A SIMPLE METHOD ENABLING STUDENTS TO MODEL IMPACT CRATERING FROM 0° TO 90°

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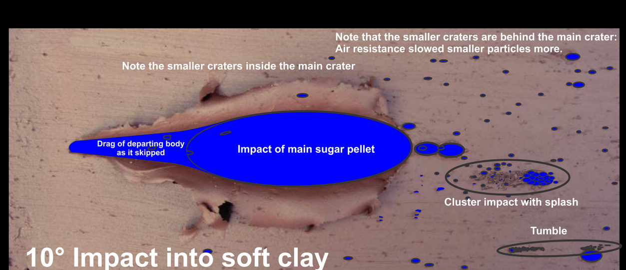
Simple Modeling of Impacts



Impact cratering is best studied with hypervelocity guns able to project impactors at speeds matching asteroids impacting Earth, 11 to 25 km/sec. The equipment to allow such experiments is expensive and most students do not have access to them. It is common in physics to scale results from small experiments to help understand larger real-world events. Although hypervelocity experiments are matching asteroid speeds, they still rely on scaling: the projectiles are tiny compared to objects able to form craters on planets and other solar system bodies.

Ideally a student experiment should be affordable, able to be executed by a person of normal skills, and still provide results that are realistic. If one does not have access to hypervelocity guns, then instead of using high speed impactors on rock targets, one can use soft materials for the targets and low speed impactors. With appropriate choice of target and impactor, one can produce craters closely matching computer generated craters and craters found on planets and other solar system bodies.

Different materials can be shot from the pellet guns allowing a wide range of impactor density and porosity. Pellets are available in plastics, copper and lead. Also one can make pellets out of other materials. For instance, sugar cubes were shaped to fit the 4.5 mm barrels and shot into the clay showing the effects of an impactor that breaks up before impact.

While this is not as accurate as hypervelocity guns, it still is able to produce craters similar to those found on Earth and other solar system bodies at a very low cost.

Pellet rifle with inclination meter, tape measurer, 10 kg of clay, spatulas, sharp knife for sectioning.

Pellet pistol used for copper pellets.

The Setup

Two people, a pellet gun, inclination meter, tape measurer, and a tray of soft clay are all that is required to demonstrate cratering.

Method: Pellets were fired into the center of a tray of clay at different angles ranging from 90° (vertical) 0° (horizontal). A pellet rifle was used to fire lead pellets, and pellet pistols were used for lower velocity shots. They are available from most sports and hardware stores for less than $200. Paint ball guns were also experimented with, but they did not perform as well. The pellet rifle fired lead .177 pellets (4.5 mm, 0.5 grams) at approximately 200 m/s (600 fps). The pistols shot copper pellets of 4.5 mm, 0.33 grams, and plastic pellets of 6 mm, 0.12 grams. at a velocity of approximately 100 m/s (300 fps). A tape measurer was used to set the end of the guns, which gave excellent repeatability (+/- 2 cm). An inclination meter, available from most hardware stores for less than $50, was mounted on the gun barrels, allowing setting the angle to +/- 1°. Allowing for human variations, the final impact angle will be +/- 3° or less. With a steady hand and reasonably good eyesight, a gun can be aimed to the center of a target with good centering for most shots. A ladder was used for high angle shots.

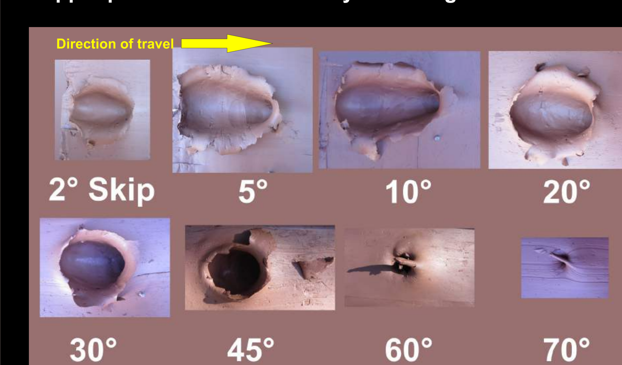
Modeling clay was used for the target material. It is available at most art stores for less than $50 for 10 kg - which is sufficient for the experiment. The target's hardness will determine the craters formed. For some of the experiments - particularly for the low speed pellets - many shots were fired into the clay without smoothing between. This ensured that the clay consistency remained the same for the set of shots.

