenetic evidence in the form of 16S small-subunit rRNA strongly suggests that all terrestrial life arose from a common ancestral population akin to present-day thermophilic or hyperthermophilic organisms[8]. This observation has been used to implicate the bombardment epoch as a means of effectively creating an impact-generated thermal bottleneck for the biosphere[16]. It has also been postulated that the energy liberated during the LHB may have precluded the continuous survival of incipient life[17] in one or more 'impact frustrations', and disrupted the crust to such a degree that no Earth rocks survive from before ~3.8 Gyr ago[18]. However, Earth rocks that coincide with or pre-date the LHB are known, and date from as early as 4.03 Gyr ago[19]. Furthermore, geochemical evidence from terrestrial zircons older than 4.0 Gyr points to there having been liquid water, crustal recycling, granitoid crust and low-temperature plate boundary processes throughout the Hadean eon (4.38–3.85 Gyr ago)[20,21]. On the basis of this new perspective of the very early Earth, it makes sense to address whether a biosphere that may have arisen in the Hadean could have survived through the LHB.

To explore the thermal state and habitability of the early Earth during the LHB, we constructed thermal models that incorporate (1) new studies of impact cratering records of the Moon and the terrestrial planets, and the size distributions of asteroid populations[22]; (2) data from a new class of early-Solar-System dynamical models that successfully reproduce impact rates during the bombardment as defined by the lunar and meteoritic record[23]; and (3) powerful numerical methods that explore the thermal response of the lithosphere to impacts of the severity and frequency ascribed to the bombardment (Fig. 1).

Impactors that bombarded the Earth and Moon are thought to have been dominated by main-belt asteroids[22], and the size–frequency distribution of the asteroid belt is unlikely to have changed significantly since that time[24]. The total mass delivered to the Earth during the LHB has been estimated at 1.8×10^{20} kg on the basis of dynamical modelling[23] and 2.2×10^{20} kg on the basis of the lunar cratering record[25,26]. For the purposes of this work, we adopt the average value of 2.0×10^{20} kg and we use the size–frequency distribution of the asteroid belt normalized to this total mass value. The duration of the LHB in this analysis is taken to be ~100 Myr, although other values (for example 10 Myr) were also investigated.

It is likely that a relatively few very large impactors were responsible for most of the mass (and energy) delivered during the LHB (Fig. 2). Our model predicts ~90 impactors 50 km or more in diameter, which formed basins ~1,000 km or more in diameter. These impacts would have been temporally separated by over 1 Myr, on average, over the course of a 100-Myr-long bombardment, and would have resurfaced less than 25% of the Earth's surface. We evaluated the immediate thermal effects of these (and smaller) impactors on the bulk lithosphere. The fraction of the Earth's lithosphere that experienced a given temperature increase during the LHB is shown in Fig. 3. The results of this study indicate that most of the crust was not melted or thermally metamorphosed to a significant degree, with less than 10% experiencing a temperature increase of over 500 °C. The total mass delivered would have to be approximately tenfold greater than that in our baseline model for most of the crustal volume to have undergone melting. Lithospheric thickness has no significant influence on these results.

