# Reports

## Apollo 12 Lunar Module Impact: Laboratory Simulation and Possible Downrange Ballistic Effects

Abstract. *Plastic pellets were fired into sand targets at a launch angle of 4 degrees and a velocity of 1.68 kilometers per second, the conditions of the Apollo 12 lunar module impact. Shallow elliptical or doublet craters were formed, similar to certain lunar craters. Analysis of the ejecta suggests (i) that lunar module debris skipped and, with some crater ejecta, reimpacted far downrange, but (ii) this ballistic rain does not account for the anomalous seismic signal.*

After a successful return to lunar orbit, the Apollo 12 lunar module (LM) ascent stage was intentionally impacted on the lunar surface at a velocity of approximately 1.68 km/sec and a launch angle of 3.7° from the local horizontal, with a total kinetic energy of $3.62 \times 10^{16}$ ergs, about 76 km from the Apollo Lunar Surface Experiments Package (ALSEP) seismometer (*1*). The seismometer began recording a broadband signal 20 to 25 seconds after the impact. The amplitude of the signal grew toward a broad maximum at about 6 minutes and then decayed away over the following 50 minutes. The seismic record produced was unusual by terrestrial standards and offers a challenge to interpretation (*2*). First, we were intrigued by the possible downrange effect of ejecta and ricocheting LM fragments on the results of the seismic experiment because the ALSEP was approximately on the forward trace of the velocity vector of the impacting LM. Because of the secondary impact of rock and LM fragments resulting from the shallow impact angle and low velocity, the seismic impulse may have originated not from a single discrete source in time and position but rather from a ballistic rain of rock fragments and spacecraft parts. Second, we were also interested in the cratering process of low-angle, low-velocity impacts. It has been suggested that many doublet craters and skewed ray patterns could be the result of such impacts. These two possibilities suggested the experimental program described below.

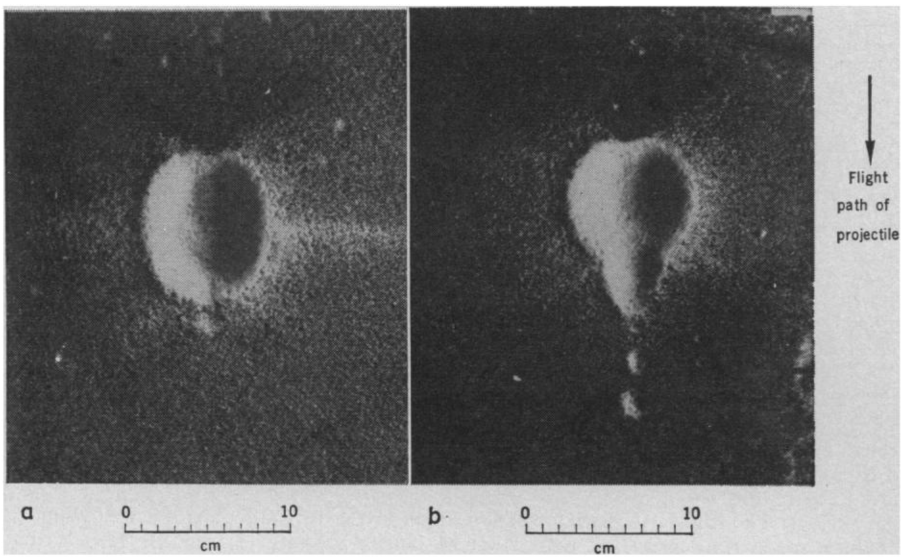



Fig. 1. Photographs of experimental craters in sand illustrating the extremes in morphological forms produced. A thin layer of dyed sand was placed over silica sand to enhance the contrast. Forms range from (a) elliptical craters to (b) doublet craters. Intermediate cases between these extremes were also observed. Note the well-developed side lobes in the ejecta surrounding the craters.

A powder gun mounted in a range capable of being evacuated to 10 torr was used to launch pellets at velocities near 1.7 km/sec. The pellets were polyethylene spheres 6.35 mm in diameter (specific gravity, 0.97) supported in plastic holders during launch and plastic cups 7.63 mm in diameter that fitted the gun bore. The pellets impacted the surface of a box 50 by 30 by 20 cm deep filled with a uniform, air-dried, cohesionless silica sand. This sand had a range of grain size of 0.15 to 0.63 mm and a uniformity coefficient of 2.0. The bulk specific gravity of the sand used for the tests was $1.60 \pm 0.03$. The acoustic velocity was not measured but is inferred to be less than 0.2 km/sec (*3*). Prior to each shot, the surface was carefully leveled and the whole box was canted to the desired impact angle. A layer of dyed sand 1 mm thick was placed over the surface to improve crater contrast and visualization of ejecta patterns.