The larger craters were produced with clay that was mixed with water until the clay was soft so that it was easily flattened with a spatula used for spreading drywall compound. These shots required smoothing between each shot. An aluminum baking tray was filled with the soft clay, and smoothed with the spatula.

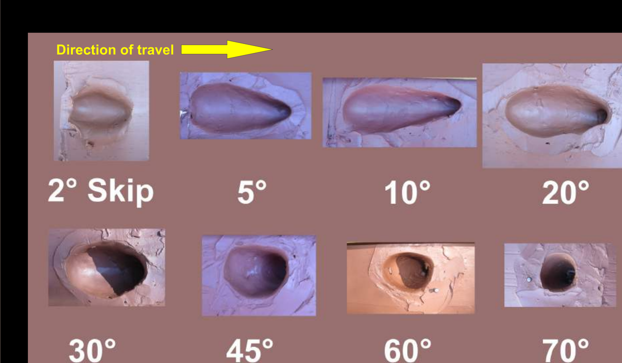
The smaller craters were produced with clay as received from the art store without adding extra water. These craters were significantly smaller, but still had similar shapes for most angles. The lower angle shots varied the most with different hardness of the target material.

The Results

Photographs of impacts:
Plastic pellets into medium clay on the left
Copper pellets into medium clay on the right

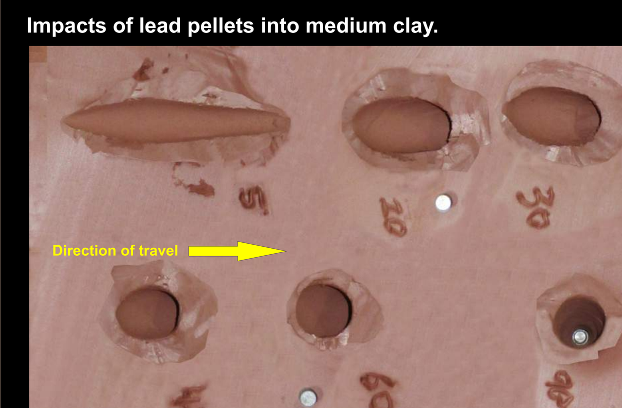


Impacts of lead pellets into soft clay.



Impacts of lead pellets into soft clay with ejecta removed.

Impacts of lead pellets into medium clay.



Impacts of lead pellets into medium clay with ejecta removed.

The Results

Axial view of 10° Impact crater in soft clay

Results: The craters produced here clearly show the effects of angle of impact. Craters produced from 90° to 60° were circular (once the ejecta and rebound material was removed) and smaller than more angled craters, with the pellet remaining near the center of the craters. For the soft clay, the 90° to 60° craters commonly collapsed and closed the crater at the surface, but removing the elevated part of the surface revealed the inner circular craters. For all targets, the craters were ellipses between 60° and 20°, with the long axis increasing as the angle of impact decreased. The largest craters were produced between 20° and 30° angles of impact. For the higher energy pellets, below 20° the craters became stretched ellipses with the widest part at the beginning of the crater and the narrowest at the end. The craters became more stretched as the angle of impact decreased until the pellets skipped.

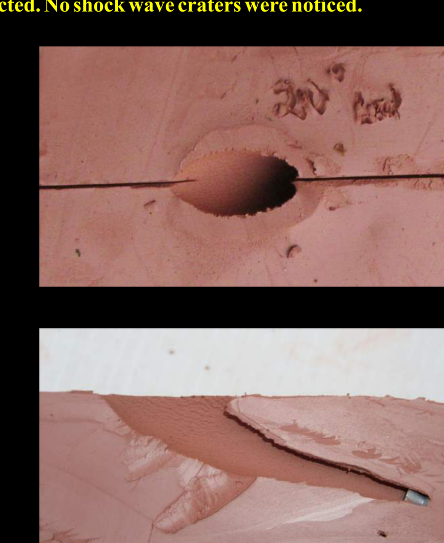
The skip angle varied with the hardness of the clay and with the energy of the pellet. Lower angles were required for skips in the softer clay, or higher energy pellets. The plastic pellets skipped at 20° and lower angles, the copper pellets at 10°, the lead pellets skipped in medium clay at 5° and the lead pellets skipped only below 2° for soft clay.

