

# Origin of the Ganymede–Callisto dichotomy by impacts during the late heavy bombardment

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**Jupiter's large moons Ganymede<sup>1,2</sup> and Callisto<sup>2,3</sup> are similar in size and composition. However, Ganymede has a tectonically evolved surface<sup>1</sup> and a large rock/metal core<sup>2</sup>, whereas Callisto's surface shows no sign of resurfacing<sup>3</sup> and the separation of ice and rock in its interior seems incomplete<sup>2</sup>. These differences have been difficult to explain<sup>4–11</sup>. Here we present geophysical models of impact-induced core formation to show that the Ganymede–Callisto dichotomy can be explained through differences in the energy received during a brief period of frequent planetary impacts about 700 million years after planet formation, termed the late heavy bombardment<sup>12–15</sup>. We propose that during the late heavy bombardment, impacts would have been sufficiently energetic on Ganymede to lead to a complete separation of rock and ice, but not on Callisto. In our model, a dichotomy between Ganymede and Callisto that is consistent with observations is created if the planetesimal disk that supplied the cometary impactors during the late heavy bombardment is about 5–30 times the mass of the Earth. Our findings are consistent with estimates of a disk about 20 times the mass of the Earth as used in dynamical models that recreate the present-day architecture of the outer solar system and the lunar late heavy bombardment<sup>15,16</sup>.**

The origin of the ‘Ganymede–Callisto dichotomy’ has puzzled scientists since the Voyager era<sup>4–7,9–11</sup>. Ganymede (radius  $R = 2,631$  km) and Callisto ( $R = 2,410$  km) have mean densities  $\rho = 1.942$  g cm<sup>-3</sup> and 1.834 g cm<sup>-3</sup>, respectively, indicating half-rock/half-ice compositions<sup>2</sup>. Ganymede's grooved terrain suggests extensive interior evolution<sup>1</sup>, and its moment of inertia indicates that all of its rock has consolidated into a central core<sup>2</sup>. Callisto's ancient surface shows no signs of endogenic resurfacing<sup>3</sup>. Its moment of inertia suggests that rock core formation has been incomplete<sup>17</sup>. The moons are thought to form in similar environments<sup>5,7,10,11</sup>, and so creating the dichotomy during their accretion is possible only if small differences in formation conditions are amplified<sup>11</sup>. It is also difficult to explain the dichotomy by appealing to differences in the satellites' later thermal evolution because divergent outcomes are achieved only for a small range of material properties<sup>6</sup>. Melting of Ganymede by tidal heating<sup>18</sup> is a possible explanation; however, strong tidal heating in Ganymede occurs in a narrow window of possible orbital evolution histories<sup>8,9,18</sup>.

We propose that the dichotomy is created by impacts onto the satellites during the late heavy bombardment (LHB). The LHB is a period of enhanced impact rates by asteroids<sup>12,13</sup> and/or comets<sup>14,15</sup>, during which the large lunar impact basins were formed<sup>12,13</sup>. It has recently been proposed that the LHB was triggered by dynamical interactions between the outer planets and a disk of icy planetesimals that created a brief shower of cometary and asteroidal material onto the terrestrial planets<sup>14,15</sup>,