In addition to impact velocity, we measured the final dimensions of the crater, the trajectory of ejecta, and pellet motion during and after impact. Sheets of graph paper fastened to plywood were mounted perpendicular to the sand surface downrange from the impact point in order that energetic ejecta patterns might be recorded. Individual sand grains either lodged in the paper or perforated it as did the ricocheting pellet. Stereoscopic photographs of craters were taken after each impact. Two high-speed cinecameras were used to observe several of the impacts. One operating at $5 \times 10^5$ frame/sec was used to analyze the motion of the pellet during and after impact. A somewhat slower camera (18,000 frame/sec) was used to observe the formation of the ejecta plume.

Five shots were fired in this experiment. Shallow craters were produced in each shot but the shape varied from elliptical craters (Fig. 1a) typically with a length-width-depth ratio of 10 : 7 : 1 to the doublet crater form (Fig. 1b).

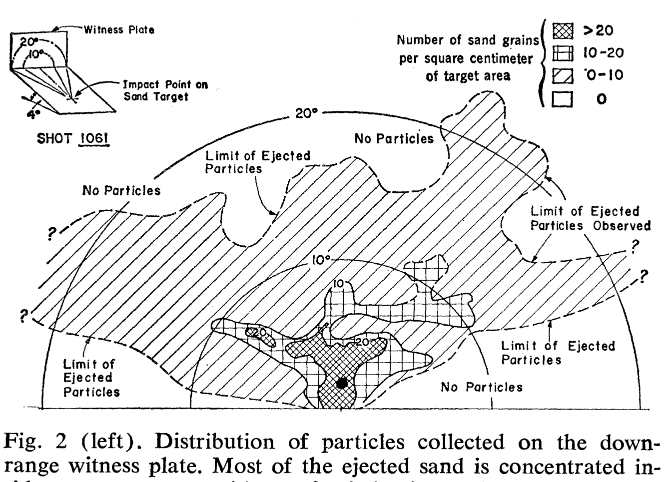
Distribution of ejecta from most craters showed distinctly well-developed side lobes and very well-developed downrange or front lobes. Projectiles did not disintegrate on impact; instead, they ricocheted off the target after penetrating only slightly. Careful measurements of the exit velocities of the projectiles were made on two shots. After impact the velocity of the projectile was reduced approximately 7 percent and the exit angle was 2.4° from the target surface. The first observable sand particles in the ejecta plume are ejected nearly parallel to the surface and at velocities less than the projectile velocity. Only a small amount of ejecta, undetectable in these photographs, could leave the target at velocities greater than the exit velocity of the projectile and most of it leaves with velocities significantly less. As the crater evolves, the ejecta velocity decreases and the ejection angle increases, both monotonically. In the sequence photographs, particles are observed at ejection angles up to 14°. Figure 2 shows the distribution of particles on the graph paper witness plate downrange from one crater. Results for other shots were similar. Most of the particles are concentrated in a narrow cone within 10° of an axis in the target surface and parallel to the trace of the trajectory of the projectile on the surface. The highest ejection angle observed in these experiments was about 22°.

The detailed nature of the lunar impact can only be the subject of conjecture and was a function of the local topography, the physical properties of the LM and lunar surface, and the orientation and possibly rotation of the LM. Upon impact, the LM was compressed and probably disintegrated into several fragments during or immediately after the cratering event. The impact must have produced a shock wave in the moon because the impact velocity (1.68 km/sec) exceeded the probable sound speed in the upper few meters of the lunar material. This would be true if the lunar material at the Apollo 12 site is similar to the soil at the Apollo 11 site, that is, if the compressional velocity $V_p = 1.07$ km/sec at zero pressure and $V_p = 1.2$ km/sec at 0.05 kb, equivalent to a depth of about 30 to 40 m (*4*). Hence, the initial stages of cratering took place as a result of the propagation of a weak shock. These conditions are qualitatively similar to those in the sandbox experiment.

Certain lunar craters, such as Messier A, have a doublet shape and strongly directional ray in the direction parallel to the long axis of the crater. It has been suggested (*5*) that low impact angle and low velocity are required to produce such craters, a conclusion supported by our experiment.

