**MODELLING THE IMPACT EJECTION OF LOW-PRESSURE MATERIAL FROM EARTH TO THE MOON.** S. H. Halim[1] (shalim03@mail.bbk.ac.uk), I. A. Crawford[1], G. S. Collins[2], K. H. Joy[3], T. M. Davison[2]. [1]Birkbeck, University of London, UK. [2]Imperial College London, UK. [3]University of Manchester, UK.

**Introduction:** The rich impact history of the Solar System has allowed for the transfer of material between many planetary bodies via ejection after hypervelocity impacts. Evidence for such transfers include martian and lunar meteorites found on Earth, which points to the possibility of finding material from Earth on other planetary surfaces, most likely on our nearest celestial neighbour, the Moon. Basin-forming, hypervelocity impacts striking Earth [1] could potentially eject terrestrial material at velocities great enough to surpass escape velocity and take up Moon-crossing orbits [2, 3]. The transfer efficiency of Earth-escaping ejecta from large terrestrial impacts to the Moon has been estimated between $10^{-5}$ to $10^{-4}$ of the original escaping mass and in some regions of the lunar surface, as much as 510 kg km$^{-2}$ of terrestrial material may have impacted in the period since 3.9 Ga [4]. Ejected terrestrial material experiencing low-shock pressures (<10 GPa) after impact may allow for the survival and transfer of organic or biological markers (biomarkers) from ancient Earth to the Moon [5]. Theoretical estimates using extrapolation of an analytical model of spallation [6, 7] suggest that a mass of ejecta equivalent to as much as $10^{-5}$ to $10^{-2}$ of the original impactor's mass ($M_i$) may escape Earth's gravity without exceeding a shock pressure of 10 GPa [2]. On the other hand, shock physics simulations of several Chicxulub-scale impact scenarios did not resolve any material ejected at escape velocity that was not shocked beyond the level likely to destroy entrained biomarkers [8, 9]. However, these simulations used a relatively low spatial resolution, with the results only tabulated in fractions of ~$10^{-3}$ $M_i$. Here, we present high-resolution, 3D simulations that resolve the fraction of ejecta with both high speed and low pressure, to show that low-shock ejection is possible from Earth.

**Methods:** We used the iSALE-3D shock physics code [10, 11] to simulate the high-speed ejection of terrestrial material via a basin-forming impact on Earth. We simulated a 50 km diameter projectile striking Earth at angles of 30°, 45°, and 60° to the surface (assumed to be horizontal) and at velocities of 20, 30, and 55 km s$^{-1}$. This impactor size is representative of Chicxulub-scale impacts on the Earth [8, 9] and sufficiently large (greater than Earth's atmospheric scale height) that the influence of the atmosphere on the impactor and high-speed ejecta fragments is assumed to be negligible. Therefore, no atmosphere was considered in the simulation. Whilst the most common values for asteroid impacts on Earth are 20 km s$^{-1}$ and 45° [12, 13], we also considered impacts for faster projectiles, such as short and long-period comets (av. 30 and 55 km s$^{-1}$ respectively [14, 15]). Angles of impact were varied to investigate any change in the proportion and location of ejected material. We used the semi-analytical equation of state (ANEOS, [16]) for dry granite to represent both impactor and target with input parameters derived by [17]. The same material models were used in every scenario, no ice was included for the simulations with cometary-like velocities. The strength of the material was modelled using the method described by [18] with parameters from [19]. Simulations were run at a high resolution of 100 cells per projectile radius (CPPR) to adequately resolve low-pressure, high-velocity ejected material. Launch speed and peak pressure of ejecta were recorded by tracer particles placed in each cell. An ejection velocity threshold of 11 km s$^{-1}$ was used as an estimate for the launch speed needed to reach a Moon crossing orbit.

**Results & Discussion:** Of the scenarios considered, only those with an impact angle of 30° resulted in escaping ejecta that experienced pressures <10 GPa. The mass of low-pressure escaping ejecta decreased with increasing impact velocity (Table 1). Additionally, increasing impact angles to 45° leads to higher pressures at every velocity, with material experiencing pressures of at least 30 GPa at 20 and 30 km s$^{-1}$ and over 50 GPa at 55 km s$^{-1}$. At 60°, minimum pressures of ejected material exceed 50 GPa at every velocity tested. The mass of low-pressure, high-velocity material ejected is on the order of $10^{-4}$ to $10^{-5}$ $M_i$, depending on the impact

