HYDROCODE MODELING OF THE MATERIAL EJECTION BY SPALLATION. K. Kurosawa¹, T. Oka-
moto, and H. Genda², ¹Planetary Exploration Research Center, Chiba Institute of Technology (2-17-1, Tsudanuma,
Narashino, Chiba 275-0016, Japan, E-mail: kosuke.kurosawa@perc.it-chiba.ac.jp), ²Earth-Life Science Institute,
Tokyo Institute of Technology (2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan).

Introduction: Impact ejection is one of the most important processes on the material exchange between
two planetary bodies [e.g., 1-4]. A process referred to
as spallation is one of the most likely mechanism to
explain the launch of the lightly-shocked rocks from
Mars [1-4]. Geochemical and petrological analyses of
the Martian meteorites showed that they suffer a shock
pressure ranged from 30 to 50 GPa [e.g., 3]. In addition,
they must be accelerated to > 5 km/s, which is the
escape velocity of Mars.

In 1980’s, a simple analytic model was proposed to
understand the mechanism of the generation of the
high-speed lightly-shocked ejecta [1]. However, it
cannot be applied directly to the ejecta at a velocity
higher than 1 km/s pointed out by [1] himself because
the analytic solution could be obtained with a too simple
EOS model. Numerical models have been de-
veloped to include a realistic EOS model to describe hy-
drodynamic and thermodynamic response of geologic
materials at the nearest-neighbor of the impact point [3,
4]. They demonstrated that the spallation process can
explain the acceleration of the surface materials up
to 5 km/s.

Numerical model: In this study, we revisited the
spallation during vertical impacts to flat targets to ob-
tain a basic understanding the acceleration processes in
an impact-driven flow field [7]. The effect of the shock
smearing near the free surface on the ejection behavior
was carefully investigated by conducting numerical
calculations with different spatial resolutions. To in-
vestigate the inter-code variability, the two-
dimensional version of the iSALE shock physics code
[e.g., 8-10], called to as iSALE-Dellen [11], and a
three-dimensional Smoothed-Particle-Hydrodynamics
code [12] were used. Since the space is highly limited,
we present the results from the iSALE calculations in
this abstract. The entire result will be presented in [7].

Global setup: We numerically calculated a vertical
impact of a sphere projectile with the radius \( R_p = 10 \)
km onto a flat target, a cylinder or a half sphere with a
radius of 1.5-3 \( R_p \). The Tillotson equation of state
(EOS) [13] the parameters for granite [14] was used
for both a projectile and a target. We ignored material
strength and gravity. We set the time to be \( t = 0 \) at the
initial contact between the projectile and the target,
and performed the simulations until \( t = 1.4 \ t_s \), where \( t_s \)
is the characteristic time for projectile penetration de-
finite to be \( t_s = D_p/v_{impact} \), where \( D_p \) and \( v_{impact} \)
are the projectile diameter and impact velocity, respectively.
The calculation time is enough to investigate the eje-
ction behavior of the target materials in the vicinity of
the impact point at ejection velocity higher than 0.1-
0.2 \( v_{impact} \). The von Neumann-Richtmyer artificial vis-
cosity [15] was introduced into both the iSALE and the
SPH calculations with the same parameter. The impact
velocity was set to 6-21 km/s.

iSALE-2D (A grid-based hydrocode): A cylindrical
coordinate was employed. The projectile radius \( R_p \)
divided into 125-2000 cells per projectile radius
(CPPR, \( n_{CPPR} \)). Lagrangian tracer particles were insert-
ed into each computational cell to analysis the change
in the position, particle velocity, and pressure.

Results: The particles in the condensed phase de-
termined by the Tillotson EOS were extracted.

Resolution effect: We investigated the effects of the
shock smearing due to the artificial viscosity using the
results with a wide range of \( n_{CPPR} \). We confirmed that
the relation between ejection velocity \( v_{eject} \) and the peak
pressure \( P_{peak} \) of the tracers converges into the same
value if we choose the tracer particles initially placed
>5 cells, which is roughly twice of the full width at the
half maximum of the shock smearing in the iSALE
[16], beneath the target surface.

Figure 1. (a) A snapshot of the iSALE calculation at \( t = 0.4 \ t_s \), (b) The time variation of the particle velocity \( u_p \),
(left Y axis) and pressure \( P \) (right Y axis) of the select-
ed tracers. The escape velocity of Mars \( v_{escape} = u_p \sqrt{\frac{2}{\mu}} \), and \( \sqrt{\frac{2}{\mu}} u_p \) of the selected tracer are also shown.
**Snapshot:** Figure 1a shows a close-up of an ejecta curtain at 12 km/s, which is a typical impact velocity onto Mars, at $t = 0.4t_{c}$. The trajectories of tracer particles and their velocity vectors are also shown. Figure 1b shows the time variation of the particle velocity $u_{p}$ and pressure $P$ of the selected tracers.

The $v_{eject} - P_{peak}$ relation: The particle velocity was stored to be the $v_{eject}$ at the time when the height from the target surface of each particle exceeded a given height, that is defined as 0.1 $R_{p}$ in this study. Figure 2 shows the ejection velocities $v_{eject}$ as a function of experienced peak pressures $P_{peak}$ and the initial depth. The particle velocity $u_{p0}$ determined by the Rankine-Hugoniot relation and $\sqrt{2}u_{ph}$, which is the maximum particle velocity obtained during a shock-release consequence [7], are also shown. The red hatched region indicates the criteria of the launch of the martian meteorites, i.e., $v_{eject} > 5$ km/s and $P_{peak} = 30-50$ GPa. Our hydrocode calculations clearly show that the spallation can explain the material ejection from the martian surface into the space.

**Conclusions:** We investigated the spallation process during vertical impacts in detail using the iSALE. The late-stage acceleration is expected to play an important role to produce a high-speed lightly shocked ejecta, such as the martian meteorites.

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