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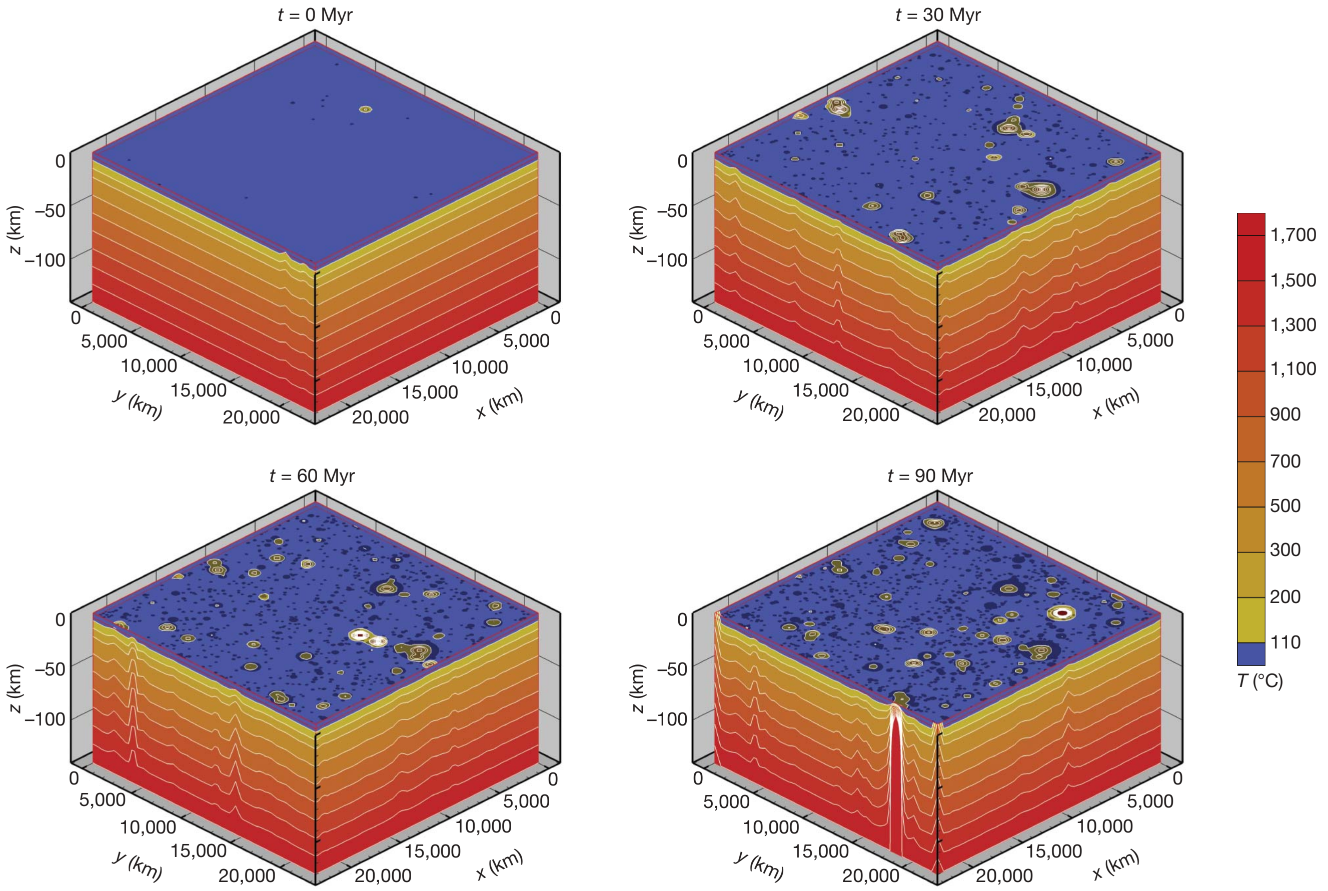

Figure 1 | A three-dimensional thermal model representing the Earth's lithosphere at various times during the LHB in our baseline scenario. Only impactors larger than 10 km in diameter are included in this plot. The upper surface shows temperatures at a depth of 4 km. Dark areas indicate crater imprints.

Whereas very large basin-forming impacts deposit most of their energy in the deep lithosphere and the mantle, smaller impacts deposit most of their energy in the potentially habitable top 4 km of the crust. Thus, for a more complete habitability evaluation, we performed an assessment of the near-surface thermal effects of a wide range of impactors. The results of this analysis show that smaller impactors (diameter, 1–10 km) were as important as much larger basin formers ($\geq$100 km) in terms of sterilization (heating above 110 °C) of the near-surface crust (Table 1). Nonetheless, large craters are more biologically significant because their near-surface crust takes orders of magnitude longer to cool ($\sim10^7$ yr for a 2,000-km impact basin versus $\sim10^5$ yr for a 20-km crater), which results in long-lived hydrothermal systems[27]. The outcomes presented in Table 1 also suggest that even if all LHB impacts had occurred simultaneously, Earth still would not have been sterilized.