Using the LM kinetic energy ($3.6 \times 10^{16}$ ergs), empirical data on explosion and missile impact experiments (*6*), and data for gravity effects on crater size (*7*), we can place upper bounds on the size of the crater produced. Because most of the kinetic energy of the LM was probably carried downrange by ricocheting fragments (hence was not delivered to the target and not expended in cratering), $10^8$ g probably represents an upper limit on displaced mass. Assuming (i) a mean bulk specific gravity of 2, (ii) the observed length, width, and depth ratio (10 : 7 : 1), and (iii) a factor of 1.4 applied to crater radius to account for gravity effects, we suggest an upper limit on crater dimensions of 12.5 by 8.4 by 1 m.

The fragments ejected from the experimental sand target exited at elevation angles less than about 22° at velocities which decrease monotonically from something near projectile exit velocity to some very low value. Our experiments would suggest that, although some lunar material was ejected from the impact site at high velocities, the bulk of the mass was ejected at less than about 1000 m/sec. In the sand experiment ejecta was concentrated within a cone about 10° in radius in the downrange direction. Lunar fragments ejected at 1250 m/sec and 10° would reach the vicinity south of the crater Kepler. Probably material ejected at angles as high as 10° left the target at velocities no greater than about 1000 m/sec, in which case most of the ejecta would be restricted to the vicinity of the craters Lansberg and Kinowski at ranges of 300 to 400 km. Flight time for this debris would not exceed about 400 seconds. A very small mass of target material could have been ejected at very low angle and high velocity (near or in excess of the projectile impact velocity) by jetting. This material might circumnavigate the moon but it probably represents a trivial amount of the total mass and an insignificant amount of kinetic energy.



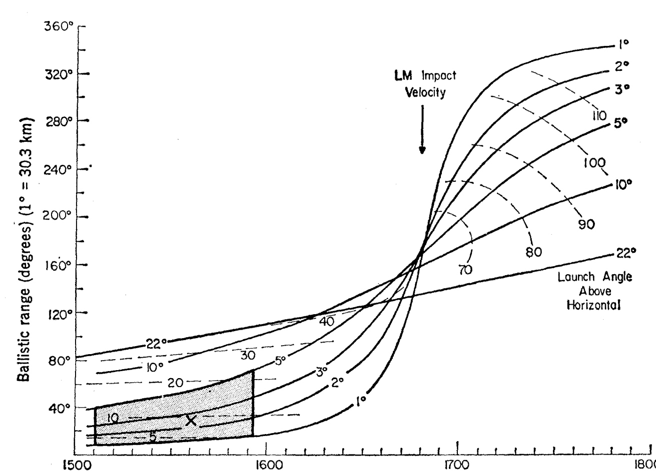




Fig. 2 (left). Distribution of particles collected on the downrange witness plate. Most of the ejected sand is concentrated inside a narrow cone within 10° of the forward trace of the velocity vector of the projectile across the target surface. The highest observed ejection angle in the forward direction was about 22° above the target surface. Fig. 3 (right). Ballistic range (in degrees) as a function of launch velocity for various launch angles with flight time (in minutes) shown in light dashed lines. At launch conditions near the surface orbital velocity (1.68 km/sec), the ballistic range is a very sensitive function of the launch velocity and angle, especially for angles less than about 10°. The initial impact velocity of the LM was 1.68 km/sec. Experimental data would suggest that LM debris was relaunched at approximately 2.4° and 1.56 km/sec. The predicted reimpact point is shown by the X. If LM fragments were scattered between launch angles of 1° to 5° and velocities between 90 and 95 percent of the initial velocity (1.509 and 1.593 km/sec), then they would be dispersed through the crosshatched area, 240 to 2100 km from the impact point.

Fragmental ejecta from the LM impact site which exists at 22° (with an initial velocity of about 400 m/sec) would impact in the vicinity of the ALSEP seismometer about 200 seconds after initial impact. Even with a larger ejection angle of 30° and an initial exit velocity of 370 m/sec the time to impact would be only 220 seconds. This can be considered an upper bound on time-of-flight of rock debris ballistically raining down near the ALSEP and clearly is not sufficient to account for the extended seismic signal.