The skip craters in soft clay were perfect ellipses, similar in shape to the craters produced for impacts between 30° and 20°. For the medium clay, the skips ranged from ellipses to lines approximately the width of the pellet, as the lower energy pellets essentially scratched the surface after the first contact rather than producing shock wave effects.

In general, the low energy pellets only produced craters slightly larger than the pellet itself. The lead pellets with 10 times higher energy were able to produce significant shock waves and craters much larger then themselves. The wet clay provided much larger craters, but they were difficult to section for cross section analysis as they were too soft to maintain their shape well.

The cross sections in the medium clay craters show significant penetration of the clay by the impacting pellets. The penetration paths still show effects of shock waves as the holes are much larger than the pellet diameter until the bottom of the holes.

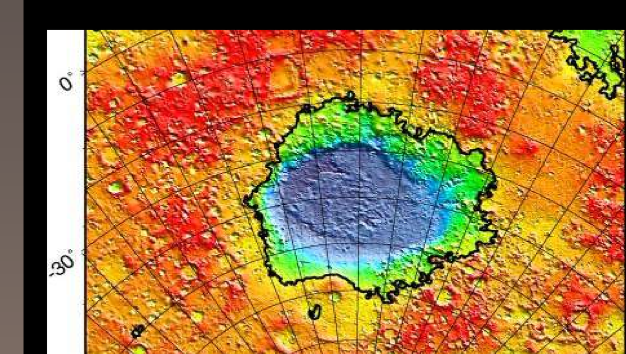
Pellets were fired at hard clay - bricks - and the observed craters were not measurable. Essentially the pellets reflected from the bricks and did not leave any craters. Dry clay was tried and also not useful - the pellets simply drilled holes the size of the pellet or reflected. No shock wave craters were noticed.



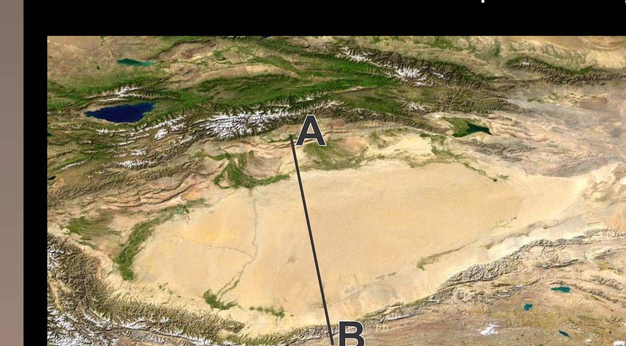
Cross Sectioning

Real World comparisons

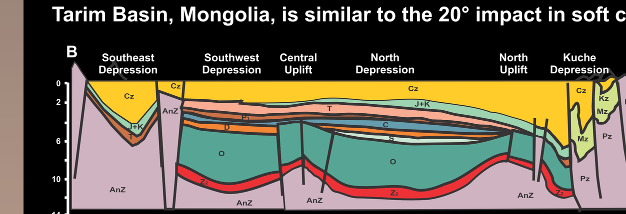
Wilpena Pound, Australia, (Google Earth image above, actual photo to the right) has a similar appearance to the axial view of the clay impacts.



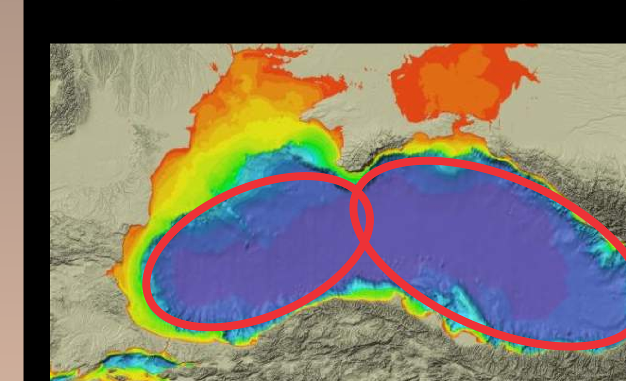
Hellas Basin on Mars is similar to the 30° impact in soft clay



