Experimental Simulations of Hypervelocity Impact Penetration of Asteroids Into the Terrestrial Ocean and Benthic Cratering

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Abstract  Seafloor cratering is an important process that records the impact history of the Earth, affects projectile survivability, and determines the mass of ejecta from benthic rock that is transported to the atmosphere. We report experimental hypervelocity impacts of chondrite and other projectiles (olivine, stainless-steel, polycarbonate) on a water-covered iron target to derive a scaling relationship for benthic cratering. In situ observations of 5-km/s impacts quantify the deceleration of projectiles in the water column by shock-induced deformation and fragmentation. The minimum water depths at which multiple craters appeared on the benthic target were two and four times the projectile diameter for chondrite and stainless steel, respectively. Based on the observed deceleration of projectiles in water, the cratering efficiency of a benthic target for a given impact velocity is predicted to follow an exponential decay law in terms of water depth normalized by projectile diameter \( V(H/d) \), given by \( \pi \propto \exp(-V(H/d)/\kappa) \), where \( \kappa \) is a scaling coefficient. The volume of the largest crater in the experiments and that derived from the scaling relation, mass ratios of the largest projectile fragment to original projectile in the 5-km/s impact were calculated to be 0.1–0.3 (\( V/H = 2–6 \)) and 1.0 ± 0.3 (\( V/H = 5.5 \)) for chondrite and stainless steel, respectively. Using the scaling relationship, the volume of the transient crater on oceanic crust by an asteroid impact is estimated to be smaller than previously predicted by hydrocode simulation when the asteroid fragmentation in the water column controls seafloor cratering.

Plain Language Summary  The hypervelocity (measured in km/s) impact of extraterrestrial bodies in the marine environment is more common than on land because ~70% of the Earth’s surface is covered by oceans. Seafloor cratering is important for recording Earth’s impact history, driving environmental, biotic, and climatic perturbations by ejecting crustal materials into the atmosphere (e.g., the K-T boundary event); impactors can also affect the fate of extraterrestrial organic matter and may have been key components of primitive life on early Earth (the so-called panspermia hypothesis). Herein, we simulated the oceanic hypervelocity impacts of asteroids in a laboratory to derive a scaling relationship for benthic cratering. Our results suggest that deformation and fragmentation of projectiles occurs during the impact penetration of water at an initial impact velocity of 5 km/s, thereby controlling the water depth conditions that enable benthic cratering. The experimentally derived scaling relationship of benthic cratering permits the estimation of transient crater volume of oceanic crust in a given water depth by a chondrite impact.

1. Introduction

Hypervelocity (measured in km/s) impact of extraterrestrial bodies in the marine environment is more common than on land. Owing to the progressive growth of continents (e.g., Komiy et al., 2011), it is likely that ocean have covered ≥ 70% of the Earth’s surface throughout geological time. Thus, over 4 billion
years, at least twice as many impacts must have occurred in the marine environment than on land (Komiya et al., 2015; Wilde et al., 2001). However, only 27 of approximately 170 known or suspected impact structures on Earth are thought to have formed in a marine environment (Dypvik & Jansa, 2003).

The relatively small number of impact structures known to have formed on the seafloor is insufficient to reconstruct the entire processes of oceanic impact, although they are important for the reconstruction of Earth’s impact history, to estimate the survivability of extraterrestrial organics in impactors, and to quantify impact-induced geohazards (e.g., tsunami hazards, biotic, and climatic perturbations during the Cretaceous/Tertiary boundary period). Hydrocode simulations and laboratory experiments have advanced our understanding of the individual processes of oceanic impacts (reviewed by Wünnemann et al., 2010), including projectile deceleration in the water column (simulations: O’Keefe & Ahrens 1982; Wünnemann & Lange, 2002), seafloor cratering (experiments: Baldwin et al., 2007; Gault & Sonett, 1982; Milner et al., 2008; simulations: Davison & Collins, 2007; Shuvalov, 2002), projectile fragmentation (experiments: Wickham-Eade et al., 2018), projectile survivability (simulations: Pierazzo & Chyba, 1999; Potter & Collins, 2013; experiments: Bowden et al., 2008; Burchell et al., 2014; Milner et al., 2008; Parnell et al., 2010), formation and atmospheric entry of ejecta (simulations: O’Keefe & Ahrens, 1982), impact-induced chemistry (experiments: Furukawa et al., 2009, 2015; Kurosawa et al., 2013; Sugita & Schultz, 2003a, 2003b), and the generation and propagation of tsunami waves (experiments: Gault & Sonett, 1982; simulations: Crawford & Mader, 1998; Shuvalov & Trubestkaya, 2002; Weiss et al., 2006).

Seafloor cratering is an important process that records the impact history of the Earth, affects projectile survivability, and ejects crustal materials to the atmosphere. Previous studies suggest that the dimensions and volume of benthic craters and projectile survivability vary with the parameter $H/d$ (the “normalized water depth”), where $H$ is the water depth and $d$ is the impactor diameter. Gault and Sonett (1982) conducted experimental impacts of Pyrex and aluminum projectiles into water at velocities ranging from 2 to 6 km/s and derived the relationship between water depth and the dimensions of the resulting underwater craters in benthic quartz sand. Baldwin et al. (2007) and Milner et al. (2008) conducted experimental impacts of stainless-steel projectiles into water-covered sandstone and granite targets at a 5 km/s velocity to derive the relationship between water depth and the dimensions and volume of the resulting underwater craters. In these studies, at $H/d$ values larger than 12–20, metal projectiles have been found to fragment within the water column without cratering the underlying benthic solids (i.e., no benthic craters were formed). Increasing the ratio to within the range of $1 < H/d < 10$ was observed to decrease the dimensions and volume of benthic craters and increase projectile survivability. By contrast, numerical models suggest a steeper decay of crater dimensions with increasing water depth than observed in the experiments. Hydrocode simulations suggest that the critical water depth to suppress seafloor cratering is 6–8 times the projectile diameter for an impact of granite with a diameter of 0.1–1 km at an initial velocity $v_i$ of 15 km/s (Davison & Collins, 2007), and 9–10 times the projectile diameter for an impact of dunite with a diameter of 1 km on sandstone at $v_i$ of 20 km/s (Milner et al., 2007).

The difference between the trends suggested by existing research and models is likely to arise from systematic gaps in projectile density, benthic material strength, and the impact velocity among experimental and modeling studies. Pi-group scaling is a useful tool for comparing different impact datasets to determine the effects of physical parameters on the dimensions and volumes of craters (e.g., Holsapple, 1993). To derive a scaling relationship of benthic cratering, it is important to perform impact experiments under a variety of conditions that fill the gaps between experimental and modeling studies. However, there have been no reported experiments involving the hypervelocity impact of chondrite on water-covered targets so far. The strengths and densities of the projectiles used in these experimental studies differed significantly from that of chondrite, and the relationship between the dimensions/volume of underwater craters and the water depth is expected to differ between metal and chondrite projectiles. There have also been no direct measurements of the deceleration and dispersal of projectiles during hypervelocity impact penetration of liquid water, which are key factors controlling the cratering efficiency of benthic material and water depth conditions utilized by a scaling relationship of benthic cratering, respectively.

This is the first report on laboratory experiments of hypervelocity impacts of ordinary chondrite projectiles on a water-covered target. For comparison, experimental data were also obtained for hypervelocity impacts of olivine, stainless steel, and polycarbonate projectiles on the same target. To trace the deceleration and
dispersal of projectiles within the water column, we measured the time evolution of cavity morphologies at resolutions of 1 and 2 μs. The relationship between the value of $H/d$ and the dimensions/volumes of the benthic craters produced by the impacts are presented to derive a scaling relationship for benthic cratering. Finally, we discuss the effects of impact velocity and projectile size on benthic cratering and estimate the transient crater volume of the seafloor crust by asteroid impact.