Habitable volumes for mesophile (20–50 °C), thermophile (50–80 °C) and hyperthermophile (80–110 °C) microbial populations in the near-surface crust (the upper $\sim$4 km) for a 100-Myr-long

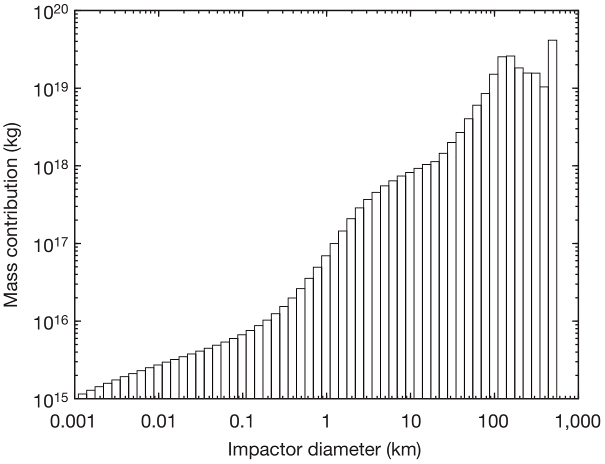

Figure 2 | Impactor mass distribution for the Earth during the LHB. Distribution derived from the main-belt size–frequency distribution[24] and estimates of the total mass delivered[23,25,26].

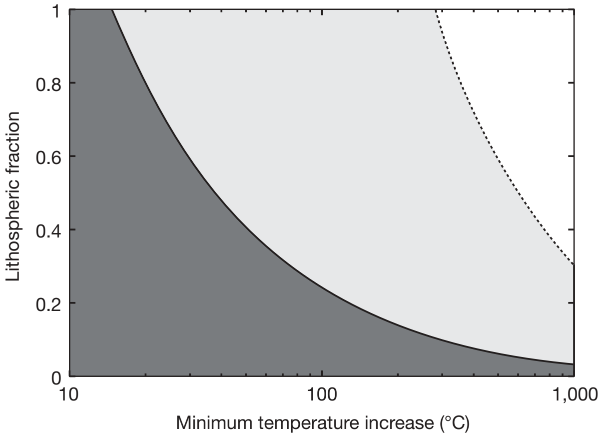

Figure 3 | Immediate thermal effects of impacts on the lithosphere. Fraction of the Earth's lithosphere to experience a given temperature increase as a result of the LHB. The solid line represents the baseline model and the dashed line represents the model with tenfold delivered mass. Lithospheric thickness has no significant effect on these results.

Table 1 | Immediate thermal effects of impacts on the habitable zone

Impactor diameter range (km)	Number of impacts	Percentage of habitable zone sterilized
≥100	33	13%
10–100	1,500	10%
1–10	170,000	13%
0.1–1	12,000,000	1%

Percentage of habitable zone (~4 km below the surface) exposed to temperatures above 110 °C (the upper limit for hyperthermophiles) in the baseline model.

LHB are shown in Fig. 4a. We find that over the course of the LHB, there would have been a significant increase in the habitable volume for thermophiles and hyperthermophiles and a decrease in the habitable volume for mesophiles. The overall habitable volume remains approximately the same, however, because of the relatively rapid cooling of the near-surface crust even in the case of large impact basins. Habitable conditions in the near-surface volume of the crust are re-established in at most ~10^5 yr after impact.

Although the LHB in our main model is insufficient to extinguish microbial life in the Hadean Earth's habitable volume of crust, the model does not explicitly incorporate thermal shock from a global layer of hot ejecta and rock-vapour rainout following a basin-forming impact[28]. However, the maximum sterilization depth for such a process is only a few hundred metres[28] and is further reduced or eliminated by vaporization of groundwater, hydrothermal circulation, the raining out of impact-vaporized and hydrothermally vented water, and the presence of oceans (Supplementary Information). Finally, the largest impactor in our baseline model (~300 km in diameter) is insufficient to vaporize the oceans[28]. As the duration of the LHB is still uncertain, one of our model test cases was an LHB with a duration of 10 Myr, with the total delivered mass held at 2.0×10^{20} kg. The output shows a pronounced increase in the hyperthermophile habitable volume and a decrease in the mesophile habitable volume (Fig. 4b). The mesophile time–temperature curve approaches the thermophile curve and crosses it at several points.