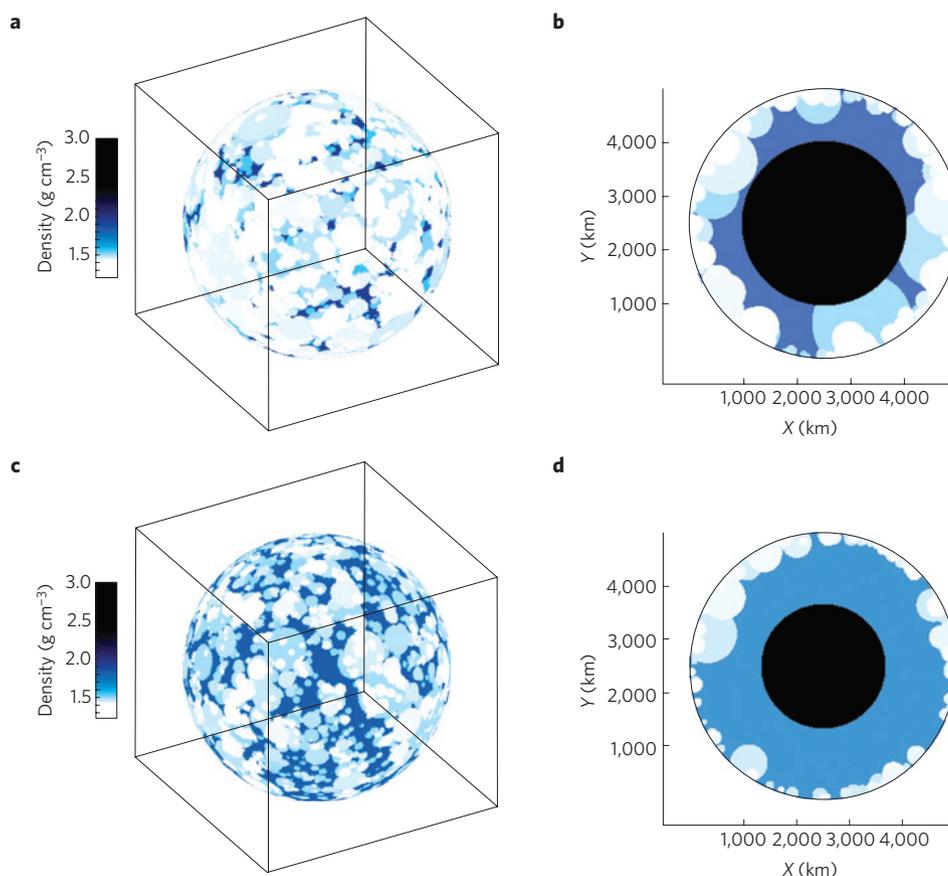
and predominantly cometary material onto the outer planet satellites<sup>14</sup>. The LHB would have been a much more energetic event at Ganymede than Callisto. Ganymede, which is closer to Jupiter, experiences twice as many impacts as Callisto with higher characteristic impact velocities ( $v_i \approx 20$  km s<sup>-1</sup> for Ganymede and 15 km s<sup>-1</sup> for Callisto<sup>19</sup>, see Table 1). Dynamical simulations of the outer solar system in the ‘Nice model’<sup>15,16</sup> show that scattering of a planetesimal disk that initially contains  $\approx 35$  Earth masses ( $M_\oplus$ ), whittled down to  $M_D \sim 20M_\oplus$  at the time of the LHB, delivers  $\approx 8 \times 10^{21}$  g of cometary material to Earth's moon during the LHB, and a similar mass in asteroids<sup>15</sup>. This is comparable to the total mass of lunar LHB impactors<sup>14,15</sup> estimated from crater counts<sup>14</sup>. During an outer solar system LHB, Ganymede receives 80 times the mass of cometary objects hitting Earth's moon owing to strong gravitational focusing by Jupiter<sup>14,19</sup>. Scattering of an  $M_D = 20M_\oplus$  planetesimal disk will deliver a total mass  $M_{LHB}^G \sim 6 \times 10^{23}$  g of cometary impactors during the LHB to Ganymede and half this amount,  $M_{LHB}^C \sim 3 \times 10^{23}$  g, to Callisto. The associated impact energy at Ganymede,  $E_{LHB} \sim (1/2)M_{LHB}^G v_i^2 \sim 10^{36}$  erg, is five times higher than the energy required to melt all of Ganymede's ice,  $E_{melt} \sim (1 - m_r)ML = 2 \times 10^{35}$  erg, where  $M = 1.48 \times 10^{26}$  g is Ganymede's mass,  $m_r = 0.52$  is its rock mass fraction<sup>20</sup> and  $L = 3 \times 10^9$  erg g<sup>-1</sup> is the latent heat of water ice<sup>21</sup>. Callisto ( $M = 1.07 \times 10^{26}$  g,  $m_r = 0.44$ ) receives  $E_{LHB} \sim 2 \times E_{melt}$ . At face value, this suggests that both satellites melt during the LHB. However, the calculation assumes that 100% of the impact energy is used to melt the satellites' ice, which is unrealistic<sup>22</sup>.