2. Materials and Methods

Impact experiments were performed using the Hypervelocity Impact Facility at ISAS/JAXA (Figure S1). A vertically configured two-stage light gas gun was used to accelerate projectiles at velocities ranging from 2 to 6 km/s onto liquid water at a normal incidence (Nishizawa et al., 2019).

The projectiles used were a polycarbonate sphere (4.7 mm diameter, 1,250 kg/m$^3$), a stainless-steel (SUS304) sphere (2 mm diameter, 7,900 kg/m$^3$), an olivine sphere (2 mm diameter, 4,150−4,600 kg/m$^3$), and a cylindrical column of ordinary chondrite (LL6, 2-mm basal plain diameter, 2 mm column height, 3,530−3,780 kg/m$^3$). The olivine sphere was shaped from a natural olivine crystal, and a cylindrical column of ordinary chondrite was cut and shaped from a block discovered in northwest Africa. The ordinary chondrite was composed primarily of olivine and iron with iron sulfides and iron oxides as accessory minerals (Figure S2). We used the stainless-steel projectile as a substitute for an iron meteoroid as the materials are comparable in terms of density and quasi-static tensile strength (7,900 kg/m$^3$ and ≥ 520 MPa for SUS304; 7,000–8,000 kg/m$^3$ and 400 MPa for the iron meteoroid; cf. 3,600 kg/m$^3$ and 30 MPa for ordinary chondrite; see Ostrowski & Bryson, 2019). The polycarbonate sphere was used to study the effects of melting and vaporization on the projectile drag within the water column. Olivine is one of the most common minerals in chondrite meteorites. Thus, the olivine sphere was used as a projectile to compare benthic cratering by olivine with that by ordinary chondrite. The compressive strength of forsterite was taken as 80 MPa (Petrovic, 2001). The projectiles were accelerated with the aid of a nylon-split sabot. Pure iron blocks (50 × 50 × 4.5 or 6 mm, 20 mm diameter × 20 mm height) were used as targets (“witness plate”) for tracking the trajectory of the projectile in water and was placed in a transparent polyvinyl chloride or acrylic resin container (500 × 500 × 200 mm) with or without liquid water. After leveling the container, the thickness of the water layer overlying the iron target was directly measured using a vernier caliper. To prevent the water from boiling and to minimize the slowing of the projectile, the target chamber was evacuated to 10 kPa (water vapor pressure = 2.3 kPa at 20°C).

The projectile velocities before first contact with water $v_i$ were estimated using time-of-flight measurements in which the passage times at two points along the flight path were measured using paired laser/detector systems at two stations within the flight tube. The hypervelocity impacts between the projectiles and the water were monitored using a high-speed video camera (HPV-1; Shimadzu Co., Ltd) at a time resolution of 1 or 2 μs. Trigger signals to initiate the filming of projectile-water impacts were sent to a video camera from either the laser/detector pairs or a photomultiplier located in the flight tube. The 3D structures and volumes of the craters formed by the impacts on the iron target were measured at ISAS/JAXA using a laser displacement sensor. Displacement measurement accuracy in the vertical direction (Z-axis) was ± 10 μm, far greater than the ± 100 μm accuracy along the horizontal directions (X- and Y-axes). A digital microscope (VHX-900, VHX-1,000; Keyence Co., Ltd) was used to measure the aerial distributions and diameters of the craters on the iron target. The craters were defined as the concave portions below a reference plane that was defined as the mechanically unaffected area of the target. In some experiments of polycarbonate, chondrite, and olivine impacts, a broad depression was formed on the benthic target. We did not classify the depression as a crater because the mode of formation may have been different from that of the other structures defined as craters (Section 3.1).

The initial shock pressure $P_i$ upon contact between the projectile and target (liquid water) was calculated from the standard shockwave impedance-match solution under a planar impact approximation (Melosh, 1989). The material parameters of the projectiles and water used in the calculation of $P_i$ are provided in Table 1. The $P_i$ value of the chondrite impact on water was approximately calculated using the material parameters of olivine and water because olivine is a major component of the chondrite used in this study (Figure S2).

When a projectile penetrating a water column decelerates by inertial resistance ($dv/dt = -αv^2$), the velocity $v$ and the penetration depth $Z$ of the projectile can be calculated as a function of time:
\[ v(t) = \frac{v_i}{\alpha v_t + 1}, \quad (1) \]
\[ Z(t) = \frac{\ln(\alpha v_t + 1)}{\alpha}, \quad (2) \]
\[ \alpha = \frac{C_d \times \rho_w \times S}{2m_p}, \quad (3) \]
\[ \alpha = \frac{k \times C_d \times \rho_w}{r_p \times \rho_p}, \quad (3') \]

where \( \alpha, C_d, \rho_w, \rho_p, S, m_p, \) and \( r_p \) are the inertial resistance coefficient, drag coefficient, mass density of liquid water, mass density of the projectile, projectile cross section in the direction of motion, projectile mass, and projectile radius, respectively. These relations are often referred to as “supersonic drag approximation” (O’Keefe & Ahrens, 1982). Form factors of \( k = 3/8 \) and \( 1/4 \) were used for the spherical and cylindrical projectiles (diameter of basal plain = height = \( 2r_p \)), respectively.

The projectile velocity as a function of penetration depth was derived from Equations 1 and 2:
\[ v(z) = v_i \times \exp(-\alpha Z). \quad (4) \]

In this study, \( \alpha \) value was determined from Equation 2 (Section 3.1).

