LETTERS

# Secondary craters on Europa and implications for cratered surfaces

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**For several decades, most planetary researchers have regarded the impact crater populations on solid-surfaced planets and smaller bodies as predominantly reflecting the direct ('primary') impacts of asteroids and comets[1]. Estimates of the relative and absolute ages of geological units on these objects have been based on this assumption[2]. Here we present an analysis of the comparatively sparse crater population on Jupiter's icy moon Europa and suggest that this assumption is incorrect for small craters. We find that 'secondaries' (craters formed by material ejected from large primary impact craters) comprise about 95 per cent of the small craters (diameters less than 1 km) on Europa. We therefore conclude that large primary impacts into a solid surface (for example, ice or rock) produce far more secondaries than previously believed, implying that the small crater populations on the Moon, Mars and other large bodies must be dominated by secondaries. Moreover, our results indicate that there have been few small comets (less than 100 m diameter) passing through the jovian system in recent times, consistent with dynamical simulations[3–6].**

Surface ages can be derived from the spatial density of craters, but this association presumes that the craters are made by interplanetary impactors, arriving randomly in time and location across the surface. Secondary craters cause confusion because they contaminate the primary cratering record by emplacing large numbers of craters, episodically, in random and non-random locations on the surface. The number and spatial extent of secondary craters generated by a primary impact has been a significant research issue[7–13]. If many or most small craters on a surface are secondaries, but are mistakenly identified as primaries, derived surface ages or characteristics of the impacting population size–frequency distribution (SFD) will be in error. Accurately identifying secondary craters and removing their contribution from the primary crater SFD would significantly improve confidence in calculations of surface ages and impactor fluxes, which are the only chronometers for planetary surfaces for which we do not have physical samples (that is, most Solar System objects). Indeed, our understanding of surface ages on unsampled regions of the Moon and for Mars is based almost entirely on the 'crater chronology' (the correlation between relative surface age and observed crater density). Thus determining the contribution of secondaries is critical.

Identifying secondaries adjacent to their parent primary has been done[14,15] on the basis of unusual morphologies and distinct spatial patterns of proximate secondaries. But the extent of distant, far-field secondaries (those far from their parent primary) has previously been indeterminate because most planetary surfaces are too densely cratered to disentangle the small crater population into primary and secondary. The first high-resolution Galileo spacecraft images of Europa, however, revealed a crater population with densities much lower than those for the Moon or most regions of Mars. Also, these craters were typically not spatially random, but instead appeared in clumps and clusters[16] even at distances far (several hundred kilometres) from the nearest large primary crater. This clustered spatial distribution contrasts with primary impacts, which are spatially random. The low spatial density and unusual non-random spatial distribution of Europa's small craters enabled us to achieve what has been previously difficult, namely unambiguous identification and quantification of the contribution of distant secondary craters to the total crater SFD. This, in turn, allows us to re-examine the overall crater age-dating methodology. We discuss the specifics of the Europa data first.

We measured more than 17,000 craters in 87 low-compression, low-sun, high-resolution Europa images (scales $<60\,\mathrm{m\,pixel^{-1}}$), which cover nine regions totalling 0.2% of Europa's surface (a much larger percentage of Europa has been imaged at lower resolutions), plus 10,000 more secondaries surrounding the large, well-imaged craters Tyre (~44 km diameter) and Pwyll (~25 km diameter). Most of the SFDs for the small, far-field craters have 'steep slopes', which means that they have a differential power-law size index of $b < -4$. (The differential SFD follows the form $\mathrm{d}N = kD^b\mathrm{d}D$, where $\mathrm{d}N$ is the number of craters of diameter $D$ in diameter range $\mathrm{d}D$, and $k$ and $b$ are constants. We use a $\chi^2$ nonlinear fit to determine $k$ and $b$.)

