Complex Crater Formation by Oblique Impacts on the Earth and Moon

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Abstract Almost all meteorite impacts occur at oblique incidence angles, but the effect of impact angle on crater size is not well understood, especially for large craters. To improve oblique impact crater scaling, we present a suite of simulations of complex crater formation on Earth and the Moon over a range of impact angles, velocities and impactor sizes. We show that crater diameter is larger than predicted by existing scaling relationships for oblique impacts; there is little dependence on obliquity for impacts steeper than 45° from the horizontal. Crater depth, volume and diameter depend on impact angle in different ways—relatively shallower craters are formed by more oblique impacts. Our simulation results have implications for how crater populations are determined from impactor populations and vice-versa. They suggest that existing approaches to account for impact obliquity may underestimate the number of complex craters larger than a given size by as much as one-third.

Plain Language Summary The relationship between impact crater size and impactor properties, such as size and speed, is key to comparing impactor and crater populations on different planets and dating planetary surfaces. Most of our understanding of this relationship, however, comes from numerical simulations of vertical-incidence impacts, and laboratory impact experiments at relatively low speed, which are comparatively rare in nature. Here we present results of numerical simulations of large crater formation on Earth and the Moon, for a range of oblique impact angles and speeds more typical of planetary scale impacts. We find that while crater size decreases as the impact angle becomes shallower, crater diameter, depth and volume are all affected by impact angle in different ways. Most importantly, we find that crater diameter depends less on impact angle than previously thought, especially for steeply inclined impacts. This implies that typical asteroid impacts on planetary surfaces form larger craters, and large craters are formed more frequently, than is currently assumed.

1. Introduction

Impact craters are ubiquitous features on all solid solar system bodies. The final morphology of a crater depends on its size: small craters have simple, bowl-shaped cavities, while larger craters are subject to more profound late-stage, gravity-driven collapse, leading to complex morphologies including flat crater floors, central peaks or rings of peaks, and a terrace zone near the crater rim (e.g., French, 1998; Grieve et al., 1981; Melosh, 1989). Due to the large length scales necessary to produce these characteristic features of complex craters, they are not reproducible in laboratory experiments. Crater size depends principally on impactor properties, for example, the mass, velocity and impact angle (Holsapple & Housen, 1986; Schmidt & Housen, 1987). Understanding this link between impactor properties and crater size is useful, as it allows estimates of the size and speed of the impactor to be inferred from an observed crater (e.g., Collins et al., 2020; Ivanov, 2005; Ivanov & Artemieva, 2002; Johnson et al., 2016). It can also be used to predict a population of craters on the surface of a planet or asteroid of a given age (e.g., Bottke & Norman, 2017; Marchi et al., 2012, 2016).

Scaling laws have been developed previously to link impactor and target properties to crater size (e.g., Holsapple, 1993; Holsapple & Housen, 1986; Schmidt & Housen, 1987). These have typically relied on vertical-incidence laboratory experiments and numerical models. However, the majority of impacts occur at an oblique incidence angle: 45° is the most probable impact angle, and ~90% of all impacts occur at angles <70° from the target plane (Shoemaker, 1962). Previous laboratory experiments (Burchell & Mackay, 1998; Gault & Wedekind, 1978) and numerical models (Davison et al., 2011; Elbeshausen et al., 2009) have investigated the effects of impact angle on crater size; however, these studies have tended to use a low impact velocity...
(<7 km s\(^{-1}\)), and to simulate small or simple craters where growth is dominated by target strength and/or exhibit little or no late-stage, gravity-driven modification of the crater rim or floor. Thus, doubt remains over how to include impact angle in crater scaling, especially for larger, complex craters where the crater undergoes substantial collapse (Johnson et al., 2016). In low-velocity impacts, crater dimensions decrease as the impact becomes more oblique (i.e., as impact angle to the horizontal decreases) if all other impact parameters are held constant (Burchell & Mackay, 1998; Gault & Wedekind, 1978). This suggests that as impact trajectory becomes shallower, the coupling of impactor momentum and energy with the target becomes less efficient. A widely adopted approach to describe this reduction in coupling efficiency is to assume that only the vertical component of the impactor momentum (and energy) contributes to crater growth and the horizontal component makes no contribution (Chapman & McKinnon, 1986; Davison et al., 2011; Elbeshausen et al., 2009). However, Ivanov and Artemieva (2002) noted that for higher-velocity (20 km s\(^{-1}\)) impact simulations, the difference in crater size between the vertical and oblique incidence impacts was less pronounced. They hypothesized that, above a critical angle, a different coupling regime may exist at high impact speeds, in which the coupling of momentum and energy is equally efficient, regardless of impact angle.