3. Results and Discussion

3.1. Projectile Deformation, Fragmentation, and Melting in the Water Column

Hypervelocity impacts of stainless steel into liquid water at a normal incidence were observed in two series of experiments conducted at \( v_i \) of 2 and 5 km/s, corresponding to initial shock pressures of 7 and 40 GPa, respectively (Table 2). Upon first contact between the stainless-steel projectiles and water, pressure waves and cavities appeared within the water column (Figure 1). The cavity shape depended on \( v_i \). Following impact at 2 km/s, an elongated cavity developed with a diameter similar to the projectile diameter and smaller than its depth. Impact at 5 km/s produced a bulb-shaped cavity with tail and cavity diameters that far exceeded the projectile diameter. When the projectile had penetrated to a depth seven times its diameter (\( Z = 7 \times d \)), the tails stretched out from the cavity wall before being disrupted by the pressure wave reflected from the benthic iron target (Figure 1k). Elongated and bulb-shaped cavities also appeared as tracks in the low-density porous targets (1,000–1,100 kg/m\(^3\)) upon impact with the dense solid projectiles at low and high velocities (e.g., 1 and 4 km/s, respectively, for nylon-on-polystyrene impact; 5 and 9 km/s, respectively, for Al\(_2\)O\(_3\)-on-aerogel impact; 2 and 6 km/s, respectively, for SUS-on-gypsum impact; Ishibashi et al., 1990; Kitazawa et al., 1999; Yasui et al., 2012). Although the cavity shape in aerogel also depends on the nature of the projectile, such as its cohesion and water content (Burchell et al., 2008; Hörz et al., 1998), the \( v_i \) dependence of the cavity shape in liquid water and that in the low-density targets for a cohesive and anhydrous projectile suggest that the mechanical behavior of stainless-steel projectiles within liquid water during hypervelocity impact is comparable to that within low-density porous targets.
| Projectile mass, $m_p$ (mg) | Initial velocity, $v_i$ (km/sec) | Initial shock pressure, $P_i$ (GPa)$^a$ | Water depth, $H$ (mm) | Normalized water depth, $H/d$ | Diameter of the largest crater (mm) | Diameter of depression (mm) | Depth of the largest crater (mm) | Depth of depression (mm) | Volume of the largest crater (mm$^3$) | Total volume of craters and depression (mm$^3$) | Projectile mass density, $\rho_p$ (g/cm$^3$) | Scaled dimensions of the largest crater | \(\pi D^b\) | \(\pi depth^b\) | \(\pi V^b\) |
|-----------------------------|---------------------------------|----------------------------------------|---------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|-------------------------------------|--------------------------------|------------------|---------------|---------------|
| SUS304 sphere, diameter ($d = 2$ mm) | 33.6 | 1.817 | 7 | 0 | 0 | 3.6 | n.d. | 1.29 | n.d. | 9.4 | 9.4 | 7.9 | 28.2 | 10.1 | 2.2 |
|                             | 33.5 | 1.916 | 7 | 4 | 2.0 | 3.8 | n.d. | 1.24 | n.d. | 14.0 | 14.0 | 7.9 | 30.1 | 9.7 | 3.3 |
|                             | 33.5 | 1.898 | 7 | 8 | 4.0 | 3.6 | n.d. | 1.08 | n.d. | 9.9 | 9.9 | 7.9 | 28.3 | 8.5 | 2.3 |
|                             | 33.4 | 1.930 | 7 | 20.5 | 10.3 | 2.8 | n.d. | 0.58 | n.d. | 3.4 | 3.4 | 7.9 | 22.1 | 4.6 | 0.8 |
| SUS304 sphere, $d = 2$ mm | 33 | 5.114 | 35 | 0 | 0 | 6.6 | n.d. | 4.10 | n.d. | 90.4 | 90.4 | 7.9 | 52.7 | 32.7 | 21.7 |
|                             | 33.5 | 4.845 | 32 | 0 | 0 | 6.8 | n.d. | 4.00 | n.d. | 75.2 | 75.2 | 7.9 | 53.5 | 31.5 | 17.7 |
|                             | 33.5 | 4.310 | 26 | 4 | 2.0 | 5.4 | n.d. | 2.89 | n.d. | 39.2 | 39.2 | 7.9 | 42.4 | 22.7 | 9.3 |
|                             | 33.5 | 4.739 | 30 | 4.1 | 2.1 | 5.4 | n.d. | 2.42 | n.d. | 25.3 | 25.3 | 7.9 | 42.4 | 19.0 | 6.0 |
|                             | 33 | 5.365 | 37 | 7 | 3.5 | 5.3 | n.d. | 1.46 | n.d. | 22.8 | 22.8 | 7.9 | 42.3 | 11.6 | 5.5 |
|                             | 33.5 | 4.359 | 27 | 7.15 | 3.6 | 3.9 | n.d. | 1.33 | n.d. | 16.9 | 16.9 | 7.9 | 30.7 | 10.5 | 4.0 |
|                             | 33 | 5.405 | 38 | 11 | 5.5 | 2.0 | n.d. | 0.62 | n.d. | 5.9 | 5.9 | 7.9 | 16.0 | 5.0 | 1.4 |
| Polycarbonate sphere, $d = 4.7$ mm | 33.6 | 5.543 | 40 | 24 | 12.0 | 1.0 | n.d. | 1.0 | n.d. | 13.3 | 13.3 | 4.2 | 90.8 | 17.5 | 6.0 |
|                             | 34 | 5.112 | 35 | 28 | 14.0 | 0 | n.d. | 0 | n.d. | 0 | 0 | 7.9 | 0 | 0 | 0 |
|                             | 33.6 | 5.285 | 37 | 96.3 | 48.2 | 0 | n.d. | 0 | n.d. | 0 | 0 | 7.9 | 0 | 0 | 0 |
|                             | 68 | 6.196 | 22 | 0 | 0 | 9.0 | n.d. | 2.80 | n.d. | 89.9 | 89.9 | 1.2 | 34.9 | 10.8 | 10.4 |
|                             | 68 | 6.143 | 21 | 2.2 | 0.5 | 10.2 | n.d. | 1.30 | n.d. | 33.5 | 33.5 | 1.2 | 39.4 | 5.0 | 3.9 |
|                             | 68 | 6.158 | 21 | 5.3 | 1.1 | 0 | 12.0 | 0 | 0.55 | 0 | 27.3 | 1.2 | 0 | 0 | 0 |
|                             | 68 | 5.700 | 19 | 7.4 | 1.6 | 0 | 13.2 | 0 | 0.35 | 0 | 17.4 | 1.2 | 0 | 0 | 0 |
|                             | 68 | 6.000 | 21 | 10.4 | 2.2 | 0 | 15.0 | 0 | 0.11 | 0 | 6.4 | 1.2 | 0 | 0 | 0 |
|                             | 68 | 6.100 | 21 | 23.6 | 5.0 | 0 | n.d. | 0 | n.d. | 0 | 0 | 1.2 | 0 | 0 | 0 |
| Olivine sphere, $d = 2$ mm | 18.8 | 5.540 | 35 | 0 | 0 | 6.0 | n.d. | 2.68 | n.d. | 40.4 | 40.4 | 4.5 | 84.0 | 37.5 | 17.0 |
|                             | 18.8 | 5.597 | 36 | 2.8 | 1.4 | 6.0 | n.d. | 1.16 | n.d. | 13.3 | 13.3 | 4.2 | 90.8 | 17.5 | 6.0 |
|                             | 18.8 | 5.845 | 38 | 5 | 2.5 | 1.5 | 11.4 | 0.60$^c$ | n.m. | 0.7$^e$ | 4.6 | 4.4 | 21.5 | 8.6 | 0.3$^o$ |
|                             | 17.8 | 5.537 | 35 | 7.1 | 3.55 | 0.8 | 7.5 | 0.72$^e$ | 0.06 | 0.2$^e$ | 1.3 | 4.3 | 11.8 | 10.6 | 0.1$^o$ |
|                             | 18.2 | 5.731 | 37 | 10 | 5 | 1.0 | n.d. | 0.11 | n.d. | 0.04$^a$ | 0.4 | 4.3 | 14.5 | 1.6 | 0.02$^a$ |
|                             | 16.6 | 5.859 | 38 | 20 | 10 | 0 | n.d. | 0 | n.d. | 0 | 4.0 | 0 | 0 | 0 | 0 |
Table 2

| Projectile | Diameter (mm) | Depth (mm) | Volume (mm³) | Total (mm³) |
|------------|---------------|------------|--------------|-------------|
| Ordinary chondrite | 22.2 | 5.377 | 33 | 143 |
| Column | 23.7 | 5.353 | 33 | 141 |
| 2-mm basal plain column | 23.6 | 5.291 | 33 | 151 |
| 2-mm column | 22.6 | 5.171 | 31 | 116 |
| 2-mm basal plain | 22.6 | 5.171 | 31 | 116 |
| 2-mm column | 22.9 | 5.263 | 32 | 106 |
| 2-mm basal plain | 23.3 | 5.549 | 35 | 116 |
| 2-mm column | 23.1 | 5.464 | 34 | 116 |

Notes:
- a: The initial shock pressure of the chondrite impact onto water was calculated roughly by using the material parameters of olivine and water because olivine is a major component of the target. The depth of the largest crater as the depth from a reference plane that was defined as the mechanically unaffected area of the target. Non measured.
- b: Normalized diameter and depth were calculated from the initial shock pressure by assuming the largest crater is half of an oblate.
- c: Volume of the largest crater was calculated from its diameter and depth by assuming that the largest crater is half of an oblate.