We find that the small craters are spatially clustered. To estimate the random (primary) background population, we developed a novel algorithm[17] that removes the strongly clustered (secondary) craters, simultaneously identifying specific clusters and any spatially random population. The method combines the single-linkage[18] (SLINK) hierarchical clustering algorithm, Monte Carlo methods, and a clustering parameter. We divide the crater population into groups on the basis of their probabilities $P$ of non-randomness, where a cluster with $P > 2\sigma$ indicates that the cluster is non-random with significance greater than two standard deviations ($2\sigma$, or 95%), and thus has only a 5% chance of occurring by random impacts. The algorithm first generates a suite of random populations (mimicking primary cratering) of craters that possess the same spatial density as the data. It then applies SLINK to each population, calculating a clustering parameter during each step of the clustering process. The clustering parameter ($\kappa$) evaluates the 'clusteredness' of a point on the basis of its local spatial density (that is, an object in a cluster has many close neighbours, not just one or two), the global density of the mosaic, and the similarity between the local and global densities. The algorithm then compares the $\kappa$ values of the Europa data with those of the simulations of random impacts. Among nine regions that we studied, the minimum, median and maximum percentage of craters strongly clustered at probabilities of non-randomness $P > 2\sigma$ is 35%, 71% and 80%, respectively. Figure 1 exemplifies our results.

We find that most of the moderately-clustered (at probabilities of non-randomness of $1\sigma < P \leq 2\sigma$, see Fig. 1) and spatially random craters are also secondaries; the actual percentage of true primaries

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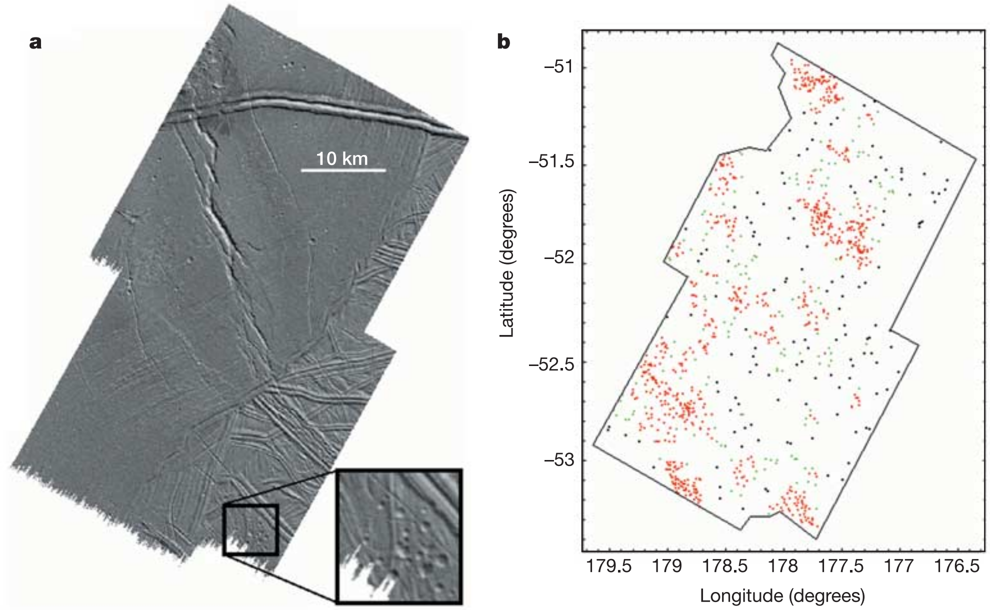


**Figure 1 | A sample region on Europa that demonstrates the extreme 'clusteredness' of Europa's small craters. a**, The ~43 m pixel$^{-1}$ E17LIBLIN01 Galileo mosaic of Europa. North is up, and the Sun is to the upper-right. About 1,000 craters are identified. The inset zooms in on a portion of one cluster. **b**, Plot of crater-centre locations, colour-coded to show the degree of clustering: red points are spatially non-random with probability $P > 2\sigma$ (strongly clustered), green points are spatially non-random with $1\sigma < P \leq 2\sigma$ (moderately clustered), and black points are spatially random. The corresponding percentages are 71%, 15% and 14%, respectively.