Here, we develop a detailed model of impact-induced melting and core formation<sup>23,24</sup> (W. B. Tonks, *et al.*, unpublished) to address the effect of an LHB on Ganymede and Callisto. A hypervelocity impact creates a shock wave that compresses and does irreversible work on a roughly spherical region beneath the impact point (see Supplementary Methods S1.2). At locations where the peak shock pressure exceeds the pressure required to induce melting of ice on release from the shock state, a buried pool of liquid water and ice crystals is created. In the region where the volume fraction of melt is  $>50\%$  post-impact<sup>25</sup>, the water/crystal/rock particle mixture has a low viscosity, comparable to that of liquid water, so that concomitant rock rapidly sinks and accumulates at the base of the melt pool (W. B. Tonks, *et al.*, unpublished). The denser rock ultimately descends through the ice/rock mantle, liberating gravitational potential energy as heat inside the satellite as it sinks to the satellite's centre in a few thousand years<sup>6</sup> (see Supplementary Methods S3.3.3, Fig. 1b,d, and Supplementary Movies). If the energy released by the impact-induced ice/rock separation is sufficient to melt the remainder of the satellite's ice, the process becomes energetically self-sustaining and will drive itself to completion (so-called ‘runaway differentiation’<sup>6</sup>).

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**Table 1 | Key model parameters and their values.**

| Property  | Symbol                | Ganymede  | Callisto  |
|---|-----------------------|---|---|
| Satellite density                                 | $\rho$                | 1.942 g cm <sup>-3</sup>  | 1.834 g cm <sup>-3</sup>  |
| Satellite radius                                  | $R$                   | 2,631 km  | 2,410 km  |
| Latent heat of water ice                          | $L$                   | 3 × 10 <sup>9</sup> erg g <sup>-1</sup>                               | 3 × 10 <sup>9</sup> erg g <sup>-1</sup>                               |
| Rock mass fraction <sup>20</sup>                  | $m_r$                 | 0.52  | 0.44  |
| Initial volume fraction of rock                   | $\phi_o$              |   |   |
| Nominal   |                       | 0.34  | 0.27  |
| High density                                      |                       | 0.19  | 0.15  |
| Low density                                       |                       | 0.46  | 0.40  |
| Characteristic impact velocity <sup>19</sup>      | $v_i$                 | 20 km s <sup>-1</sup>   | 15 km s <sup>-1</sup>   |
| Characteristic projectile radius                  | $\langle r_p \rangle$ | 30 km   | 30 km   |
| Melt region, radius                               | $\chi$                | 5.06 $r_p(v_i/15 \text{ km s}^{-1})^{0.6}$                            | 5.06 $r_p(v_i/15 \text{ km s}^{-1})^{0.6}$                            |
| Melt region, burial depth                         | $\xi$                 | 2.85 $r_p(v_i/15 \text{ km s}^{-1})^{0.47}$                           | 2.85 $r_p(v_i/15 \text{ km s}^{-1})^{0.47}$                           |
| Impact probability relative to Moon <sup>19</sup> |                       | 80  | 40  |
| Mass of impactors during LHB                      | $M_{\text{LHB}}$      | $M_{\text{LHB}}^{\text{C}}$   | $M_{\text{LHB}}^{\text{G}}$   |
| LHB disk mass                                     | $M_{\text{D}}$        | $(M_{\text{LHB}}^{\text{C}}/1.68 \times 10^{22} \text{ g})M_{\oplus}$ | $(M_{\text{LHB}}^{\text{G}}/1.68 \times 10^{22} \text{ g})M_{\oplus}$ |



**Figure 1 | Interior structures of Ganymede and Callisto after the LHB.** Heterogeneous interior structures created by an outer solar system LHB with  $M_{\text{D}} = 14M_{\oplus}$ ,  $\langle r_p \rangle = 30$  km, and our nominal ice/rock composition model. **a–d**, Satellite density at the surface as a function of latitude and longitude (**a,c**) and longitudinal slice through the ice/rock (blue) and ice (white) globes in the  $y$ - $z$  plane, illustrating the rocky core (black) (**b,d**), for Ganymede (**a,b**) and Callisto (**c,d**).

A simple estimate is that runaway differentiation of the entire satellite will occur if

$$f_m = \frac{\Delta E_{\text{gr}}}{(1 - m_r)(1 - \frac{x^3}{\phi_o})ML} > 1 \quad (1)$$

where  $\Delta E_{\text{gr}}$  is the difference in gravitational potential energy between the initial uniform-density and final differentiated states<sup>6</sup>,

$\phi_o$  is the bulk volume fraction of rock in the satellite’s interior and  $x$  is the fractional radius of the rocky core ( $x \equiv R_{\text{core}}/R$ ).