To explore cratering efficiency in large-scale, high-speed oblique impacts, we simulate complex crater formation using the iSALE3D shock physics code. We extend previous work to higher impacts speeds (up to 30 km s\(^{-1}\)), to probe potentially different regimes of cratering (Ivanov & Artemieva, 2002), and to larger scales on Earth and the Moon (final crater diameters up to ~200 km), where the excavated transient crater undergoes major gravity-driven collapse of the crater rim and uplift of the crater floor to form a complex crater. We show that both the transient and final crater depth and diameter depend on impact angle in different ways. While crater depth depends only on the vertical component of the impactor momentum (and energy), crater diameter (and volume) depend(s) on both vertical and horizontal components. Using these results, we quantify the effect that impact obliquity has on crater populations.

2. Methods

The iSALE3D shock physics code (Collins, Elbeshausen, et al., 2016; Elbeshausen et al., 2009; Elbeshausen & Wünnemann, 2011) was used to simulate oblique incidence complex cratering events. The code uses a solver as described in Hirt et al. (1974) and Amsden and Ruppel (1981). iSALE3D has previously been used to investigate the effects of impact angle on crater formation: Elbeshausen et al. (2009) simulated low-velocity (7 km s\(^{-1}\)) impacts into cohesionless materials, and found an angle dependence of crater size consistent with experiments in granular materials (e.g., Gault & Wedekind, 1978); Davison et al. (2011) simulated impacts into strong metal targets that very closely replicated experimental impacts (Burchell & Mackay, 1998) including key dependencies between crater dimensions and impact angle. Here we extend these investigations to the gravity-dominated regime of complex cratering.

The target was composed of a 33 km thick granitic crust overlying a dunite mantle; a similar model set up to recent simulations of the Chicxulub impact (Collins et al., 2020). Both materials used an analytical equation of state (ANEOS)-derived tabular equation of state (Benz et al., 1989; Pierazzo et al., 1997). The impacting asteroid was modeled as a sphere, and also used the ANEOS for granite. This material was chosen to match the crust, because of a current limitation of iSALE3D which does not allow more than one boundary between materials in a grid cell.

iSALE3D includes a strength model appropriate for geologic materials (Collins et al., 2004; Ivanov et al., 1997; Melosh et al., 1992). Strength parameters for the crust and mantle were chosen based on previous simulations of the Chicxulub impact, using iSALE3D (Collins et al., 2020), iSALE2D (Christeson et al., 2009; Collins et al., 2008; Morgan et al., 2016) and Simplified Arbitrary Lagrangian Eulerian-B (Ivanov & Artemieva, 2002; Stöffler et al., 2004), and can be found in Table S1 in Supporting Information S1. The acoustic fluidization “block model” (Melosh & Ivanov, 1999; Wünnemann & Ivanov, 2003) was used to allow late-stage collapse of the transient crater, with parameters also based on Collins et al. (2020).

To explore the effect of surface gravity, two sets of simulations were performed with gravity appropriate for the Earth or Moon. Impact velocity (\(u\)) was varied between 10 and 30 km s\(^{-1}\) on Earth, and 5–30 km s\(^{-1}\) on the Moon. Impactors had diameters (\(L\)) of 6.22, 8.96, and 14 km. We used a range of impact angles (\(\theta\), defined as the angle between the impactor trajectory and the horizontal target surface) between 30° and 90° (vertical incidence).
All models employed a spatial resolution of 14 cppr (cells per projectile radius), which was previously found to reproduce the Chicxulub crater on Earth well (Collins et al., 2020). Technical details of the model setup can be found in Supporting Information S1.