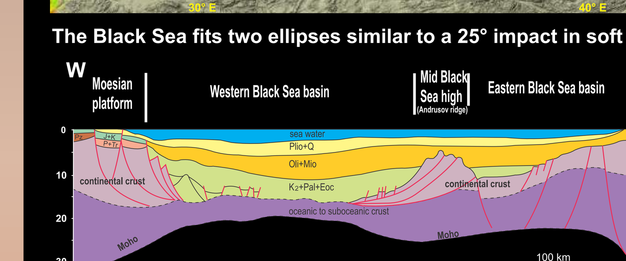
Tarim Basin, Mongolia, is similar to the 20° impact in soft clay



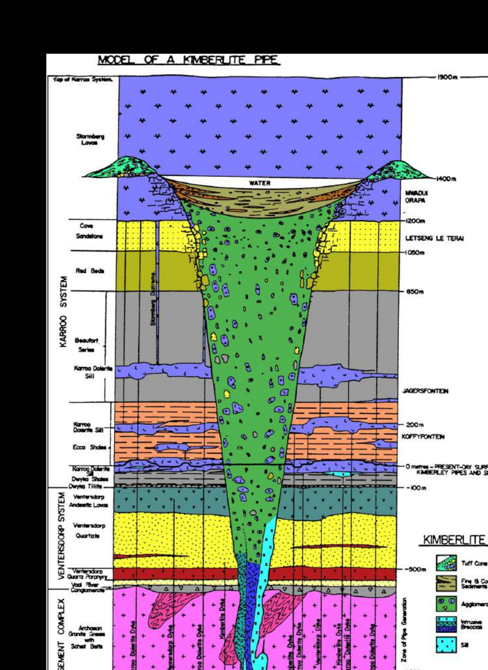
Geological Cross Section of Tarim Basin, Mongolia



The Black Sea fits two ellipses similar to a 25° impact in soft clay



Geological Cross Section of the Black Sea

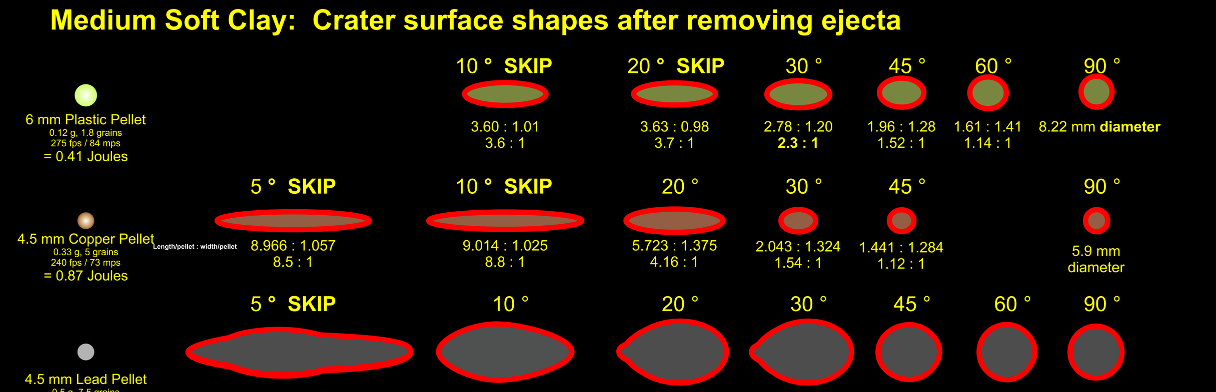


Hawthorne's (1975) model of a kimberlite pipe. is similar to the vertical impact cross section
From: Matthew Field, Johann Stiefenhofer, Jock Robey, Stephan Kurszlaukis, "Kimberlite-hosted diamond deposits of southern Africa: A review" Ore Geology Reviews 34 (2008) 33–75