First, we use analytical estimates of the gravitational potential energy released by impact-induced ice/rock separation to show that the Ganymede–Callisto dichotomy can be produced during an outer solar system LHB. For the dichotomy to form, Callisto must avoid runaway differentiation. This gives an upper limit on LHB mass ( $M_{\text{LHB}}$ ), and by extension, an upper limit on the planetesimal

disk mass ( $M_D$ ) consistent with dichotomy creation. Requiring Ganymede to experience runaway differentiation gives a lower limit on  $M_{LHB}$  and  $M_D$ . We consider an initially uniform-density satellite containing a volume fraction  $\phi_o = m_r(\rho/\rho_r)$  of rock (density  $\rho_r$ ) hit by a total mass  $M_{LHB}$  of objects with a characteristic projectile radius  $r_p$ , velocity  $v_i$ , and vertical impact angle. The bombardment has  $N = M_{LHB}/[(4/3)\pi r_p^3 \rho] = (M_{LHB}/M)(R/r_p)^3$  objects, where impactor and satellite densities are assumed to be equal and constant.

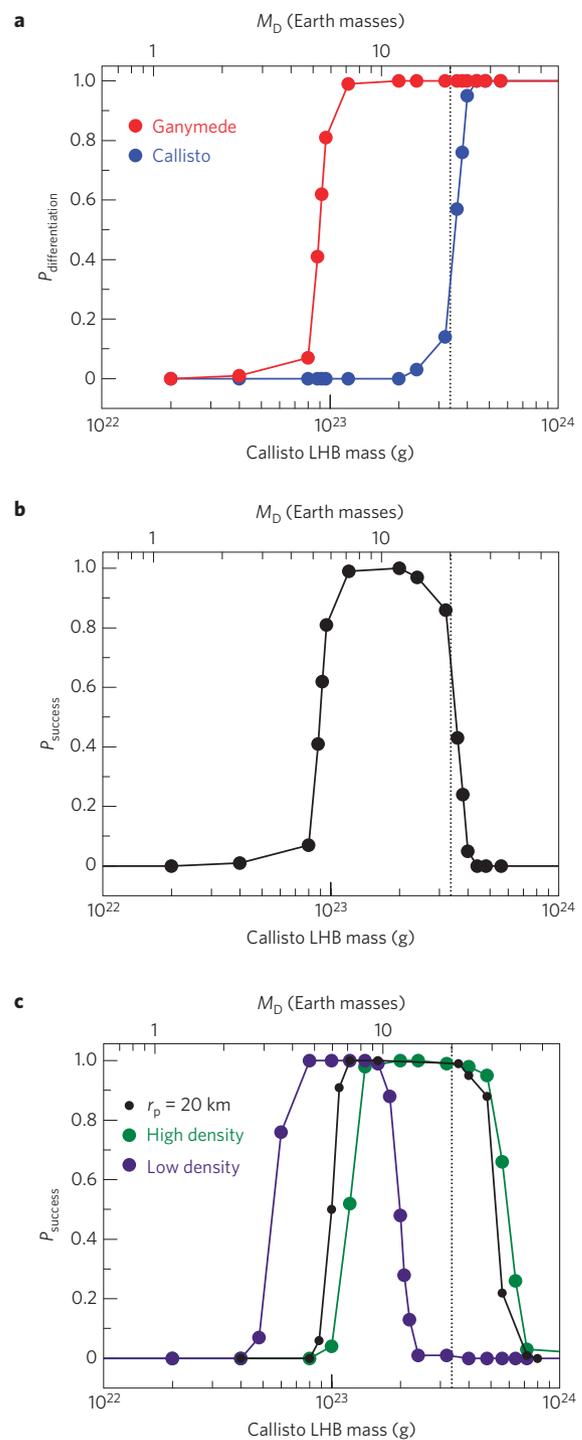
If impactors are large and melt pools from successive impacts do not overlap, the satellite evolves to a two-layered structure: a rock core of radius  $xR$  produced by the rock liberated from impact-produced melt pools, and a rock-depleted mantle. Our numerical impact simulations (see Supplementary Methods S1) show that the region shocked to  $>50\%$  melt is well described by a sphere of radius  $\chi r_p$ , buried at a depth  $\xi r_p$  (ref. 22), where  $\chi = 5.06(v_i/15 \text{ km s}^{-1})^{0.6}$  and  $\xi = 2.85(v_i/15 \text{ km s}^{-1})^{0.47}$ . Each impact melts a volume  $V_i \sim (4/3)\pi(\chi r_p)^3$ . The volume of rock removed by  $N$  impacts,  $V_{\text{core}} = NV_i\phi_o$ , forms a core  $x \sim [(M_{LHB}/M)\chi^3\phi_o]^{1/3}$  (see Supplementary Methods S2.1). For non-overlapping large impacts,  $x$  is independent of  $r_p$ , so core formation outcomes in this regime are insensitive to the size-frequency distribution of LHB impactors, and the final core size depends primarily on the total mass of LHB impactors.