Formation of complex craters involves two major phases of crater growth. During initial excavation, a deep, bowl-shaped crater grows by outward displacement and ejection. The form of the crater at the end of excavation is termed the transient crater. Subsequently, the steep walls of the crater rim collapse inwards while the floor of the crater is uplifted by gravitational instability. During this modification stage the crater depth and volume decrease, while diameter increases. Here we follow the common convention to measure transient crater dimensions at the time of maximum crater volume (Elbeshausen et al., 2009; Turtle et al., 2005). We note that the time of maximum crater volume and maximum depth are typically different; the transient crater depth reported here is not the maximal crater depth. Transient crater diameter is measured at the pre-impact surface; crater depth is measured from the pre-impact surface; and transient crater volume is the volume of the crater excavated below the pre-impact surface. Since the along-range and cross-range diameters can sometimes be quite different in oblique impacts, here we use the diameter of a circle with an area equivalent to the area of the crater planform at the pre-impact elevation to allow direct comparisons between models (termed the “equivalent diameter”, $D_{tr,eq}$).

Final crater measurements were taken after all material in the simulation had ceased moving (with the exception of some melt). To find the final rim-to-rim diameter ($D_{rr}$), radial surface profiles were drawn at azimuths with a spacing of $2^{\circ}$, from the center of the crater measured at the pre-impact surface. For each profile, the maximum height was found; the outline of the crater rim was found by connecting these peaks. The reported rim-to-rim diameter is the radius of a circle with an area equivalent to the area of the crater rim outline.

3. Results

Transient craters ranged in diameter from 38 to 98 km on Earth and 54–150 km on the Moon. Final craters ranged in diameter from 72 to 200 km on Earth and 80–230 km on the Moon (see Tables S2 and S3 in Supporting Information S1). The craters exhibit flat crater floors and a broad central structural uplift that extends to the base of the crust (Figure 1). A detailed analysis of final crater morphologies is possible due to the spatial resolution of our simulations; however, as in previous simulations of complex crater formation (Collins et al., 2020), in all cases final crater formation involves the formation of an over-heightened central uplift and its subsequent collapse, resulting in a central peak or peak ring final crater morphology. The initial geometry of a typical simulation is shown in Figure 1a, for $L = 14$ km, $v = 20$ km s$^{-1}$ and $\theta = 45^{\circ}$ on Earth. The crater reaches its maximum depth at $t = 20$ s, (Figure 1b), and its maximum volume at $t = 65$ s (Figure 1c). Note that the start of the collapse process is not the same at all azimuths in oblique impacts—in this simulation, collapse on the uprange side begins 5–10 s before the time of maximum volume, and downrange collapse starts 10–15 s after the time of maximum volume. The amount of enlargement in the uprange direction (i.e., the distance the crater wall moved outwards during collapse) is approximately 20% greater than in the downrange direction. By 500 s, modification has ended and the crater has reached its final morphology (Figure 1d).

3.1. Dependence of Crater Morphology on Impact Angle

Surface profiles of the transient and final craters (along the symmetry plane) reveal several morphological differences that are exhibited as the impact angle changes from vertical ($90^{\circ}$) to oblique ($30^{\circ}$) incidence (Figures 1e and 1f). Both transient and final craters are centered further downrange from the impact point for more oblique impacts. The transient crater depth/diameter ratio decreases with increasing obliquity for all suites of simulations, consistent with impact experiments in quartz sand (Gault & Wedekind, 1978).

The slope of the downrange wall of the transient crater is less steep in more oblique impacts (Figure 1e). This has previously been observed in modeling (e.g., Davison et al., 2011; Elbeshausen et al., 2009) and experimental studies (e.g., Gault & Wedekind, 1978). In most simulations, the steeper uprange wall leads to more enlargement of the crater on that side compared to the enlargement on the downrange side. The collapse of the uprange wall also starts earlier than the downrange collapse. In the uprange direction, the rim height of the final crater decreases in more oblique impacts (Figure 1f); for the $30^{\circ}$ impact, there is almost no detectable rim on the uprange side of the crater.
The floor of the final crater also exhibits asymmetries for impact angles <60°. The crater floor on the downrange side of the crater has a higher elevation compared to the uprange side (Figure 1f), due to melt being distributed on the downrange side of the crater. While the crater walls cease moving by the simulation end time, melt can still be mobile. Thus, the trough on the uprange side of the crater at the end of our simulations will likely be infilled later by down-slope migration of melt.