The polycarbonate impacted on liquid water at 6 km/s produced five features distinct from those produced by the SUS-on-H₂O(l) impact at 5 km/s (Figure 2 and Figure S3). First, an impact flash occurred in the contact and compression stages (Figure 3b). Second, a hemispherical cavity expanded into the water layer. When the reflected pressure wave from the benthic iron target crossed the basement of the cavity (Z = 3.8 × d), a square frustum-like cavity emerged (arrows in Figure 3g). Third, the normalized water depth at which the multiple craters appeared on the iron target was shallower than that of the SUS-on-H₂O(l) impact (H/d = 1.1). Fourth, a depression was formed on the iron target at H/d values ranging from 1.1 to 2.2 (Figure S5b). The main features of the depression were smooth cone-shaped surfaces without rims and diameters that were enlarged relative to those of dry-condition craters. Fifth, the polycarbonate projectiles that were recovered following the experiments contained cloud-like aggregates of fibrous structures (Figures S5a7 and S5a8) that did not appear in the recovered stainless-steel projectiles.

The difference in cavity shape between the polycarbonate-on-H₂O(l) and SUS-on-H₂O(l) impacts probably arose from the differences in the projectile-to-target density ratios (ρ/ρ₀). In hypervelocity impacts on low-density porous targets, hemispherical cavities form at ρ/ρ₀ < 3, whereas elongated or bulb-shaped (with or without tails) cavities form at ρ/ρ₀ > 3 (reviewed by Kadono, 1999). Our experimental results therefore suggest that this trend might be applicable to solid-on-liquid water impacts (ρ/ρ₀ = 1.2 for polycarbonate-on-liquid water impact, 3.6 for SUS-on-liquid water impact).

The cloud-like aggregate structures indicate that polycarbonate projectiles were melted (temperature for incipient thermal decomposition ~250°C; Davis & Golden, 1969) and then formed gel clusters. Partial vaporization of polycarbonate in the 6-km/s impact is also inferred from the observed emission spectra of the impact vapor cloud and the calculated thermodynamic path in density versus internal energy space (Sugita & Schultz, 2003a, 2003b).
Figure 1. Sequential photographs of impact penetration of a stainless-steel projectile into liquid water with a benthic iron target. Initial projectile velocities $v_i$ are 1.9 and 5.1 km/s for shots S#1 (a–h) and S#2 (i–p), respectively. Thickness of the water layer above the iron block before shots 1 and 2 ($H$) are 20.5 and 28 mm, respectively. Arrows show a 2 mm diameter stainless-steel projectile (a and i), pressure wave (k), and tails emanating from the side and bottom of the expanding cavity (k and l). The first contact between the projectile and water is set as time zero. Scale bar: 20 mm.

Figure 2. (a) Relationship between crater structures formed on a benthic iron target and thickness of the overlying water layer in impact experiments involving a stainless-steel projectile with initial velocities of 2 km/s (a–d) and 5 km/s (e–h). $H/d$ denotes normalized water depth. Scale bar: 5 mm.
gel clusters might have expanded within the water layer following dynamic interaction with the pressure waves reflected from the water bottom (Figure 3g).

In the olivine-on-\(\text{H}_2\text{O}(l)\) impact at 5 km/s, no impact flashes were observed, and a cylindrical cavity without tails developed in the water layer (Figure S6). Multiple craters with and without a background depression appeared on the iron target at normalized water depths ranging from 2.5 to 5 (Figures S7a and S7b).

The hypervelocity impact of ordinary chondrite on liquid water at 5 km/s exhibited three characteristics. First, impact flashes often occurred in the contact and compression stages in a manner similar to the polycarbonate-on-\(\text{H}_2\text{O}(l)\) impact (Figure 4c). Second, the dispersal of chondrite fragments occurred during the traverse of the water column. In a manner similar to the stainless-steel projectile impact, fragments dispersed outward from the main cavity prior to its dynamic interaction with the reflected wave (arrows in Figure 4g). However, the penetration depths of the chondrite projectiles at which their fragments started dispersing were shallower than that of the stainless-steel projectiles (\(Z = 4–5 \times d\) for chondrite, \(n = 2\); Figure 4 and Figure S8). Third, multiple craters and a background depression appeared on the iron target at values of \(H/d > 2\) (Figure S9). The diameter of the depression was larger than that of dry-condition craters and approximately constant between 11 and 12 mm for \(H/d\) values ranging from 2.0 to 4.1, whereas that of the largest crater decreased with increasing \(H/d\). The diameters of impact craters on a solid target generally decrease with impact velocity or the size of the projectile with the same density (Melosh, 1989). Thus, the different depth trends between the depression and the largest crater suggest that the depression may not be formed by the collision between the projectile fragments and the benthic target but by the interaction of the shock wave in the water with the benthic target.

Figure 3. Sequential photographs of hypervelocity impact penetration of a polycarbonate projectile into liquid water with a benthic iron target. Sequential photographs of shot PC#1 are shown in (a–j). \(v_i = 6.1\) km/s; \(H = 23.6\) mm. Arrows show (a) a polycarbonate projectile, (b) impact flash, (c) pressure wave, (e) reflected pressure wave, and (g) tails emanating radially from the bottom of expanding cavity. The first contact between the projectile and water is set as time zero. Scale bar: 20 mm.
Figure 4. Sequential photographs of the hypervelocity impact penetration of an ordinary chondrite projectile into liquid water. Sequential photographs of shot OC#1 are shown in (a–h). Those of shot OC#2 are shown in (i–m). Initial projectile velocities $v_i$ are 5.5 and 5.6 km/s for shots OC#1 and OC#2, respectively. $H = 60$ mm (OC#1), 30 mm (OC#2). Arrows show (a) chondrite projectile, (c) impact flash, (g) tails emanating from the side and bottom of the expanding cavity, and (j–m) spherical bubbles. Photographs (a–h) are transmitted light images taken with an electronic flash unit located at the rear side of the water container. Photographs (i–m) are taken with two electronic flash units located at the lateral sides of the water container. The first contact between the projectile and water is set as time zero. Scale bar: 20 mm.
It is also noted that 1–2 μm spherules with white rims and black cores appeared in the main cavity (arrows in Figures 4j–4m). As the initial shock pressure of the chondrite-on-H2O(l) impact (∼30 GPa) exceeded the pressure for the incipient vaporization of water (5 GPa; Kieffer & Simonds, 1980), we interpret that these spherules represent water bubbles that appear during the adiabatic decompression of water (see Movie S1 for details).

Figure 5 depicts time-dependent penetration depths for the SUS-on-H2O(l), polycarbonate-on-H2O(l), and chondrite-on-H2O(l) impacts. Notably, the vertical growth rates of the main cavity and tail are comparable.
to theoretical rates of projectile penetration in which the projectile decelerates through inertial resistance. For the SUS-on-H₂O(l) impact at 2 km/s, the vertical growth of the elongated cavities can be explained by projectile penetration with an inertial resistance coefficient \( \alpha \) of 0.028 ± 0.002 mm\(^{-1}\) for \( H/d = 0-9 \) (Equation 2, \( R^2 = 0.98 \)), which corresponds to a drag coefficient \( C_d \) of 0.56 ± 0.02 for a rigid sphere of stainless steel (Figure 5a). The value of \( C_d \) is close to that measured for metal projectiles penetrating without severe deformation/disruption into low-density porous targets (1.1 ± 0.3; Okamoto et al., 2013) and that expected for a sphere (0.5; Anderson, 2006), which supports the hypothesized nondisruptive, less-deformed penetration of stainless-steel projectiles at 2 km/s.