For Callisto to avoid runaway differentiation,  $x < 0.52$  (see Supplementary Methods S2.2), requiring that the mass of LHB impactors hitting Callisto,  $M_{LHB}^C$ , is  $M_{LHB}^C < 4 \times 10^{23}$  g (assuming a nominal  $\rho_r = 3.0 \text{ g cm}^{-3}$ ,  $\rho_i = 1.4 \text{ g cm}^{-3}$ ). For Ganymede to fully differentiate,  $x > 0.52$ , which occurs for  $M_{LHB}^C > 10^{23}$  g. The dichotomy is then created for  $10^{23} \text{ g} < M_{LHB}^C < 4 \times 10^{23}$  g, equivalent to  $6M_{\oplus} < M_D < 23M_{\oplus}$ . Per arguments above, simulations of an outer solar system LHB that reproduce the present-day orbital architecture of the outer solar system<sup>16</sup> predict  $M_D \sim 20M_{\oplus}$  at the time of the LHB, within the range required for dichotomy creation in the large impactor limit. If the impactors are small and melt pools overlap, the resulting core size does depend on  $r_p$  (see Supplementary Methods S2.1). Outcomes of our numerical core formation model are generally consistent with the large impactor case, although some dependence on  $r_p$  is observed.

Next, we construct a numerical model to simulate impact-induced core formation for a realistic distribution of impactors, impact velocities and angles (see Supplementary Methods S3 and the Methods section). Consistent with our analytical estimates, we find a  $>50\%$  chance that the LHB creates the Ganymede–Callisto dichotomy if  $8.8 \times 10^{22} \text{ g} < M_{LHB}^C < 3.6 \times 10^{23}$  g, corresponding to  $5M_{\oplus} < M_D < 21M_{\oplus}$  (Fig. 2a,b) for a most likely impactor radius ( $r_p$ ) = 30 km. For ( $r_p$ ) = 20 km, there is  $>50\%$  probability of creating the dichotomy for  $10^{23} \text{ g} < M_{LHB}^C < 5 \times 10^{23}$  g, corresponding to  $6M_{\oplus} < M_D < 29M_{\oplus}$ . Broadly similar estimates of  $M_D$  result if the density of the satellites' ice and rock components are changed (see the Methods section and Fig. 2c). For  $M_D = 20M_{\oplus}$  predicted for the time of the LHB (refs 15, 16), there is a  $\sim 70\%$  ( $\sim 95\%$ ) chance of creating the dichotomy for ( $r_p$ ) = 30 km ( $r_p$ ) = 20 km).

We have compared our model results to predictions from a particular outer solar system evolution model for the origin of the LHB (refs 15, 16), but our results are relevant to any scenario that invokes an outer solar system LHB (ref. 14). A key strength of our hypothesis is that creating the dichotomy is relatively insensitive to variations in uncertain parameters. The dichotomy arises primarily because of differences in gravitational focusing by Jupiter, giving a larger total impact energy at Ganymede compared with Callisto.

If the LHB triggers runaway differentiation in Ganymede, melting by tides<sup>18</sup> is not required and a simple story for Ganymede and Callisto's early evolution emerges. Both satellites form undifferentiated<sup>10,11</sup>. Ganymede evolves into its current orbital state through interactions with the circumjovian disk<sup>26</sup> or later



**Figure 2 | Results of Monte Carlo modelling constraining the probability of forming the Ganymede–Callisto dichotomy as a function of LHB mass.**

The vertical line shows  $M_{LHB}^C$  predicted by the Nice model. **a**, Probability of runaway differentiation for Ganymede (red) and Callisto (blue) for our nominal compositional case. **b**, Probability of creating the dichotomy during the LHB. **c**, Probability of creating the dichotomy considering variation in the impactor size distribution (black) and rock density (colours; see the Methods section).

tidal evolution<sup>8,18</sup>. Ganymede differentiates during the LHB; the burst of energy from runaway differentiation could drive melting and provide a natural explanation for the formation of its grooved terrain. Callisto is partially differentiated during the LHB and remains geologically inactive.