In our laboratory experiment the projectiles bounded off the surface at low angles after slight penetration with their velocities reduced by about 7 percent. The LM, unlike the plastic projectiles, was a lumpy distribution of relatively weakly bound masses. It almost certainly fragmented upon impact but some components probably remained intact. In the absence of better data, we may speculate that the exit velocities and angles of the debris scattered around those values observed in our experiment. Clearly, in this speculation we ignore the possible important effects of local topography and possibly significant violations of similitude. However, if our speculation is approximately correct, the LM debris ricocheted with a velocity of 1.56 km/sec at an angle about 2.4° above the horizontal. The LM fragments launched under these conditions would impact at 29° (880 km) away at a point southwest of the Marius Hills with a flight time of about 9.8 minutes. However, if the rebound velocity and angle of the LM debris were scattered around 1.56 km/sec and 2.4°, respectively, this scatter would have important consequences on the distribution of the LM debris over the lunar surface because of the sensitivity of ballistic range to launch angle and velocity at conditions near orbital velocity (1.68 km/sec) (Fig. 3). If we assume that elevation angles were scattered between 1° and 5°, and the launch velocities between 1.509 and 1.593 km/sec (90 and 95 percent of the impact velocity, respectively), the resulting impact sites are dispersed westward across the moon between 8° (240 km) and 70° (2100 km) from the impact site near Fra Mauro (Fig. 4). The impacts would occur between about 3 and 22 minutes after the original impact.

Because the conditions upon reimpact are so similar to the initial conditions, at least part of the debris probably rebounded, forming a cascade of LM fragments across the moon. The duration of such a cascade depends on the launch angles and velocities, but the range and flight times diminish rapidly when velocity falls much below the orbital velocity (see Fig. 3). A cascade would quickly die out after a few repeated impacts but could last perhaps an hour. Since the ballistic calculations suggest impacts extending to the topographically rough upland terrain on the lunar backside, the likelihood of a large-scale cascade is probably low.

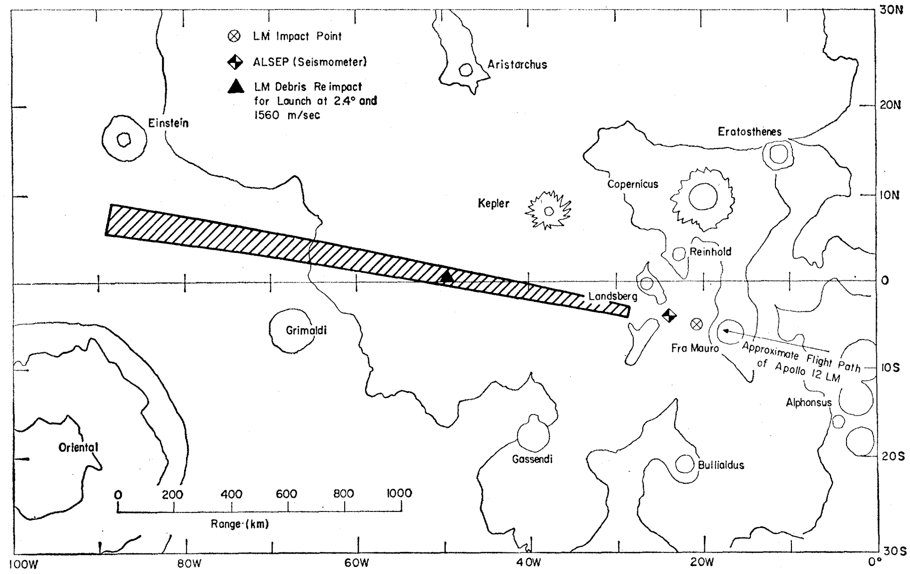



Fig. 4. Schematic diagram showing the inferred downrange distribution of LM fragments (crosshatched area) resulting from the impact of the Apollo 12 LM northwest of the crater Fra Mauro. The LM fragments reimpacting at 2100 km (south of the crater Einstein) would have flight times of about 22 minutes and kinetic energies capable of producing (directly) only a marginally detectable seismic signal (under optimum assumed conditions). Most of the rock fragments ejected from the lunar surface probably reimpacted in a pie-shaped area in the downrange direction at distances less than about 300 km, although a very small amount of target rock, ejected at low angle and high velocity, possibly could have attained circumlunar ranges. The duration of a ballistic rain of lunar rock falling on or very near the ALSEP would not have exceeded 4 minutes from the initial impact of the LM if forward-flying ejecta was concentrated at low angles as in the experiments (see Fig. 2).

The detectability of a seismic signal produced by an impact depends on the sensitivity of the instrument, the efficiency of the mechanical coupling between the projectile and the target, and the attenuation of seismic waves in the lunar interior. For fairly efficient coupling [for example, if the seismic impulse contained about $3 \times 10^{-5}$ times the initial kinetic energy of impact (*8*)], and a low attenuation of seismic waves in the lunar interior (a specific seismic attenuation coefficient $Q$ of 500), it appears that the Apollo 12 LM impact ($3.6 \times 10^{16}$ ergs) could not be detected directly beyond about 1000 km, if we assume the published estimate for the sensitivity of the ALSEP seismometer (*9*). We conclude that the scattered reimpacts of LM fragments probably produced signals at or very near the sensitivity limit of the instrument. However, if they served as a triggering mechanism for downrange geological processes, such as landslides, then they might contribute in an important way to the generation of the seismic signal recorded. The large number of subsequently recorded, similar seismic events, however, substantially weakens the case in support of a ballistic hypothesis to account for the Apollo 12 seismogram.