may be only a few per cent or less. There are several reasons for this conclusion. First, the craters clustered at lower significances are, in aggregate, statistically still clustered. Second, the SFDs of the spatially random craters do not exhibit a uniform shape (that is, a similar exponent $b$), as would be expected for craters caused by interplanetary impactors. Instead, they vary from region to region, which is not consistent with a single impacting flux. For example, one region's spatially random population has $b = -5.4 \pm 1.0$, while another region's spatially random population has $b = -2.2 \pm 0.7$. Third, evidence for unclustered secondaries comes from some crater populations that are spatially coincident with crater rays. The best example is a region roughly 1,000 km distant from the fresh impact crater Pwyll that contains a bright Pwyll ray (a known ejecta product from primary cratering). The spatial coincidence[19] between the small craters in this region and the Pwyll ray assures us that these are secondaries, yet within the ray the strongly clustered craters are 'only' 60% of the population. Fragments that make distant secondary craters have longer flight times (in this case, tens of minutes), which give the fragments more time to spatially separate.

Therefore, the percentage of spatially random craters in our study regions represent a strong upper limit on the percentage of small craters that are primaries; among the nine regions studied, the median percentage of spatially random craters is 10%. But we can refine this estimate because a certain fraction of the spatially-random craters are in fact secondaries. Our conservative evaluation is that at least 50% of the spatially random craters need to be secondaries to account for the observed variation in SFDs and spatial density (from 0.01 to 0.17 craters km$^{-2}$) between measured regions—that is, at least half must be secondaries to account for a variation in $b$ from $-2.2$ to $-5.4$. We note that all regions (visible in the available high-resolution data) contain multiple crater clusters, and that the spatial density of the random population is directly correlated with the spatial density of the clustered population.

There are (at least) three significant implications of our discovery that the bulk of Europa's small crater population consists of secondary craters. (1) Using the more numerous, and thus statistically more significant, small craters to derive surface ages of small geological units is now suspect for Europa. Far-flung secondaries from a single, distant primary crater can dominate a local crater population, so a high-density crater population does not necessarily reflect a greater integrated exposure time; it could instead result from a single, possibly recent, exposure to a cluster of ejecta from a single impact, in an instant of time. (2) The jovian system's primary impacting population, which is dynamically understood to be mostly comets derived from the Kuiper belt/scattered disk[3–6,20,21], is evidently deficient in objects smaller than 100 m diameter (that is, the size distribution is shallower than expected from extrapolations of comet SFDs). Fewer small primary impacts indicate fewer cometary impactors. This may be the first observational constraint for the Kuiper belt at those diameters; perhaps small comets are rarely made, or perhaps some process depletes them before reaching the jovian system. (3) On Europa, the production of ejecta that make secondary craters is unexpectedly efficient. ('Secondary cratering efficiency' refers to the fraction of ejected material that generates secondaries for a given primary impact energy.) There are very few large primary craters on Europa (less than 40 with diameter >10 km are currently known globally[22] as seen in the lower resolution images), yet our identification of tens of thousands of secondaries in only ~0.2% of Europa's surface imaged at high resolution implies that the few large primaries made at least 10 million secondaries larger than 100 m. The steep size distributions suggest yet more numerous craters at smaller diameters.

At least for Europa, our work unequivocally resolves the relative abundance of primary and secondary craters. We now return to questions of crater distributions in the Solar System in general, and the implications for impactor size distributions and age dating. Laboratory-scale experiments demonstrate that impacts into ice and rock targets yield ejecta fragments with steep SFDs, with ice-impacts generating ejecta more efficiently[23–25]. We note that the laboratory ice-impact experiments took place at temperatures warmer (255 K) than Europa's surface (~110 K), and at lower impact velocities (tens of m s$^{-1}$ to 1 km s$^{-1}$, compared with the ~20 km s$^{-1}$ average comet impact velocity[3]). The Moon and Mars both possess a steep branch in their crater SFD at sizes below a few kilometres[26,27].