Increasing the total mass delivered by a factor of ten (to 2.0×10^{21} kg), with a 100-Myr-long bombardment, results in a marked enhancement of the hyperthermophile habitable volume and a sharp decrease in the mesophile habitable volume (Fig. 4c). The calculated total habitable volume of the Hadean crust (1.7×10^9 km^3) at the end of the LHB is slightly lower than the habitable volume (2.1×10^9 km^3) at the start of the simulation. A similar plot of habitable volume can be produced by doubling the impact speed from 20 to 40 km s^{-1} (Supplementary Information).

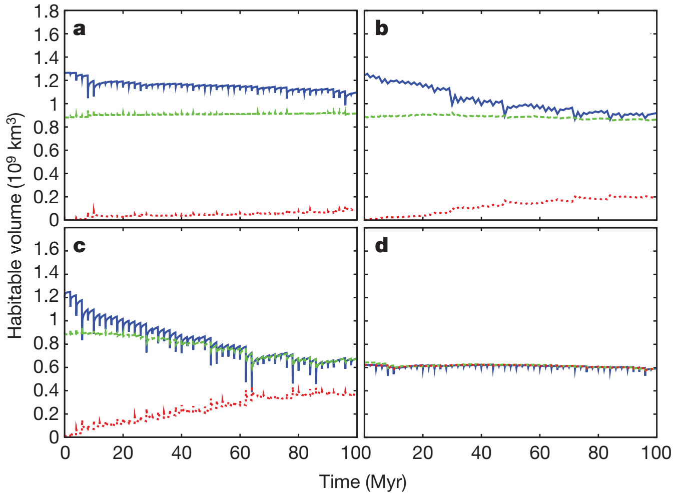

Figure 4 | Global habitable volumes. **a**, Habitable volumes for mesophiles (20–50 °C, blue), thermophiles (50–80 °C, green) and hyperthermophiles (80–110 °C, red) during a 100-Myr-long LHB. **b**, Habitable volumes during a 10-Myr-long LHB with the same delivered mass. **c**, Habitable volumes during a 100-Myr-long LHB with tenfold delivered mass. **d**, Habitable volumes during a 100-Myr-long LHB with the geothermal temperature gradient doubled.

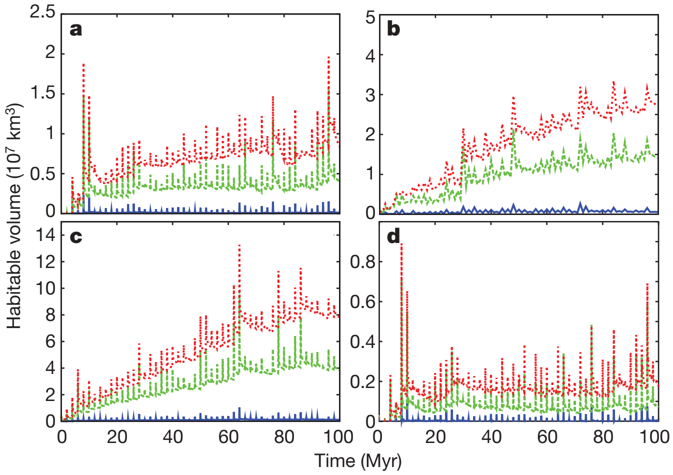

Figure 5 | Global habitable volumes in hydrothermal environments. **a**, Habitable volumes for mesophiles (20–50 °C, blue), thermophiles (50–80 °C, green) and hyperthermophiles (80–110 °C, red) during a 100-Myr-long LHB in active hydrothermal environments. **b**, Hydrothermal habitable volumes during a 10-Myr-long LHB with the same delivered mass. **c**, Hydrothermal habitable volumes during a 100-Myr-long LHB with tenfold delivered mass. **d**, Hydrothermal habitable volumes during a 100-Myr-long LHB with the geothermal temperature gradient doubled.