For the SUS-on-H₂O(l) impact at 5 km/s, the vertical growth of the bulb-shaped main cavity can be explained by projectile penetration with an \( \alpha \) of 0.123 ± 0.001 mm\(^{-1}\) for \( H/d = 0-5 \) (Equation 2, \( R^2 = 0.99 \); Figure 5b). The \( \alpha \) value of the 5-km/s impact is five times greater than that of the 2-km/s impact. The \( \alpha \) value suggests that the value of \( C_d \times S \) in the 5-km/s impact is five times greater than the 2-km/s impact (Equation 3). This is consistent with the flattening of stainless steel in the 5-km/s impact by shock-induced deformation and fragmentation (so-called pancaking) that leads to the increases in \( C_d \) and \( S \). The flattening of copper projectiles by shock-induced deformation and fragmentation was also observed in the peak shock pressure from 10 to 60 GPa (McDermott et al., 2016).

For the chondrite-on-H₂O(l) impact at 5 km/s, the vertical growth of the main cavity can be explained by chondrite penetration with an \( \alpha \) of 0.184 ± 0.002 mm\(^{-1}\) for \( H/d = 0-5 \) (Equation 2, \( R^2 = 0.98 \); Figure 5d). For a rigid sphere of chondrite with the same cross-sectional area as the chondrite projectile used in this study, the \( \alpha \) value during the penetration of liquid water at \( v_i \) of 5 km/s is calculated to be 0.054 mm\(^{-1}\) (\( C_d = 0.5 \), \( d = 2 \text{ mm}, S = 3.14 \text{ mm}^2, m_p = 14.7 \text{ mg} \); Equation 3). Therefore, the value of \( C_d \times S \) in the 5 km/s impact is suggested to be five times larger than the rigid sphere of chondrite.

For the polycarbonate-on-H₂O(l) impact at 6 km/s, the vertical growth of the main cavity can be explained by polycarbonate penetration with an \( \alpha \) of 0.189 ± 0.009 mm\(^{-1}\) for \( H/d = 0-3 \) (Equation 2, \( R^2 = 0.98 \); Figure 5c). If a polycarbonate projectile penetrates water as a rigid sphere, the \( \alpha \) value is calculated to be 0.066 mm\(^{-1}\) at \( v_i \) of 6 km/s (\( C_d = 0.5 \); Equation 3). The factor of increase in the \( \alpha \) value relative to the rigid sphere is 3 for a polycarbonate projectile, smaller than that of stainless steel and chondrite projectiles during a 5-km/s impact. Stainless steel and ordinary chondrite were only affected by solid-state deformation and fragmentation, whereas polycarbonate was affected by melting and vaporization during traverse of the water column. As the \( \alpha \) value depends not only on \( C_d \) and \( S \) but also on the mass of the projectile during the traverse of the water column (Equation 3), it is not clear whether the extent of polycarbonate projectile flattening was smaller than that of the stainless steel and chondrite projectiles. Alternatively, the \( \alpha \) value can be explained if the polycarbonate projectile lost 66% of the original mass by shock-induced vaporization but maintained a constant cross-sectional area and a constant drag coefficient (i.e., equal to the initial values). As discussed later, melting and vaporization may stimulate the deceleration of a projectile in the water column less than solid-state deformation and fragmentation.

### 3.2. Relations Among Water Depth and Diameter, Depth, or Volume of Underwater Craters

Pi-group scaling is a useful tool for comparing different impact datasets to determine the effects of physical parameters on the dimensions and volumes of craters (e.g., Holsapple, 1993). In the Pi-group scaling theory, the following dimensionless crater parameters are used:

\[
\pi_D = \left( \frac{\rho_l}{m_p} \right)^{1/3} \times \text{diameter},
\]

(5)

\[
\pi_{\text{depth}} = \left( \frac{\rho_l}{m_p} \right)^{1/3} \times \text{depth},
\]

(6)

\[
\pi_v = \frac{\rho_l V}{m_p},
\]

(7)
where $\pi_D$, $\pi_{\text{depth}}$, $\pi_v$, $V$, and $\rho_t$ are the dimensionless crater diameter, dimensionless crater depth and cratering efficiency, crater volume, and mass density of the benthic solid target, respectively. This study focuses on the dimensions and volume of the largest crater but not on the broader depression in the benthic target that was observed for some polycarbonate-on-H$_2$O(l), chondrite-on-H$_2$O(l), and olivine-on-H$_2$O(l) impacts (Table 2). This is because the dimensions and volume of the depression are not representative of the residual kinetic energy of the projectile (fragments) when it (they) reaches the seafloor (Section 3.1).

Figure 6 summarizes the relationship between normalized water depth and $\pi_D$, $\pi_{\text{depth}}$, or $\pi_v$ for the largest crater of a variety of projectile-benthic target combinations examined in laboratory experiments (iron target: this study; rock targets: Baldwin et al., 2007; Milner et al., 2008). In the calculations of $\pi_D$ and $\pi_{\text{depth}}$, and $\pi_v$, projectile mass is set to equal the original projectile mass $m_p$ ($m_p = m_p$). For the chondrite-on-H$_2$O(l) and the olivine-on-H$_2$O(l) impacts of $H/d > 2$, the largest crater was superimposed on the broader depression in the benthic iron target. Therefore, it was difficult to separately measure the volume of the largest crater from that of the depression. In this case, the volume of the largest crater was calculated from its diameter and depth by assuming that the largest crater was half of an oblate spheroid (Table 2).

The $\pi_D$ and $\pi_{\text{depth}}$ values decreased with normalized water depth for all projectile-benthic target combinations (Figures 6a and 6c and Table S1). Figures 6b and 6d shows the relations between $H/d$ and $\pi_D$/$\pi_{D0}$ and $\pi_{\text{depth}}$/$\pi_{\text{depth0}}$, where $\pi_{D0}$ and $\pi_{\text{depth0}}$ are the dimensionless crater diameter and the dimensionless crater depth at reference impact velocity $v_0$ in the dry condition. The decrease of $\pi_D$ and $\pi_{\text{depth}}$ values per 1 unit of $H/d$ varied with $v_i$ and projectile-benthic target combinations. As discussed later, this probably reflects the fact that $v_i$ and projectile properties (strength, mass density) control the deceleration and fragmentation of projectiles during the traverse of a water column. In the 5-km/s impact, the decrease in $\pi_D$ and $\pi_{\text{depth}}$ values of ordinary chondrite and olivine with $H/d$ were comparable. This suggests that the extent of shock-induced fragmentation and deceleration of ordinary chondrite in water are comparable to those of olivine.

The $\pi_v$ value in the benthic target and normalized water depth followed an exponential relationship for all SUS-benthic target combinations:

$$\pi_v = \pi_{v0} \left( \frac{v_i}{v_{i0}} \right)^{3\mu} \exp \left( -\frac{H}{d} \frac{\pi}{\kappa} \right),$$

(8)

where $\pi_{v0}$ and $\mu$ denote the cratering efficiency at $v_{i0}$ in the dry condition, and a scaling exponent specific for the target material, respectively (see caption of Figure 6 for the $\mu$ values of iron, sandstone and granite targets) (Figure 6f). Equation 8 has been also identified for the cratering efficiency of a basalt target covered by a thin weak mortar layer ($\kappa = 0.38 \pm 0.03$; Dohi et al., 2012). The $\kappa$ value varied with $v_i$ and the projectile-benthic target combinations (Table S2) and exhibited the following trends:

1. The $\kappa$ value decreases with $v_i$. For the SUS-on-Fe + H$_2$O(l) impact, the $\kappa$ value at $v_i$ of 2 km/s (17 ± 14; $H/d \leq 10$) was 2–15 times larger than that of 5 km/s (2.0 ± 0.2; $H/d \leq 6$).
2. The $\kappa$ value depended on the benthic target material for the impact penetration of stainless steel at $v_i$ of 5 km/s. The $\kappa$ value increased from 1.5 ± 0.1 ($H/d \leq 5$; granite target; Milner et al., 2008) to 2.0 ± 0.2 ($H/d \leq 6$; iron target), to 2.9 ± 0.7 ($H/d \leq 8$; water-unsaturated sandstone; Baldwin et al., 2007), and finally to 2.8 ± 0.2 ($H/d < 8$; water-saturated sandstone; Baldwin et al., 2007).