***Table 1**: Mass of terrestrial material ejected at velocities >11 km s$^{-1}$ (as a proportion of impactor mass, $M_i$) with peak pressures less than the specified thresholds.*

| Simulation | Mass ejected ($M_i$) reaching >11 km s$^{-1}$ | | |
|---|---|---|---|
| | <10 GPa | <30 GPa | <50 GPa |
| 20 km s$^{-1}$, 30° | $1.68\times10^{-4}$ | $9.57\times10^{-4}$ | $5.96\times10^{-3}$ |
| 20 km s$^{-1}$, 45° | 0 | 0 | $9.33\times10^{-4}$ |
| 20 km s$^{-1}$, 60° | 0 | 0 | 0 |
| 30 km s$^{-1}$, 30° | $1.29\times10^{-4}$ | $1.17\times10^{-3}$ | $6.65\times10^{-3}$ |
| 30 km s$^{-1}$, 45° | 0 | 0 | $9.22\times10^{-4}$ |
| 30 km s$^{-1}$, 60° | 0 | 0 | 0 |
| 55 km s$^{-1}$, 30° | $1.44\times10^{-5}$ | $5.37\times10^{-5}$ | $1.26\times10^{-5}$ |
| 55 km s$^{-1}$, 45° | 0 | 0 | 0 |
| 55 km s$^{-1}$, 60° | 0 | 0 | 0 |

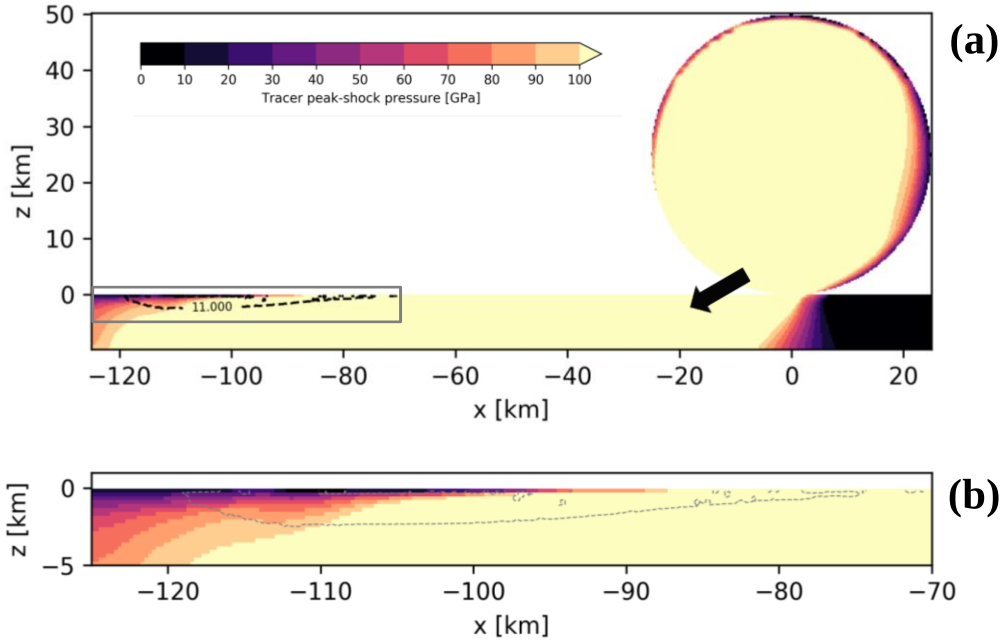


***Figure 1**: Cross section provenance plot of high-speed ejecta that experiences different peak shock pressures for a simulation of a 50 km diameter impactor striking Earth at 30° to the surface and at 20 km s$^{-1}$. The low-pressure zone from (a) is highlighted in (b), shown in the highlighted box. The direction of impact is from right to left (black arrow). Dashed lines show the extent of volume of target ejected at >11 km s$^{-1}$.*

conditions, consistent with prior estimates [6, 7]. In the simulation with the largest mass of low-pressure material ($1.68\times10^{-4}$ $M_i$: 20 km s$^{-1}$, 30°), ejected material originates from the near-surface, over 100 km from the impact zone (Figure 1).

The clear favourability of low-pressure ejecta at more oblique impact angles may be a consequence of a process called 'post-shock acceleration' [20]. Sustained compression in the target produces a gradual acceleration with less shock, alongside higher acceleration efficiency in oblique impacts compared to vertical. Higher spatial resolution models could provide additional evidence for larger masses of low-pressure ejecta, as resolution tests as resolution tests show that 100 cppr is not sufficient to resolve small fractions of low-shock, high-speed ejecta in some scenarios [5]. Additionally, targets with a weaker or lower density layer atop a stronger or denser layer may amplify the mass ejected at high speed as has been shown to be the case for regolith layers on Mars [21]. The influence of a top layer of water could also be explored.

**Conclusions:** We show that high-resolution, 3D simulations of projectiles impacting Earth at 20 km s$^{-1}$ with low impact angles (30°) can produce low-shock pressure material (<10 GPa) ejected at speeds fast enough (>11 km s$^{-1}$) to reach Moon-crossing orbits. This material, if it landed and was found on the Moon as terrestrial meteorites, could provide a window to the Archean Earth's environment that we no longer have on Earth itself [2-5, 22].

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