Doubling the geothermal temperature gradient from 12 °C km^{-1} to 24 °C km^{-1} results in approximately equal habitable volumes (~6×10^8 km^3) for mesophiles, thermophiles and hyperthermophiles throughout the LHB (Fig. 4d). This is due to their initial equal volumes in the habitable zone and the relatively rapid linearization of the vertical temperature gradients after each impact. We also investigated an extreme endmember case in which the surface temperature is 50 °C, the geothermal gradient is 48 °C km^{-1} and the total delivered mass is 2.0×10^{22} kg (100 times the baseline), and found that this is insufficient to extinguish subsurface microbial life owing to the relatively rapid cooling of the near-surface crust following an impact (Supplementary Information).

If the subsurface is saturated with water and hydrothermal circulation is established, heat is lost from the upper boundary up to ten times faster, and habitable conditions are re-established up to an order of magnitude more rapidly after crater formation[29]. This is particularly relevant if the impact occurs in the ocean. For craters ~200 km in diameter, colonization by thermophiles in the central regions is possible after ~20,000 yr (ref. 29). This observation provides further support to the conclusion that subsurface microbial life could have persisted throughout the bombardment.

We also estimated habitable volumes in impact-induced temperature anomalies that are likely to drive hydrothermal activity (Fig. 5). For the purposes of this study, a hydrothermal environment is defined as a thermally anomalous environment with a geothermal temperature gradient in excess of double the normal value. Comparison of Fig. 4 and Fig. 5 shows that habitable volumes in active hydrothermal environments are a relatively small fraction of the total—in no case is the habitable volume dominated by hydrothermal environments. This would seem to argue against the idea of an impact bottleneck in which only thermophiles survived[28], and instead supports the hypothesis that widespread hydrothermal activity during the LHB was conducive to life's emergence and early diversification[30].

METHODS SUMMARY

Our stochastic cratering model was used to populate all or part of the Earth's surface with craters within a probability field of constraints established from the models and observations cited above. The thermal field of each crater was introduced into a three-dimensional block model of the Earth's lithosphere and allowed to cool by conduction in the subsurface and radiation/convection at the atmosphere interface (Fig. 1). We used the computer code HEATING, which is a general-purpose, three-dimensional, finite-difference heat-transfer program written and maintained at Oak Ridge National Laboratory, USA, that solves transient heat-conduction problems and contains a library of thermal properties of geologically relevant materials, such as basalt and granite. The physical and thermal properties of each target rock (for example thermal conductivity, density and specific heat) are temperature dependent. Target crust was allowed by the code to undergo changes of phase, permitting the inclusion of impact melt. Boundary conditions included a bottom boundary with a prescribed heat flux and a surface–atmosphere interface where heat is transferred out of the system by convection and radiation. The lateral boundaries of the block model are defined as continuous 'wrap arounds', so that all deposited heat stays in the system until it is lost through the upper boundary.

