HYDROCODE MODELING OF THE MATERIAL EJECTION BY SPALLATION. K. Kurosawa[1], T. Okamoto, and H. Genda[2], [1]Planetary 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), [2]Earth-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 developed to include a realistic EOS model to describe hydrodynamic 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 launch of the surface rocks from Mars. An ejection behavior from a shock compression to an adiabatic expansion in detail, however, has not been investigated well. Especially, [5] and [6] argued that the obtained-low-peak shock pressure in the numerical model is an artifact by an artificial viscosity, which is necessary to capture shock waves in hydrocodes. Thus, an in-depth analysis is necessary whether the spallation 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 obtain 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 investigate 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 defined 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 ejection 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 viscosity [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 was divided into 125-2000 cells per projectile radius (CPPR, n_{CPPR}). Lagrangian tracer particles were inserted into each computational cell to analysis the change in the position, particle velocity, and pressure.

Results: The particles in the condensed phase determined 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.

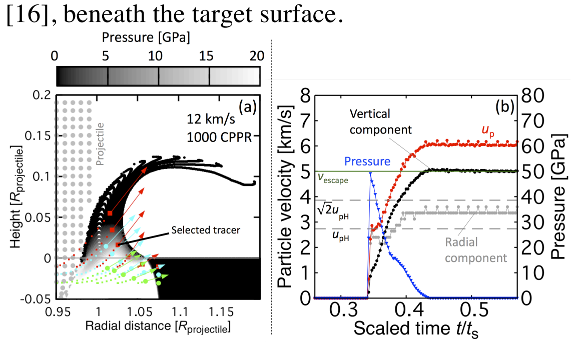

Figure 1. (a) A snapshot of the iSALE calculation at t = 0.4 t_s (b) The time variation of the particle velocity u_p (left Y axis) and pressure P (right Y axis) of the selected tracers. The escape velocity of Mars v_{escape}, u_{pH}, and $\sqrt{2}u_{pH}$ of the selected tracer are also shown.

Snapshot: Figure 1a shows a close-up of an ejecta curtain at 12 km/s, which is a typical impact velocity onto Mars, at $t = 0.4t_s$. 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_{pH} 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.

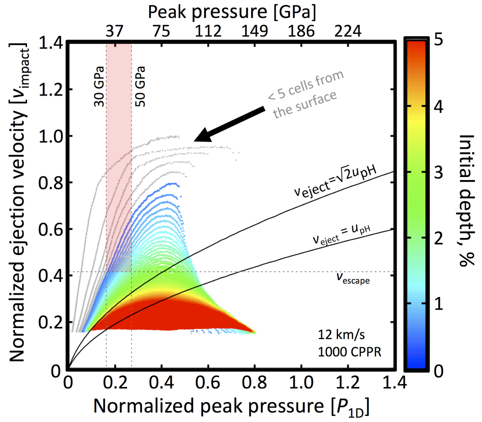

Figure 2. The ejection velocities of tracers as a function of the peak pressures. The color indicates the initial depth from the target surface in a percentage with respect to R_p. The escape velocity of Mars v_{escape}, u_{pH}, and $\sqrt{2}u_{pH}$ are also shown.

Late-stage acceleration: We have to address the reason why the ejected materials can obtain such high-speed exceeded the upper limit determined by the shock physics. We newly found that a late-stage acceleration of the shocked materials above the target surface occurs due to the compressive nature of the root of the ejecta curtain (Figures 1ab). The pressure gradient is produced by the difference in the particle velocities at the shocked state depending on the distance from the impact point. The shocked material initially placed at a near/deeper position obtains a highly u_{pH} and extrudes the outside shallower materials (Figure 1a).

The launch position: Figure 3a shows the initial position of the ejected materials in the calculations. The lower part of the target surface, ~2% of R_p, in the vertical direction.

The ejected mass at > 5 km/s: Figure 3b shows the cumulative mass of the ejected materials at > 5 km/s until the end time of the calculation, 1.4 t_s. The mass of the candidates of the Martian meteorites is 0.01-0.1 wt% of the projectile mass.

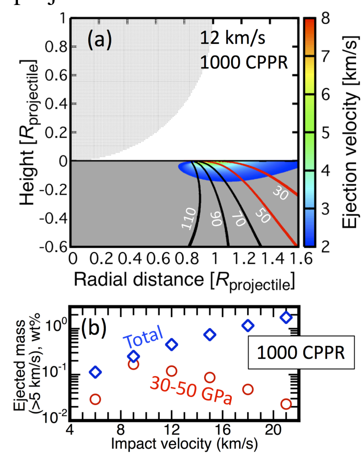

Figure 3. (a) The initial position of the ejecta. The color indicates the ejection velocity. The isolines of the peak pressure in GPa are also shown. (b) The cumulative mass at > 5 km/s as a function of impact velocity.

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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References: [1] Melosh, H. J. (1984) *Icarus*, **59**, 234. [2] Vickery A. M. and Melosh H. J. (1987) *Science*, **237**, 738. [3] Head J. N. et al. (2002) *Science*, **298**, 1752. [4] Artemieva N. and Ivanov B. (2004) *Icarus*, **171**, 84. [5] DeCarli P. S. et al. (2007) *AIP Conf. Proc.*, **955**, 1371. [6] DeCarli P. S. (2013) *Proc. Eng.*, **58**, 570. [7] Kurosawa K. et al., to be submitted. [8] Amsden A. A., et al. (1980) *LANL Report* LA-8095. 101 p. [9] Ivanov B. A., et al. (1997), *IJIE*, **20**, 411. [10] Wünnemann, K., et al. (2006), *Icarus*, **180**, 514. [11] Collins G. S. et al. (2016) *iSALE-Dellen manual: figshare*,https://dx.doi.org/10.6084/m9.figshare.3473690.v2. [12] Genda H. et al. (2012) *ApJ*, **744**, 137. [13] Tillotson, J. H. (1962), *Technical Report GA-3216*, General Atomic Report. [14] Allen R. T. (1967) General Dynamics Report #GA MD-7834. [15] Monaghan J. J. (1992) *Annu. Rev. Astron. Astrophys.*, **30**, 543. [16] Johnson B. C. et al. (2014) *Icarus*, **238**, 12.