Impacts occurring in the 700 Myr before the LHB also drive differentiation. Our calculated limits on impacting mass assume that all of the energy of differentiation is retained. Unlike during the LHB (which lasts only  $\sim 10$ – $100$  Myr, see Supplementary Methods S3.3.4), some fraction of the energy of differentiation may be removed by vigorous convection during the earlier, more prolonged impact period. In the limit that no energy of differentiation is retained, the total mass of objects striking Callisto can be constrained by its moment of inertia. Requiring that Callisto's moment of inertia is greater than the value implied by Galileo data constrains the total mass of hypervelocity impactors onto Callisto over its entire lifetime to be less than  $\sim 10^{24}$  g. In the context of simulations of a disk scattering event<sup>15</sup>, Callisto's interior state limits the initial mass of the planetesimal disk to  $M_{D,initial} < 65$ – $130M_{\oplus}$  (see Supplementary Methods S2.3).

## Methods

Model satellites are represented by a three-dimensional Cartesian sphere that contains an initially uniform volume fraction  $\phi_0$  of rock. Such a state is probable if the satellites formed in a cold, 'gas-starved' disk around Jupiter produced during the final stages of slow gas accretion by the planet<sup>10,11,27</sup>. Latitude, longitude,  $v_i$ ,  $r_p$  and impact angle for each of several thousand impacts are selected using a Monte Carlo approach. Radii are drawn from a population similar to the jovian Trojan asteroids<sup>28</sup>, with a double-power-law size distribution for small ( $dN_{sm}/dr_p \propto r_p^{-3}$ ) and large objects ( $dN_{lg}/dr_p \propto r_p^{-6.5}$ ). For a size distribution of impactors that changes slope at magnitude  $V = 9$ , the average radius of LHB impactors is  $\langle r_p \rangle = 30$  km. The LHB impact energy is delivered on a timescale that is short compared with solid-state heat transport, so these processes do not affect model outcomes and are not included (see Supplementary Methods S3.3.4). The core formation model sums the volume fraction of rock,  $\phi$ , from impact-melted elements to determine the amount of rock added to the core during each impact. That amount of rock is removed from impact-melted elements in the icy mantle. New core elements are added to the core's outer edge in a radially symmetric fashion (see Fig. 1, Supplementary Movies S1, S2, and Supplementary Methods S3.3.3). Values of  $f_m$  (equation (1)) are calculated using  $E_{gr,f} = \int (Gm/r(m))dm$  based on the model satellite's final heterogeneous density structure, and  $E_{gr,i} = -(3/5)GM^2/R$ . One hundred bombardment histories are calculated for each LHB mass to determine the probability of runaway differentiation.

The density and extent of hydration of Callisto's rock is unknown<sup>2,17,20</sup>, so we explore how outcomes vary for three compositional models. In our nominal model, we assume that Callisto is composed of rock (density  $\rho_r = 3.0 \text{ g cm}^{-3}$ , mid-way between densities for CI chondrite and Prinn–Fegley rock, two models for the composition of the satellites' rock<sup>29</sup>) and ice (with density  $\rho_i = 1.4 \text{ g cm}^{-3}$  chosen to give  $m_r = 0.44$  for Callisto and  $m_r = 0.52$  for Ganymede, consistent with detailed interior modelling<sup>20</sup>). This gives a rock volume fraction  $\phi_0 = 0.34$  for Ganymede and  $\phi_0 = 0.27$  for Callisto. We explore two alternative models for rock composition. In our 'high density' model, a plausible upper limit on rock density,  $\rho_r = 3.8 \text{ g cm}^{-3}$ , is paired with  $\rho_i = 1.5 \text{ g cm}^{-3}$  to give a lower limit on Callisto's  $\phi_0 = 0.15$  and Ganymede's  $\phi_0 = 0.19$ . In our 'low density' model, a plausible lower limit on rock density,  $\rho_r = 2.8 \text{ g cm}^{-3}$  (ref. 29), is paired with  $\rho_i = 1.2 \text{ g cm}^{-3}$  to give an upper limit on  $\phi_0 = 0.40$  for Callisto and  $\phi_0 = 0.46$  for Ganymede. We also consider the effects of an impactor size distribution that changes slope at  $V = 10$ , which gives an average impactor size  $\langle r_p \rangle = 20$  km (see Fig. 2c).

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## Author contributions

A.C.B. and R.M.C. formulated the model; A.C.B. carried out the calculations, and A.C.B. and R.M.C. jointly interpreted the results.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on [www.nature.com/naturegeoscience](http://www.nature.com/naturegeoscience). Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions>. Correspondence and requests for materials should be addressed to A.C.B.