3.2. Dependence of Crater Dimensions on Impact Angle

Figure 2 shows how different crater dimensions are affected by impact angle. Crater dimensions are normalized by the dimensions of the crater formed by a vertical impact of the same impactor size and speed and the same gravity. For impacts steeper than 45°, transient crater diameter shows very little dependence on impact angle (Figure 2a). All transient diameters for angles 45° and steeper are within ~5% of the vertical incidence simulation.

Transient crater depth (Figure 2b) and volume (Figure 2c) both show a greater dependence on impact angle than crater diameter; all craters formed at angles shallower than 75° are smaller than the equivalent crater formed at vertical incidence. There is also some co-dependence of crater depth on impact velocity: for low velocity impacts (5 km s\(^{-1}\) on the Moon, and 10–15 km s\(^{-1}\) on Earth), the normalized depths of craters formed at shallow impact angles are smaller than the equivalent impacts at higher velocity. A larger effect of impact angle on crater depth at lower impact speeds is consistent with the simulation results of Ivanov and Artemieva (2002).
of impact angle on crater diameter, depth and volume does not appear to be affected by the impactor size (in the range $L = 6.22–14$ km) or target planet (gravity in the range $1.62–9.81 \text{ ms}^{-2}$).

Final crater diameter (Figure 2d) shows a greater dependence on impact angle than transient crater diameter. This demonstrates that the expansion of the crater rim during the modification stage depends on the impact angle: while transient crater diameter does not depend on impact angle above 45°, the final crater diameter does. This is because the enlargement of the crater rim during modification depends on the geometry of the transient crater. Deeper transient craters exhibit more enlargement, and the transient depth depends more on impact angle than does the diameter.

4. Oblique Impact Crater Scaling

The relationship between crater size and impactor and target parameters is complex (e.g., Holsapple, 1993; Melosh, 1989; Schmidt & Housen, 1987). Hence, empirical scaling relationships derived from laboratory experiments and numerical simulations are typically used (known as $\pi$-group scaling; Holsapple, 1993), in which dimensionless measures of impactor size ($\pi_2 = 1.61 gL/u^2$, where $g$ is the surface gravity) and crater size ($\pi_D = D_0 \alpha_R (\rho/m)^{1/3}$, where $\rho$ is the target density and $m$ is the impactor mass) are related to each other with a simple power-law:

$$\pi_D = C_D \pi_2^\beta,$$

where $C_D$ and $\beta$ are material-specific constants. Commonly adopted values for dense rock are $C_D = 1.6, \beta = 0.22$ (Melosh, 1989; Schmidt & Housen, 1987).

The influence of impact angle on $\pi$-group scaling is not well understood. A common method to quantify how impact angle influences crater size is to examine how a given crater dimension (e.g., diameter, $D$, depth, $d$, or volume, $V$) scales with impact angle, when normalized by the same dimension in a vertical-incidence impact event; for example, $D_V/D_L = \sin^{\alpha_V} \theta$, or $V_2/V_1 = \sin^{\beta} \theta$, where $\alpha_V$ and $\alpha_R$ are constants to be determined. It is often assumed that $\alpha_V = 3\alpha_R$ which would imply that the crater depth-to-diameter ratio is independent of impact angle. Pioneering oblique impact experiments showed that $\alpha_V = 1$ for gravity-dominated impacts in cohesionless sand and $\alpha_V \approx 2$ for strength-dominated impacts in granite (Gault & Wedekind, 1978).

Based on these trends, Chapman and McKinnon (1986) proposed that $\pi$-group scaling of crater dimensions could be extended to include angle dependence by replacing the impact speed $u$ with the vertical component of impact velocity $u \sin \theta$ in the definition of $\pi_2$.