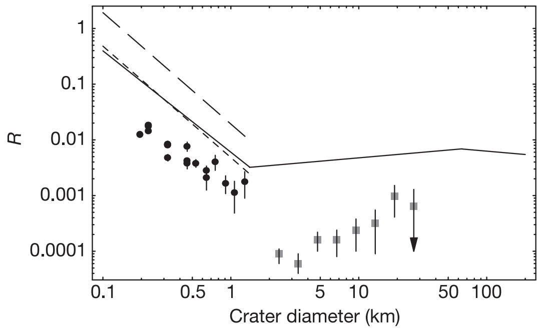


**Figure 2 | A comparison of europan and lunar crater size–frequency distributions, demonstrating that lunar secondaries could account for most of the observed small lunar craters.** The size–frequency distributions (SFDs) are given in *R* format[1]; *R* is the differential distribution divided by $D^{-3}$, where *D* is the crater diameter. The grey squares are the measured[22] europan primary crater population for diameters greater than 2 km (diameters least affected by secondaries). The filled circles represent some of our measurements from high-resolution images of Europa, including data from the crater population that appears in Fig. 1 (the error bars for both populations are the standard $\sqrt{N}$, representing one standard deviation for counting statistics). The solid black line is the average lunar maria crater SFD (taken from ref. 26). The long-dashed line is the calculated secondary crater population generated by the lunar post-mare primary crater population with diameters10 km $< D <$ 64 km, assuming the same secondary cratering efficiency we measured on Europa. This is clearly too high, generating a small crater population that not only meets but exceeds the observed lunar population. The short-dashed line is the calculated secondary population with the europan efficiency decreased by a factor of about four (consistent with laboratory-scale impact experiments[24]).

We integrated our derived secondary cratering efficiency over the visible large (10 km $< D <$ 64 km), post-mare, primary impact craters on the Moon. We calculate that the steep branch of the lunar crater SFD at small diameters could be fully accounted for by secondary cratering, even if the Moon's secondary cratering efficiency is less than Europa's—that is, even if rock targets generate ejecta less efficiently than ice targets (Fig. 2).

Our work raises doubts regarding methods that use the lunar small-crater distribution to calibrate other inner Solar System surface ages (for example, Mars[28,29]). If, as on Europa, lunar and martian secondaries are 95% of the small crater (less than a few kilometres) population, the error bars (and thus derived surface ages) on any residual primary crater population become large (uncertainties are 20 times the measured density value). This uncertainty applies to both the measured population on a martian surface unit and the lunar SFD that supposedly represents absolute age. We emphasize that traditional age-dating analyses still derive robust ages when using large craters (greater than a few kilometres diameter), which are less likely to be secondaries. However, the technique becomes increasingly unreliable when applied to dating tiny geographical units using small craters, which may be mostly secondaries.

Our discovery that even spatially random crater populations contain numerous secondaries confounds the general rule-of-thumb that one can 'avoid' secondaries by excluding obviously clustered craters from measurements and analysis. Rather, secondaries are intimately mixed, both non-randomly and randomly, into crater distributions on planetary surfaces. The ability of a few large impacts to distribute a globally extensive secondary crater population demonstrates that one cannot use distance from a primary to minimize contributions from secondaries.

Finally, any attempt to derive surface ages or traits of impacting populations (that is, of near-Earth objects at diameters below what is robustly sampled in telescopic surveys) based on lunar or martian[28,29] small-crater statistics may suffer a significant and perhaps uncorrectable bias due to the contribution from secondaries. Indeed, other research[30] finds that a single 10 km primary contributed $\sim 10^7$ secondary craters from 10 m to 100 m diameter to the martian crater distribution.

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