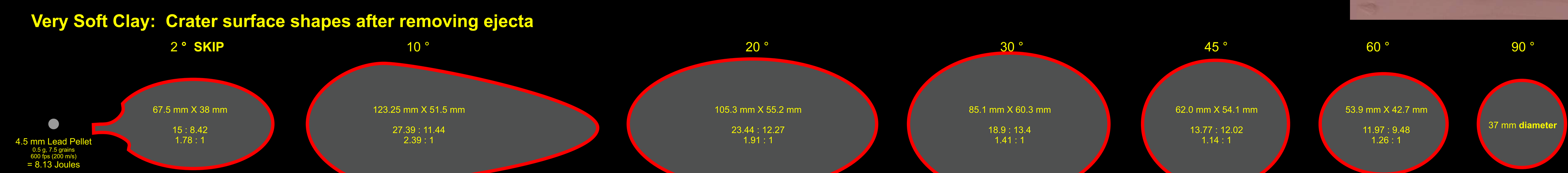
Sample Craters, 1:1 scale, various pellet guns and hardness of clay.

Baked Clay / Brick: No Craters, just slight staining at impact surface, reflections.

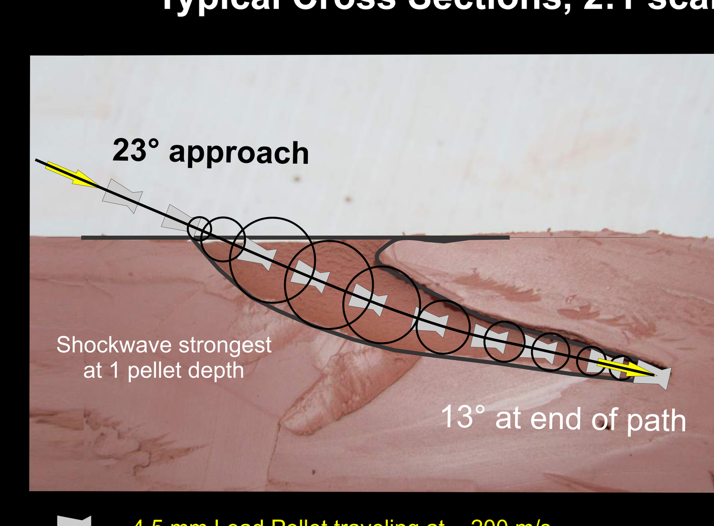
Medium Soft Clay: Crater surface shapes after removing ejecta

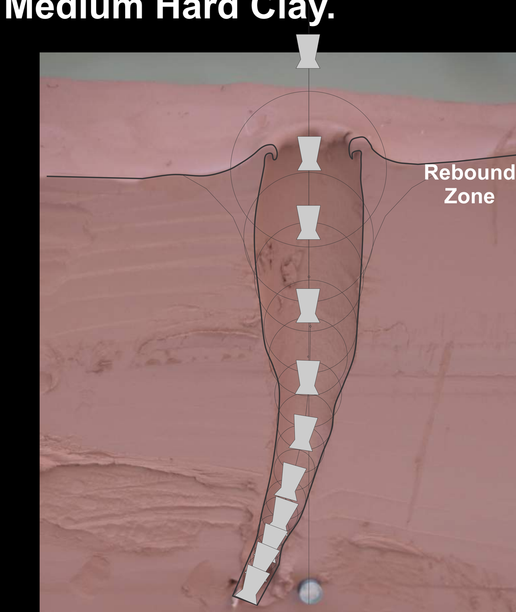


Very Soft Clay: Crater surface shapes after removing ejecta



Typical Cross Sections, 2:1 scale, Medium Hard Clay.





Discussion

This method allows one to produce low angle impacts, skips, and penetration / non-explosive impacts - all poorly studied to date. The craters produced by this method more likely relate to a large comet impacts than to asteroid impacts.

This experiment allows students to experience impact cratering in a simple and affordable way. The hardness of the clay can be varied from nearly liquid to as hard as rock when baked (a brick is baked clay), allowing a wide range of experiments with the same apparatus. Pellet guns can be obtained with various power levels, allowing different speeds of impactors for the same hardness of the clay. Different materials can be shot from the pellet guns allowing a wide range of impactor density and porosity. While this is not as accurate as hypervelocity guns, it still is able to produce a wide range of craters at a very low cost. With this method, it is easy for students to produce craters and data to use to calculate the energy expended in the craters, and personally observe the effects of different hardness of the targets and energy of the impactors.