These trends can be largely explained in the context of benthic cratering following projectile deceleration by the water layer. Generally, cratering efficiency in the strength regime is described as follows:

$$\pi_v = k_v \left( \frac{Y}{P_p v^2} \right)^{3\mu} \left( \frac{P_p}{P_p} \right)^{3\mu+1-3\nu},$$

(9)

where $Y$ is a measure of the target strength in units of stress (Pa), $v$ is the impact velocity, $\nu$ is a scaling exponent specific to the target material, and $k_v$ is a constant (e.g., Holsapple, 1993). Equation 9 indicates that cratering efficiency depends on impact velocity $v$. For an impact in the absence of a water layer, the value of $\nu$ equals $v$. Thus, Equation 9 can be rewritten as follows:
\[ \pi_{vi} = k_v \left( \frac{Y}{\rho_p \mu v_i^2} \right)^{\frac{3\mu}{2}} \left( \frac{\rho_i}{\rho_p} \right)^{\frac{3\mu-1}{2}} \]  

(10)

For an impact with the presence of an overlying water layer, the value of \( v \) should be smaller than \( v_i \) owing to deceleration by the water layer, as shown in Figure 5. From Equation 4, the projectile velocity during the impact penetration into liquid water can be written as a function of normalized water depth:

\[ v = v_i \exp \left( -\frac{H/d}{\lambda_t} \right), \]  

(11)

where

\[ \lambda_t = (ad)^{-1}. \]  

(12)

From Equations 3 and 3’, Equation 12 can be rewritten as follows:

\[ \lambda_t = \frac{2m_p}{C_d \times \rho_w \times S \times d} \quad \text{or} \]

\[ \lambda_t = \frac{\rho_p}{2k \times C_d \times \rho_w}. \]  

(12’)

Thus, cratering efficiency of the benthic target is exponentially related to normalized water depth (Equations 9–11):

\[ \pi_v = \pi_{vi} \times \exp \left( -\frac{3\mu}{\lambda_t} \times \frac{H}{d} \right), \]  

(13)

when the projectile mass does not decrease during impact penetration into water.

Equation 9 shows that \( \pi_{vi} \) equals to \( \pi_{i0} (v_i/v_{i0})^{3\mu} \). Therefore, \( \kappa \) is related to \( \lambda_1 \) and \( \mu \) by comparing Equations 8 and 13:

\[ \kappa = \frac{\lambda_1}{3\mu}. \]  

(14)

Combining Equations 12’ and 14,

\[ \kappa = \frac{2}{3} \times \frac{m_p}{C_d \times \rho_w \times S \times d \times \mu}. \]  

(15)

This indicates that \( \kappa \) is a function of physical properties of the stainless-steel projectile \((m_p, S, d, C_d)\) and the benthic target \((\mu)\). Furthermore, \( \kappa \) is a function of \( v_i \) due to an increase in the \( S \) of the stainless-steel projectile with \( v_i \) (Section 3.1).

---

**Figure 6.** Pi-group scaling relationships between normalized water depth \((H/d)\) and (a) dimensionless diameter \(\pi_D\), (c) dimensionless depth \(\pi_d\), and (e) cratering efficiency \(\pi_v\) of the largest crater on the iron or rock targets. Relationships between \(H/d\) and (b) \(\pi_D\) normalized by \(\pi_D0\) of the reference impact velocity \(v_{i0}\) at \(H/d = 0\), (d) \(\pi_d\) normalized by \(\pi_{d0}\) of \(v_{i0}\) at \(H/d = 0\), and (f) \(\pi_v\) normalized by \(\pi_{v0}\) of \(v_{i0}\) at \(H/d = 0\). In the calculations of \(\pi_d\), \(\pi_depth\), and \(\pi_v\), projectile mass is set as equal to the original projectile mass \((m_p = m_{p0})\). The \(\mu\) value of the iron target is calculated to be 0.71 ± 0.07 from cratering experiments under the dry conditions \(\left(R^2 = 0.98; \right. \text{Figure S10})\); this is consistent with the \(\mu\) value of a metal target \((0.709 \pm 0.027; \text{Holsapple} \& \text{Schmidt, 1982})\). The \(\mu\) values of the sandstone and granite targets are not reported in Baldwin et al. (2007) and Milner et al. (2008). Thus, we set 0.51 ± 0.05 (sandstones; Poelchau et al., 2014; Suzuki et al., 2012) and 0.76 ± 0.07 as the \(\mu\) values of the sandstone and granite targets, respectively. The latter is calculated from the relation \((\text{crater diameter in granite}) \propto v_i^\mu \) under dry conditions using the data in Table 2 of Milner et al. (2008) and is comparable to the \(\mu\) value of an igneous rock target \((0.75)\) as reported by Gault (1973). For reference, Figure 6f shows exponential decay curves that provide \(\pi_v\) values when chondrite and stainless-steel projectiles decelerate in water with the measured inertial resistance coefficients. Baldwin et al. (2007), Milner et al. (2008), and Davison & Collins (2007).
Table 3 depicts the $\lambda_1$ value estimated from Equations 12 and/or 14 using the $\alpha$ value derived from the growth of the main cavity (Figure 5) and/or the $\kappa$ value, respectively. The $\lambda_1$ values exhibited the following features:

1. The $\lambda_1$ value calculated from the $\alpha$ value was dependent on the projectile material. In the 5–6 km/s impact, $\lambda_1$ increased from $1.10 \pm 0.04$ (polycarbonate; $H/d = 0–3$) to $2.71 \pm 0.03$ (ordinary chondrite; $H/d = 0–5$), and finally to $4.07 \pm 0.02$ (stainless steel; $H/d = 0–5$).

2. For the 5 km/s impact penetration of the stainless-steel projectile into water, the $\lambda_1$ value derived from the $\alpha$ value was comparable to that derived from the hydrocode simulation of the projectile penetration velocity ($3.8 \pm 0.6$; Milner et al., 2008). This indicates consistency between the experiment and the numerical model (AUTODYN-2D).

3. For the 5 km/s impact penetration of the chondrite projectile into water, the $\lambda_1$ value derived from the $\alpha$ value was $\sim2.2$ times greater than that derived from the hydrocode simulation of the penetration velocity of a granite projectile with a mass density of 2,700 kg/m$^3$ ($1.7$; calculated from Figure 6 in Wünnemann et al., 2010). The difference in the $\lambda_1$ values of chondrite and granite can be explained by the difference in the $p_v$ values when their shapes during the traverse of the water column were identical (Equation 12).

4. For the 5 km/s impact penetration of the stainless-steel projectile into water, the $\lambda_1$ value derived from the $\kappa$ value was independent of the benthic target material. The $\lambda_1$ values derived from the $\kappa$ values were $4.3 \pm 0.6$ (H/d = 0–5; iron target), $4.4 \pm 1.1$ (H/d = 0–7.5; water-saturated sandstone; Baldwin et al., 2007), $4.3 \pm 0.6$ (H/d = 0–7.5; water-saturated sandstone; Baldwin et al., 2007), and $3.4 \pm 0.4$ (H/d = 0–5; granite; Milner et al., 2008). Although the $\lambda_1$ value calculated from the $\kappa$ value of the granite target was slightly smaller than that of the other targets, the $\lambda_1$ value calculated from the empirical relationship between the benthic impact velocity and crater diameter on the granite target ($3.9 \pm 0.5$; Figure 12 in Milner et al., 2008) was close to the latter.