We suggest: (i) Low-angle, low-velocity impacts may be responsible for the formation of elliptical and doublet craters on the moon. (ii) The Apollo 12 LM may have bounded off the lunar surface after impact, probably in pieces at somewhat less than 1.6 km/sec and at a low angle of about 2.5°. Fragments ejected under these conditions would impact 29° (880 km) away in Oceanus Procellarum, southwest of Kepler, just under 10 minutes later. (iii) Because ballistic range near orbital velocity is such a sensitive function of the launch conditions, a very small scatter in angle and velocity would spread the LM debris for a large distance along the orbital path, perhaps to the west limb or even onto the backside. (iv) Experiments suggest that fragments ejected from the crater probably exited at relatively low velocity. If so, this debris would be restricted to a range of less than a few hundred kilometers from the impact site in a narrow forward path about 20° wide containing the Apollo 12 ALSEP. A very small amount of ejecta launched at very low angle and high velocity by jetting in the early stages of cratering could reach the backside or could even orbit. (v) In the experiment forward-flying debris was restricted to angles below 22° above the horizontal; hence flight time for ejected lunar material raining down near the ALSEP and therefore directly detectable by the seismometer probably did not exceed 3 or 4 minutes. (vi) It is unlikely that impacts of LM fragments were detected *directly* by the ALSEP seismometer because these fragments lack sufficient kinetic energy upon reimpact. (vii) These impacts, however, could trigger distant geological events such as landslides and thereby introduce unknown ambiguities into seismic experiments. Such may have occurred in the impact of the Apollo 12 LM. (viii) The deliberate low-angle impact of spacecraft on the lunar surface may create a serious hazard to men and instruments on and near the lunar surface in the downrange direction.

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10. The idea for this project resulted from an informal seminar at M.I.T. in December 1969 on the early results of the Apollo 12 seismic experiment. Work supported by the Research Institute of the University of Dayton and by funds from NASA contract NGR-22-009-123 to M.I.T. We thank the staff of the Air Force Materials Laboratory for the use of their facilities and gratefully acknowledge the support of W. C. Turpin during the experiments and the encouragement and interest of F. Press and N. Toksöz.

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## Isopod from the Pennsylvanian of Illinois

Abstract. Hesslerella shermani *is described as the oldest representative of the crustacean superorder Peracarida, order Isopoda, suborder Phreatoicidea. This description is based on a single specimen of exceptional preservation from the Middle Pennsylvanian of Illinois. The existence of isopods in the Pennsylvanian raises some questions concerning peracarid and eumalocostracan evolution.*

The Essex fauna, a marine facies of the Mazon Creek area of northeastern Illinois, is affording us an exceptional look at life in the Middle Pennsylvanian (*1*). An extensive array of Crustacea from this locality has already yielded significant information which permits new insights into an understanding of crustacean evolution (*2*).

Some years ago Levi Sherman of Des Plaines, Illinois, collected a small concretion 21 mm in diameter. Recently, while taking a census of Sherman's collection of Mazon Creek fossils, I examined this concretion under a microscope and found it to have a phreatoicid isopod preserved in near-perfect condition, exceptional even for the Mazon Creek area. This is the earliest known, definite fossil peracarid. Because of its specialized nature, it forces us to reconsider the evolution of the Peracarida and the Eumalacostraca as a whole (*3*).

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|---|---|
| Phylum | Arthropoda |
| Superclass | Crustacea |
| Class | Malacostraca |
| Subclass | Eumalacostraca |
| Superorder | Peracarida |
| Order | Isopoda |
| Suborder | Phreatoicidea |

Family Paleophreatoicidae, Birshtein 1962

*Hesslerella*, new genus

*Type-species*: *Hesslerella shermani*, new species. The characteristics of the genus are the same as those of the species.

*Hesslerella shermani*, new species

*Holotype*: Number PE 16527 in the fossil invertebrate collections of the Field Museum of Natural History, Chicago, a single half of a small ironstone concretion (Fig. 1).

Fig. 1. Holotype of *Hesslerella shermani*, PE 16527 in the fossil invertebrate collections of the Field Museum of Natural History, Chicago. Specimen is 11 mm long from head to tip of pleotelson.