The 10° skip crater shown below shows the wide range of results possible from this simple experiment. The pellet was made from a sugar cube, and the firing from the rifle caused the sugar pellet to partly shatter as it left the barrel. This produced many tiny craters around the main impact crater, including smaller craters inside the main crater. The tiny particles were slowed by air resistance more than the large body, so they arrived later. The effects included a cluster of grains landing in one spot, a large irregular shaped crystal tumbling rather than cratering, and some the of the late arrival grains hitting into the edge of the splash, leaving half craters or parabolic craters. Many of the ellipsoidal craters were narrower or wider than the others - narrower ones probably from slower moving grains that arrived later. A real comet would likely break up on approach to a planet, so in addition to a main crater, similar additional smaller craters should be expected for real comet impacts.

The "Earth Impacts Effects Program" uses the assumption that all planetary craters are scalable from hypervelocity experiments, explosions and nuclear explosions - all of which are single point explosions near the surface. This is considered valid for all asteroid impacts as their speeds only range from 11 to 25 km/sec - too low of a speed to allow the impact to interact with the mantle or to allow the impactor velocity/energy to exceed the lithosphere's shear forces.

From the "Earth Impacts Effects Program" (G. S. Collins, H. J. Melosh, & R. A. Marcus 2004), the formula for the diameter of a crater is:

$$D_{tc} = 1.161\left(\frac{\rho_i}{\rho_t}\right)^{1/3} L^{0.78} v_i^{0.44} g_E^{-0.22} \sin^{1/3}\theta$$

The D_{tc} is the transient crater diameter, and it is dependant on the density of the target P_t, density of the impactor P_i, impactor diameter L, velocity on impact V_i, Gravity, and $\mathrm{Sin}^{1/3}\ \Theta$. This can be simplified to Constant * $\mathrm{Energy}^{1/3}$ * $\mathrm{Sin}^{1/3}\ \Theta$.

With the diameter relative to $\mathrm{Sin}^{1/3}\ \Theta$, the angled craters should be SMALLER than the 90° craters, but here they are always LARGER.

The formula shows that the diameter is relative to the target density, but the wet clay has a higher density than the medium hard clay. So the shear strength is more significant than density in these experiments.

A calculation of the energy of the pellets indicates that explosive single point craters would be much larger than the ones produced by this method. Here the speed and energy of the pellets exceeds the shear strength of the target material, so the pellets penetrate the target rather than exploding, while forming craters from the shock waves as they travel into the target.

With these craters not being identical to standard asteroid impacts, the usefulness of the experiments can be questioned. However, it is recognized that some craters in the solar system will match these. For instance, the Deep Impact satellite was expected to produce a penetrating crater in comet Tempel 1 instead of an explosive crater.
(Schultz et al, 2005, "Expectations for Crater Size and Photometric Evolution from the Deep Impact Collision")(K. R. Housen, K. A. Holsapple & M. E. Voss "Compaction as the origin of the unusual craters on the asteroid Mathilde", Nature 402, 155-157 (11 November 1999) | doi:10.1038/45985)

Comets are often very large. There are thousands of objects in the Kuiper Belt (expected source of short period comets) over 100 km in diameter vs a few in the asteroid belt. Comets can hit Earth at speeds up to 72 km/sec. If a comet larger than the thickness of the lithosphere hits Earth, it will mainly interact with the mantle which has a lower shear strength than the lithosphere. Perhaps there are some large comet impacts on Earth that had significant penetration and instead of forming a surface single point explosion crater, formed craters similar to those in this experiment.

Most asteroids will hit Earth with impact angles between 90 ° and 45° due to Earth's gravity providing half or more of the speed, causing asteroids to be pulled significantly towards the center of the planet. All of these impacts will be nearly perfect circles with minimal distortion as the angle approaches 45°.

Comets will hit Earth at much higher speeds - up to 72 km/s, so the gravitation pull has minimal effect on the angle of incidence of the incoming comet. This will allow comets to have impact angles between 90° and 0°. While half will be between 90° and 45° producing circular craters, half will be arriving at low angles, and produce elliptical craters. Most elliptical craters and skips on Earth will be formed by comet impacts.