This simple and elegant approach, which assumes that the horizontal component of the impactor momentum (and energy) makes no contribution to crater size, gives $\alpha_V = 1$ for cohesionless sand ($\beta = 0.16–0.17$), and $\alpha_V = 1.7$ for dense rock or metal in the strength regime (Chapman & McKinnon, 1986). This form of scaling has been widely adopted (e.g., Ivanov, 2001; Ivanov et al., 2001) because it is broadly consistent with results of low-velocity impact experiments (Burchell & Mackay, 1998; Gault & Wedekind, 1978) and numerical simulations (Davison et al., 2011; Elbeshesnien et al., 2009). Using this scaling and adopting a nominal value of $\beta = 0.22$ in Equation 1 for a dense rock target (Schmidt & Housen, 1987) implies $\alpha_V = 1.32 (\alpha_R = 0.44)$.

On the other hand, simulations of low-velocity, gravity-dominated oblique impacts in dense, cohesionless targets offer more equivocal support for scaling by the vertical component of the impact velocity (Elbeshesnien et al., 2009). Results from these simulations instead suggest $\alpha_V \approx 1 (\alpha_R \approx 0.33)$ for a wide range of target friction coefficients. As a result, an alternative form of angle dependence in popular use is to simply scale the crater volume by $\sin \theta$ and diameter (or depth) by $\sin^{0.33} \theta$ (e.g., Collins et al., 2005; Johnson et al., 2016).
Our simulation results demonstrate that dependence of crater dimensions on impact angle is more complicated than either of these scaling approaches predict (Figures 2a–2c). Transient crater diameters formed at oblique incidence in this study are larger than those predicted using $\alpha_D = 0.33$ (dashed line) or $\alpha_D = 0.44$ (dotted line) (Figure 2a). Transient crater volumes are also typically larger than predicted by $\alpha_D = 1$ or $\alpha_D = 1.32$ for $\theta \leq 60^\circ$ (Figure 2c).

One suite of simulations (with $u = 5$ km s$^{-1}$ on the Moon) lies between those two scalings, but almost all other simulated craters have volumes larger than predicted by $\alpha_D = 1$. On the other hand, transient crater depth is fit reasonably well by $\alpha_D = 0.33$ or $\alpha_D = 0.44$ for most simulations, particularly if the lowest impact speed simulations are excluded (Figure 2b).

Using $\alpha_D = 0.33$, and assuming that the process of crater collapse is independent of impact angle, Johnson et al. (2016) proposed that for complex craters final crater diameter should scale with $\alpha_R = 0.38$. While agreement with this scaling is closer than for transient crater diameter, our oblique impact simulation results of final rim-to-rim crater diameters are also larger than predicted by Johnson et al. (2016).

Our results demonstrate that different crater dimensions are affected by impact angle in different ways. A single scaling relationship is unable to describe the angle dependence of depth, diameter and volume. In particular, while crater depth appears to be independent of the horizontal component of the impact velocity, both crater diameter and volume depend to some extent on the impactor's horizontal motion.

Ivanov and Artemieva (2002) hypothesized that the influence of impact angle on the transient crater size depends on impact velocity. They proposed the existence of two regimes: in low velocity oblique impacts, only the vertical component of the velocity affects crater size (i.e., $\alpha_D = 0.44$) while in high velocity oblique impacts impact angle has no influence on crater size (i.e., $\alpha_D = 0$) above a certain threshold angle. According to this idea, the threshold impact angle and speed between these regimes is defined by the vertical velocity necessary for the impactor to penetrate below the pre-impact surface during contact and compression; that is, before the impactor is unloaded from high pressure. High-speed impactors that quickly penetrate below the target surface are therefore able to couple all their momentum and energy with the target. We find partial support for this concept in our simulation results. Transient crater diameter appears to exhibit two regimes of angle dependence: at steep angles (>45°) there is almost no dependence of diameter on impact angle ($\alpha_D = 0$), whereas at shallow angles diameter drops abruptly. However, the transition angle between these regimes does not appear to depend on impact speed. On the other hand, the effect of impact angle on transient crater depth is diminished as impact speed increases, but there is no clear evidence of a distinct high-speed, angle-independent regime for depth.