5. For the stainless-steel projectile, the $\lambda_1$ value calculated from the $\kappa$ value was close to that calculated from the $\alpha$ value for H/d of 0–5.

Collectively, the exponential relationships between the H/d and $\pi_\nu$ in the 5 km/s impacts of stainless steel suggest that the mass of the largest projectile fragment that collided with the benthic target $m_{pl}$, was close to that of original projectile $m_{pl}$ so that the apparent $\pi_\nu$ value of the largest crater $p_vV/m_{pl}$ was close to true $\pi_\nu$ value $p_vV/m_{pl}$. Comparing the volume of the largest craters in experiments and that derived from the theoretical scaling relation, the $m_{pl}/m_{pl}$ ratios are estimated to be $1.0 \pm 0.3$, $0.4 \pm 0.1$, and $1.4 \pm 0.3$ in the impacts onto iron, granite, and sandstone targets at H/d of 5–5.5, respectively. The latter theoretical volumes are calculated from Equations 8, 12, and 14 using the $\alpha$ value in this study ($\alpha = 0.123 \pm 0.001$ mm$^{-1}$) (i.e., $\kappa = 1.9 \pm 0.2$, $1.8 \pm 0.2$, and $2.6 \pm 0.3$ for SUS-on-Fe + H$_2$O(l), SUS-on-granite + H$_2$O(l), and SUS-on-
sandstone + H₂O(l), respectively). Because the diameter of stainless-steel projectile in this study is different from the previous studies (d = 2 mm for SUS-on-Fe + H₂O(l) impact, 1 mm for SUS-on-granite + H₂O(l) and SUS-on-sandstone + H₂O(l) impacts), the α value in this study may not be strictly equal to the previous studies as inferred from the size-dependent variations in the degree of shock-induced flattening of steel at a given P_i (Katsura et al., 2014). Thus, the variation in the calculated m_pL/m_pl ratios may originate in the variation in α.

By contrast, the π_v values of the largest craters in the chondrite-on-Fe + H₂O(l) impact at v_i of 5 km/s do not show an exponential relationship with H/d. In the H/d−π_v/π_v0 (v_i/v_0)½ diagram, 4 of 5 data points for H/d = 2.0–5.9 scatter below the exponential decay curve of κ = 1.3 (i.e., μ = 0.71 and λ_1 = 2.7), whereas all two data points for H/d ≤ 1.3 are plotted along the exponential curve (Figure 6f). The exponential curve provides the true π_v value when a chondrite penetrates the water column, decelerates through inertial resistance, and then collides with the benthic iron target (α = 0.184 ± 0.002 mm⁻¹); the difference in the true and apparent π_v/π_v0 (v_i/v_0)½ values suggest that m_pl is significantly lower than m_pl when H/d is larger than 2. We estimate that the m_pl/m_pl ratio of the chondrite projectile was 0.1–0.3 for 4 of 5 experiments of H/d = 2.0–5.9.

Based on these results, the transient crater volume of underwater oceanic crust can be estimated. Basalt is a typical oceanic crust material, and its μ value is 0.64 (Moore & Gault, 1962). When a cylinder of ordinary chondrite (basal plain diameter = column height = d) impacts underwater basalt at v_i of 5 km/s, κ is calculated to be 1.4 assuming λ_1 of 2.7 for normalized water depths of up to 1.3 (Equation 14). Rearranging Equation 13, the crater volume of underwater basalt in the strength regime is predicted as follows:

\[
V = \frac{m_{pl}}{\rho_l} \times \pi_{vi} \times \exp\left(-\frac{H}{d} - \frac{1}{1.4}\right), \text{ for } H/d \leq 1.3.
\] (16)

For H/d of 2–6, at which multiple craters appear, the volume of the largest crater is expected to be 10%–30% of the volume derived from Equation 16.

\[
V = (0.1 – 0.3) \times \frac{m_{pl}}{\rho_l} \times \pi_{vi} \times \exp\left(-\frac{H}{d} - \frac{1}{1.4}\right), \text{ for } H/d = 2 – 6
\] (17)

If benthic cratering occurs in the gravity regime (d > several tens meter; Holsapple, 1993), κ is related to λ_1 and μ as follows:

\[
\kappa = \frac{\lambda_1 (2 + \mu)}{6\mu}.
\] (18)

Thus, the crater volume of underwater basalt in the gravity regime is predicted as follows:

\[
V = \frac{m_{pl}}{\rho_l} \times \pi_{vi} \times \exp\left(-\frac{H}{d} - \frac{1}{1.9}\right), \text{ for } H/d \leq 1.3,
\] (19)

\[
V = (0.1 – 0.3) \times \frac{m_{pl}}{\rho_l} \times \pi_{vi} \times \exp\left(-\frac{H}{d} - \frac{1}{1.9}\right), \text{ for } H/d = 2 – 6,
\] (20)

for a chondrite impact at v_i of 5 km/s (see supplementary text for the derivation of Equation 18).

### 3.3. Extrapolation to Oceanic Impacts

To extrapolate our laboratory-scale impact results to planetary-scale oceanic impacts, we analyzed the effects of impact velocity and projectile size on λ_1. The impact velocities of near-Earth asteroids at the top of the Earth’s atmosphere range from 10–50 km/s (mean: 20 km/s; Greenstreet et al., 2012), which is 2–10 times larger than the maximum velocity used in our experiments. Stony asteroids smaller than 100 m in diameter (<10^8 kg in mass) are unlikely to impact the Earth’s surface at the velocities of > 1 km/s owing to the deceleration, ablation, and disruption in the atmosphere (e.g., the Chelyabinsk event in 2013; O. P. Popova et al., 2013). In contrast, stony asteroids larger than several hundreds of meters in diameter can impact the
Earth’s surface without substantial deceleration (Bland & Artemieva, 2006; Ceplecha, 1992). Therefore, we estimate the $\lambda_1$ values of hypervelocity impact penetration into the ocean by cylindrical stony asteroids of $\geq 200$ m in dimensions (basal plain diameter = column height = $d$) at $v_i$ of 10–20 km/s.

The major effect of impact velocity on $\lambda_1$ is the deformation and fragmentation of the projectile. Our experimental results demonstrate that an SUS-on-H$_2$O(l) impact at $v_i$ of 5 km/s results in the pancaking of the projectile due to deformation and fragmentation. This pancaking enhances the deceleration of the projectile in the water column and decreased the value of $\lambda_1$ when compared with a 2-km/s impact of a stainless-steel projectile (Figures 5a and 5b). In previous hypervelocity impact experiments in which low-density sintered glass beads were used as a target, the mass of the largest fragment of rock or metal projectiles decreased with increasing impact velocity at initial dynamic pressures exceeding 10–20 times the tensile strength of the projectile (Okamoto et al., 2013). The microparticulation of the projectile in the early stages of impact resulted in a decrease in penetration depth within low-density porous targets (e.g., glass-on-aerogel impact; nylon-on-polystyrene impact; Al$_2$O$_3$-on-aerogel impact; Al$_2$O$_3$-on-polystyrene impact; SUS-on-gypsum impact; Burchell et al., 2001; Ishibashi et al., 1990; Kitazawa et al., 1999; Tsou, 1990; Yasui et al., 2012). As ordinary chondrite projectiles also deformed and fragmented during the traverse of the water column in the 5-km/s impact (Figure 4 and Figures S8 and S9), the chondrite-on-H$_2$O(l) impact at $v_i > 5$ km/s should result in further fragmentation and an increase in the effective cross-sectional area of the chondrite fragments. Thus, the $\lambda_1$ value in the > 5-km/s impact may be smaller than that of the 5-km/s impact when the chondrite projectile is only fragmented but not melted during penetration (i.e., $\lambda_1 < 2.7$).