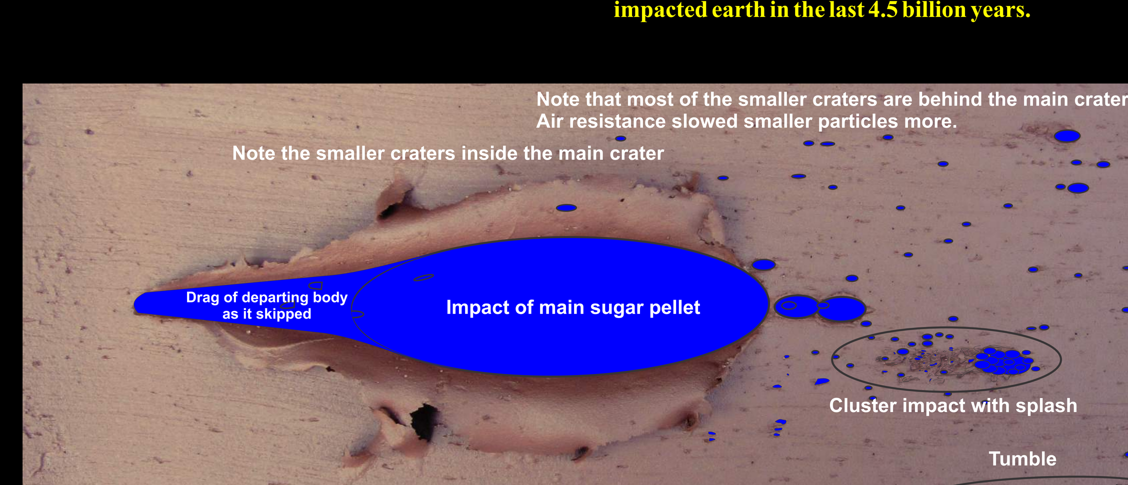
It is conceivable some comet impacts do exist on Earth. If Shoemaker-Levy 9 could hit Jupiter in our lifetimes, than some comets must have impacted earth in the last 4.5 billion years.

At present, when the Earth Impact Database of the University of New Brunswick assigns an impactor to a crater, they are always asteroids. Some comet craters on Earth may match the penetration craters produced with this experimental method, and be dramatically different than asteroid craters.

In the Real World Comparisons column are some interesting shapes found on Earth and Mars that look similar to the craters produced in this experiment. The Hellas Basin on Mars is identified as an impact crater. The ones on Earth have not been studied as impact features. It would be interesting to evaluate them as craters.

The Black Sea and Tarim Basin are ellipsoidal, and neither is well explained by Plate Tectonics. Impact origins may explain their unusual features. For instance, both are surrounded by tectonic events, with well measured movements around them, but there is insignificant tectonic activity in them. They are distinctly different than the lithosphere touching their edges - which does not fit normal tectonic events. The Black Sea is also much deeper (including the sediments that extend in perfectly horizontal layers to a depth of 15 km) than the deepest trenches in the Ocean, so it is unlikely to be a tectonic formed ocean basin.

Kimberlite pipes are well studied and believed to be vents from cracks in the lithosphere. They are not presently associated with impacts. The similarity to the vertical cross sections of the experiments is remarkable. The experimental impactors are not ablating during the impact, but a comet hitting Earth would ablate as it penetrated the crust, so the deepest part of a kimberlite caused by an impact would be a narrow point. It is worth noting that some kimberlites have no diamonds while others beside them do have diamonds. If the vent theory was correct, then the diamond content should be the same for neighboring kimberlites. If they were due to impacts, each one's diamond content would depend on the object impacting the Earth, not on a source from the mantle layer.



This 10° single shot of a sugar pellet (carved out of a sugar cube) shows many features that would be difficult to show with a hyper velocity gun. The main pellet produced a simple skip crater, while the tiny grains that separated in the process of being fired by the gun produced a wide range of craters, tumbles, and a splash.

Note that the crater shapes are not consistent - some are much narrower than others and those hitting into the prime crater leading edge produced parabolic craters.