To account for impact angle in planetary crater scaling relationships, therefore, we propose that separate, empirical relationships based on our simulations should be used. For transient crater diameter, a single fit to our simulation data gives an exponent of $\alpha_D = 0.18$ (Figure 2a). For final crater diameter an angle exponent of $\alpha_D = 0.23$ is suggested by our results (Figure 2d), although further exploration of acoustic fluidization parameters would be prudent to confirm this trend. Additional modeling should also examine the effects of unexplored impactor and target parameters (e.g., equations of state, porosity, strength and crustal thickness). We note that as the surface gravities of Mercury and Mars are intermediate between the values for Earth and the Moon we expect the scaling relationships presented here to also be applicable to those planets, although further modeling should also confirm this.

The observation that transient crater diameter is not affected significantly by impact angle for angles steeper than 45° is reinforced by plotting our results in $\pi_\theta - \pi_\beta$ space (Equation 1; Figure 3a). Fitting constants $C_\pi$ and $\beta$ in Equation 1 for all impacts with $\theta \geq 45^\circ$ yields $C_\pi = 1.57$ and $\beta = 0.20$ ($R^2 = 0.99$), similar to values often adopted for dense rock ($C_\pi = 1.6$, $\beta = 0.22$; Melosh, 1989; Schmidt & Housen, 1987). Our results also provide insight
into the enlargement of crater diameter caused by late-stage gravitational collapse of complex craters (Figure 3b). Final rim-to-rim crater diameter after collapse, $D_{f,rr}$, is well described by:

$$D_{f,rr} = AD_{SC}^{-\eta}D_{tr}^{1+\eta}$$

(2)

where $D_{tr}$ is the transient crater diameter at the pre-impact level, $D_{SC}$ is the final rim-to-rim diameter at the simple-to-complex transition, and $A$ and $\eta$ are constants (e.g., Johnson et al., 2016). Since the data collapse onto a single trend (Equation 2) the effects of impact angle on transient–final crater enlargement are minor compared to the influence of transient crater size.

By assuming a value of $D_{SC}$ for the Earth and Moon, a least-squares fit can be used to estimate $A$ and $\eta$ (Figure 3b). On Earth, Brent crater ($D_{tr} = 3.8$ km; Dence et al., 1977) is one of the largest observed simple craters, which we use here to define the simple-to-complex transition of $D_{SC} = 4$ km. Fitting Equation 2, we find $A = 1.59$, $\eta = 0.07$. For the Moon, assuming $D_{SC} = 20$ km (Pike, 1980), we find $A = 1.48$, $\eta = 0.05$. These values of $\eta$ are close to the value of 0.08 proposed by Holsapple (1993), but lower than that proposed by Johnson et al. (2016) based on vertical impact simulations alone.

For simple craters, the ratio of final rim-to-rim diameter to transient crater diameter is a constant $\gamma = D_{f,rr} / D_{tr}$. To give a consistent relationship at the simple-to-complex transition, $A$ and $\eta$ are related to $\gamma$ by $\gamma = A^{\frac{1}{1+\eta}}$. Extrapolation of our simulation results to the simple-to-complex transition therefore implies simple crater enlargement ratios of $\gamma = 1.54$ (Earth) and $\gamma = 1.45$ (Moon). While this range of $\gamma$ is larger than often used values of 1.25–1.3 (Collins et al., 2005; Grieve & Garvin, 1984; Holsapple, 1993), it is consistent with recent simulations of both Barringer crater (Collins, Mason, & Kring, 2016) and Brent crater (Collins, 2014) that well reproduce geological and geophysical observations.