Another effect of impact velocity on $\lambda_1$ is the deceleration of the projectile by melting and vaporization. Using the iSALE hydrocode, Potter and Collins (2013) calculated the effect of impact velocity on the fraction of a dunite projectile that remains solid (shocked below 105 GPa) $F_1$ and that does not vaporize (shocked below 186 GPa) $F_2$, for vertical impact penetration into liquid water. The calculation predicted that the $F_1$ and $F_2$ values decrease from 100% to 20% and 100%–70%, respectively, with an increasing impact velocity from 10 to 20 km/s. Although vaporization can contribute to a decrease in density and decelerate a projectile more rapidly than predicted for the original rigid projectile, the numerical simulation suggested that the deceleration of a rock projectile at $v_i$ of 15 km/s is smaller than at $v_i$ of 5 km/s and is closer to predictions for the original rigid projectile for penetration depths up to 10 times the projectile diameter (Wünnemann et al., 2010). Such numerical simulation results are consistent with our experimental results in that the $\lambda_1$ value of the polycarbonate projectile in the 6-km/s impact, affected by melting and vaporization, was closer to that predicted for the original rigid projectile when compared with the $\lambda_1$ value of the stainless-steel projectile in the 5-km/s impact, which was only affected by deformation and fragmentation (Table 3). However, it is currently unknown if asteroid projectiles are melted and vaporized before reaching the seafloor owing to a lack of kinetic data of shock-induced melting and vaporization.

The size of projectile can also affect $\lambda_1$ if size-dependent growth and coalescence of cracks control the dynamic strength of the projectile. House and Holsapple (1999) demonstrated the effective weakening of a granite target as its size (diameter and length) increased from 2 to 30 cm (mass range $10^3$–$10^9$ g) in collision tests in which the kinetic energy per unit target mass and impact velocity remained constant. However, the high porosity of asteroid material relative to that of granite (Consolmagno et al., 2008) suggests that dynamic strength for an asteroid might remain constant with increasing size. This conclusion is consistent with the fact that apparent bulk strength at atmospheric disruption (ram pressure) does not depend on the size of a meteor that is within $10^{-2}$–10 m in diameter (mass range $10^3$–$10^9$ g; O. Popova et al., 2011; Slyuta, 2017).

Collectively, assuming the effects of impact velocity and projectile size on $\lambda_1$ established above, the $\lambda_1$ value of oceanic impact by a cylinder of stony asteroid of $\geq 200$ m in dimension is predicted in the following two cases. First, if shock-induced asteroid fragmentation in the water column controls subsequent penetration into deeper water (e.g., $v_i \approx 10$ km/s), the $\lambda_1$ value is smaller than 2.7 (i.e., $\kappa < 1.9$). In this case, the relation between the penetration depth and transient crater volume of underwater basalt in the gravity regime changes at the depth at which asteroid fragments start penetrating water individually. Similar to meteoroid dispersal in air, it is predicted that the depth at which projectile fragments start penetrating individually is independent of $v_i$ if $C_d$ is constant during penetration (Kadono et al., 1999). In our experiments at $v_i$ of
5 km/s, multiple craters appeared at the normalized water depth above 2. Collectively, the transient crater volume of underwater basalt in the gravity regime is predicted as follows:

\[ V < \frac{m_{pl}}{\rho_i} \times \pi_v \times \exp\left(-\frac{H}{d} \right), \text{for } \frac{H}{d} \leq 1.3, \text{or} \]

\[ V < \left(0.1-0.3\right) \frac{m_{pl}}{\rho_i} \times \pi_v \times \exp\left(-\frac{H}{d} \right), \text{for } \frac{H}{d} = 2-6. \]  

(21)

(22)

In the second case, if most of the asteroid fragments are melted and vaporized before they start penetrating the water individually, the \( \lambda_1 \) value may be close to the value predicted for the rigid sphere of chondrite \( (\lambda_1 = 8.5 \text{ by substituting } C_d \text{ of 0.56 and } \rho_p \text{ of 3,500 kg m}^{-3} \text{ in Equation 12" i.e., } \kappa = 5.8) \). The transient crater volume of underwater basalt in the gravity regime is much larger than that of the first case.

\[ V \approx \frac{m_{pl}}{\rho_i} \times \pi_v \times \exp\left(-\frac{H}{d} \right) \]  

(23)

Hydrocode simulations suggest that, in the second case, approximately 100–200 craters of > 10 km in diameter should have formed on the seafloor in the last 100 Ma, assuming the present ratio between landmasses and oceans (Davison & Collins, 2007). In contrast, only 12 craters or structures that have formed by marine impacts in the last 100 Ma have been identified (Dypvik & Jansa, 2003 and references therein). Thus, current observations appear to be more compatible to the first case than the second. However, late stage modification of transient craters and long-term sedimentation may obscure impact-related structures on the seafloor. Therefore, the prediction of the \( \lambda_1 \) value should be tested in the future using a high-resolution global survey of the seafloor together with experimental determination of the kinetics of shock-induced melting and vaporization of chondrite.

4. Conclusions

We performed laboratory experiments of the hypervelocity impact of chondrite and other projectiles (olivine, stainless steel, and polycarbonate) on a water-covered iron target to derive a scaling relationship for benthic cratering. The main findings of this study are as follows.

1. In situ observations of 5-km/s impacts quantify the deceleration of projectiles in the water column by shock-induced deformation, fragmentation, and melting/vaporization. For SUS-on-H₂O(l) impact, the vertical growth of the main water cavity is explained by projectile penetration into water with an inertial resistance coefficient \( \alpha \) of 0.130 ± 0.002 mm⁻¹ for normalized water depth \( H/d \) of 0–7, 5 times greater than that predicted for a rigid sphere of stainless steel. This suggests a 5-fold increase in the effective cross-sectional area and/or drag coefficient by the flattening of stainless steel through solid-state deformation and fragmentation. The factors of increase in the \( \alpha \) value relative to the rigid sphere were 5 and 3 for ordinary chondrite and polycarbonate projectiles penetrating water at 5–6 km/s, respectively. Stainless-steel and ordinary chondrite were only affected by solid-state deformation and fragmentation, whereas polycarbonate was affected by melting and vaporization during the traverse of the water column. Melting and vaporization may thus stimulate the deceleration of a projectile in a water column less than solid-state deformation and fragmentation.

2. For the 5-km/s impact, the minimum water depths at which multiple craters appeared on the benthic iron target were two and four times the projectile diameter for ordinary chondrite and stainless steel, respectively.

3. Based on the observed deceleration of the projectiles in water, the cratering efficiency of the benthic target at a given impact velocity is predicted to follow an exponential decay relation with the normalized water depth, given by \( \pi_v \propto \exp(-(H/d)/\kappa) \) when a projectile of original mass collides with the target. Comparing the volume of the largest crater from our experiments with that derived from the scaling relation, mass ratios of the largest projectile fragment to original projectile in the 5-km/s impact were calculated to be 0.1–0.3 (\( H/d = 2–6 \)) and 1.0 ± 0.3 (\( H/d = 5.5 \)) for chondrite and stainless steel, respectively.

4. Using the experimentally derived scaling relation, the transient crater volume of benthic oceanic crust by an asteroid impact is predicted as \( V < \frac{m_{pl}}{\rho_i} \times \pi_v \times \exp(-(H/d)/1.9) \), for \( H/d \leq 1.3 \), or \( V < (0.1-\)
Collectively, our experiments suggest the possibility of a much smaller number of impact-related crater/structures on the present seafloor than previously predicted by hydrocode simulations.

**Data Availability Statement**

The data used in this work are available at Mendeley Data (Nishizawa et al., 2020) (https://data.mendeley.com/datasets/wn7vkj89h3/3).

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