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1. Turner, G., Cadogan, P. H. & Yonge, C. J. Argon selenochronology. *Proc. Lunar Sci. Conf.* **4,** 1889–1914 (1973).
2. Tera, F., Papanastassiou, D. A. & Wasserburg, G. J. Isotopic evidence for a terminal lunar cataclysm. *Earth Planet. Sci. Lett.* **22,** 1–21 (1974).
3. Dalrymple, G. B. & Ryder, G. ^{40}Ar/^{39}Ar age spectra of Apollo 15 impact melt rocks by laser step-heating and their bearing on the history of lunar basin formation. *J. Geophys. Res.* **98,** 13085–13095 (1993).
4. Cohen, B. A., Swindle, T. D. & Kring, D. A. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. *Science* **290,** 1754–1756 (2000).
5. Kring, D. A. & Cohen, B. A. Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga. *J. Geophys. Res.* **107,** doi:10.1029/2001JE001529 (2002).
6. Ash, R. D., Knott, S. F. & Turner, G. A 4-Gyr shock age for a Martian meteorite and implications for the cratering history of Mars. *Nature* **380,** 57–59 (1996).
7. Ryder, G. Lunar samples, lunar accretion, and the early bombardment history of the Moon. *Eos* **71,** 313–323 (1990).
8. Pace, N. R. A molecular view of microbial diversity and the biosphere. *Science* **276,** 734–740 (1997).
9. Trail, D., Mojzsis, S. J. & Harrison, T. M. Thermal events documented in Hadean zircons by ion microprobe depth profiles. *Geochim. Cosmochim. Acta* **71,** 4044–4065 (2007).
10. Zahnle, K. J. & Sleep, N. H. in *Comets and the Origin and Evolution of Life* (eds Thomas, P., Chyba, C. & McKay, C.) 175–208 (Springer, 1997).
11. Baross, J. A. & Hoffman, S. E. Submarine hydrothermal vents and associated gradient environments as sites for the origin and evolution of life. *Orig. Life Evol. Biosph.* **15,** 327–345 (1985).
12. Manning, C. E., Mojzsis, S. J. & Harrison, T. M. Geology, age and origin of supracrustal rocks at Akilia, West Greenland. *Am. J. Sci.* **306,** 303–366 (2006).
13. Dauphas, N. *et al.* Clues from Fe isotope variations on the origin of early Archean BIFs from Greenland. *Science* **206,** 2077–2080 (2004).
14. Mojzsis, S. J. *et al.* Evidence for life on Earth by 3,800 million years ago. *Nature* **384,** 55–59 (1996).
15. McKeegan, K. D., Kudryavtsev, A. B. & Schopf, J. W. Raman and ion microscopic imagery of graphitic inclusions in apatite from older than 3830 Ma Akilia supracrustal rocks, west Greenland. *Geology* **35,** 591–594 (2007).
16. Gogarten-Boekels, M., Hilario, E. & Gogarten, J. P. The effects of heavy meteorite bombardment on the early evolution - the emergence of the three domains of life. *Orig. Life Evol. Biosph.* **25,** 251–264 (1995).
17. Maher, K. A. & Stevenson, D. J. Impact frustration of the origin of life. *Nature* **331,** 612–614 (1988).
18. Hamilton, W. B. in *Precambrian – Conterminous United States* (eds Reed, J. C. Jr *et al.*) 597–614, 630–636 (Geol. N. Am. Vol. C-2, Geological Society of America, 1993).
19. Bowring, S. A. & Williams, I. S. Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. *Contrib. Mineral. Petrol.* **134,** 3–16 (1999).
20. Mojzsis, S. J., Harrison, T. M. & Pidgeon, R. T. Oxygen isotope evidence from ancient zircons for liquid water at Earth's surface 4,300 Myr ago. *Nature* **409,** 178–181 (2001).
21. Hopkins, M., Harrison, T. M. & Manning, C. E. Low heat flow inferred from $>$4 Gyr zircons suggests Hadean plate boundary interactions. *Nature* **456,** 493–496 (2008).
22. Strom, R. G., Malhotra, R., Ito, T., Yoshida, F. & Kring, D. A. The origin of planetary impactors in the inner solar system. *Science* **309,** 1847–1850 (2005).
23. Gomes, R., Levison, H. F., Tsiganis, K. & Morbidelli, A. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* **435,** 466–469 (2005).
24. Bottke, W. F. *et al.* The fossilized size distribution of the main asteroid belt. *Icarus* **175,** 111–140 (2005).
25. Hartmann, W. K., Ryder, G., Dones, L. & Grinspoon, D. in *Origin of the Earth and Moon* (eds Canup, R. & Righter, K.) 493–512 (Univ. Arizona Press, 2000).
26. Ryder, G., Koeberl, C. & Mojzsis, S. J. in *Origin of the Earth and Moon* (eds Canup, R. & Righter, K.) 475–492 (Univ. Arizona Press, 2000).
27. Abramov, O. & Kring, D. A. Impact-induced hydrothermal activity on early Mars. *J. Geophys. Res.* **110,** doi:10.1029/2005JE002453 (2005).
28. Sleep, N. H. & Zahnle, K. Refugia from asteroid impacts on early Mars and the early Earth. *J. Geophys. Res.* **103,** 28529–28544 (1998).
29. Abramov, O. & Kring, D. A. Numerical modeling of an impact-induced hydrothermal system at the Sudbury crater. *J. Geophys. Res.* **109,** doi:10.1029/2003JE002213 (2004).
30. Ryder, G. Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth. *J. Geophys. Res.* **107,** doi:10.1029/2001JE001583 (2002).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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