**5. Implications for Crater Populations on Planetary Surfaces**

Our results have obvious implications for estimating impactor size for a specific event, such as the Chicxulub impact. The size of the impactor that triggered the K-Pg extinction has been controversial owing to conflicting interpretations of geophysical and geochemical evidence (Morgan, 2008; Paquay et al., 2008). Collins et al. (2020) showed that an impact angle of 45–60° is most consistent with geophysical observations of the Chicxulub crater. Using the Johnson et al. (2016) scaling relationship ($\alpha_p = 0.38$) suggests a 14 km diameter impactor is required to produce the 160 km diameter Chicxulub crater, assuming a 20 km s$^{-1}$ impact at 45° and that the impactor and target densities are similar. If, instead, we remove the angle dependence, as suggested by the transient crater scaling for angles $>45°$ (Figure 2a), the required impactor size reduces to 12 km (a 14% reduction in diameter and a 36% reduction in mass).

Our revisions to oblique crater scaling also have implications for interpreting crater populations. Gault and Wedekind (1978) used the results of their experiments to show that the effects of obliquity would reduce the apparent population of craters on a planetary surface larger than a given diameter by a factor of $\sim$2 when compared with a population formed by vertical impacts. In their derivation (their Equations 1–8), they used kinetic energy scaling to relate impactor mass to crater size. Following a similar approach (see Supporting Information S1), the total number of craters larger than a given diameter formed at all trajectories $N_i$ can be expressed in terms of the number of craters formed if obliquity is neglected, $N_i$:

$$N_i = \left(\frac{2(1 - \beta)}{2(1 - \beta) - 3\alpha_p \psi}\right)N_{i,\perp}$$

(3)

where $\beta$ is the exponent in Equation 1, $\alpha_p$ is the exponent that describes how much impact angle affects crater diameter, and $\psi$ is the exponent of the mass–number distribution of impactors ($N_i \propto m_i^\psi$). Since $\psi$ is a negative number, the effect of obliquity reduces the apparent number of craters for any $\alpha_p > 0$.

Using $\beta = 0.22$ (Schmidt & Housen, 1987) we can then determine how different values of $\alpha_p$ affect the apparent number of craters. Here we use values of $\psi = -0.78$ (for 10$^{10}$ kg $< m_i < 10^{16}$ kg; Harris & D’Abramo, 2015) or $-0.93$ (for $m_i < 10^{10}$ kg; Bland & Artemieva, 2006). Using the fit to final rim-to-rim craters ($\alpha_p = 0.23$,
Figure 2d), we find that $N_d/N_{\perp} = 0.71$–0.74, and using the fit to transient crater diameters ($\alpha_d = 0.18$, Figure 2a) yields $N_d/N_{\perp} = 0.76$–0.79.

These estimates of $N_d/N_{\perp}$ are substantially larger than 0.5 (Gault & Wedekind, 1978)—our results therefore suggest that impact obliquity has less of an effect on crater populations than previously proposed. Rather than reducing the apparent population by a factor of 2, obliquity reduces the population by $\sim 20$%–30%. Conversely, the use of previously proposed crater size scaling relationships that account for impact angle (e.g., Ivanov, 2001; Ivanov et al., 2001; Johnson et al., 2016) to convert an impactor population into a crater population likely underestimates the crater population size by $\sim 20$%–40%.

The effect of impact angle on complex crater formation in the size range $\sim 70$–230 km is less pronounced than previously thought, especially for hypervelocity (>15 km s$^{-1}$) impacts. Thus, the often-used simplification of vertical incidence in impact modeling is warranted, as a first approximation, for analysis of crater size in most impact scenarios on large planetary bodies. However, impact angle does influence crater size at low impact speeds and important asymmetries exist in the formation and final crater morphology of complex craters, particularly at angles shallower than 45°. Future 3D oblique impact simulations will extend our understanding of the effect of impact angle on crater size and other structural dimensions to shallower angles, both smaller and larger impacts, as well as different planetary bodies (e.g., icy satellites).

Data Availability Statement

At present, the iSALE code is not fully open source. It is distributed via a private GitHub repository on a case-by-case basis to academic users in the impact community, strictly for non-commercial use. Scientists interested in using or developing iSALE should see https://isale-code.github.io for a description of application requirements. Simulation input files, post-processing scripts and reduced output data files are available on Zenodo (Davison & Collins, 2022, https://doi.org/10.5281/zenodo.7041587).

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