Phase transitions in low-velocity impact phenomena

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Motivation

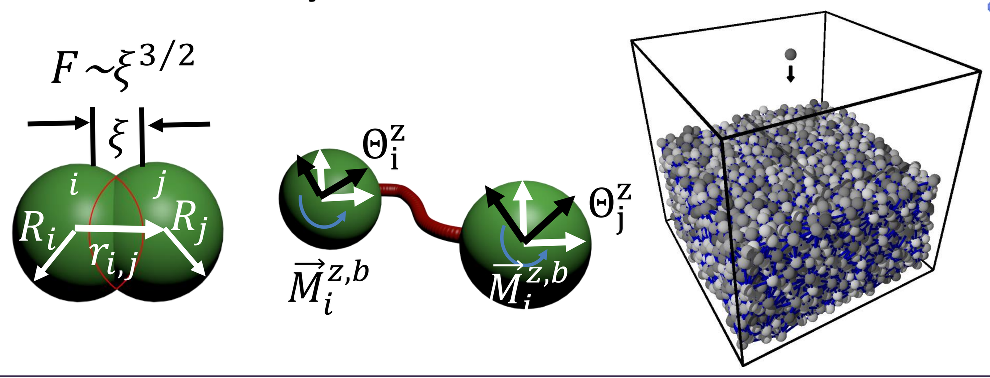
The instantaneous dynamic fragmentation of heterogeneous materials is abundant in nature (asteroid collision, volcanic eruption), and has many industrial applications as well [1].
Repeated subcritical impacts cause the shape evolution of river pebbles. Due to these abrasion and spallation processes, pebble shapes become smoother and rounder during the size reduction [2].

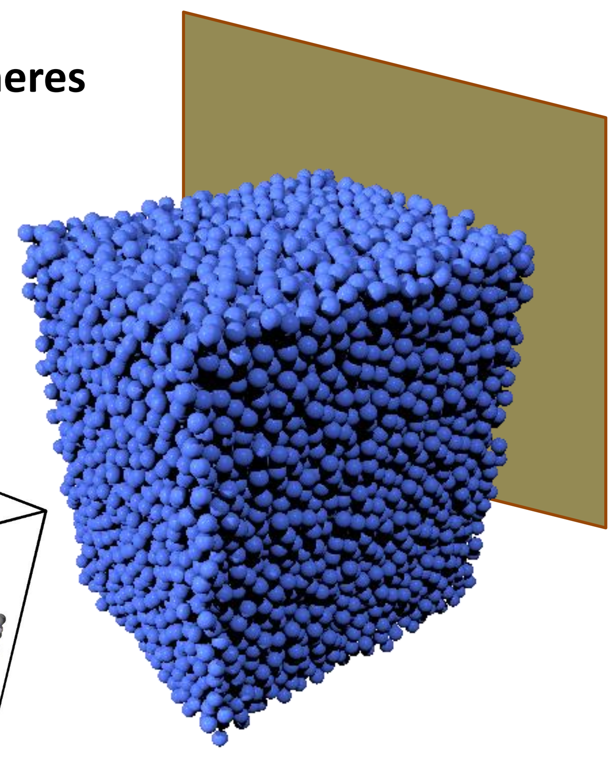
Top. Stone mine explosion emitting rocks.
Bottom: shape of river pebbles.

Model construction

We investigate the subcritical fragmentation of heterogeneous materials due to **repeated impacts** by mean of the **Discrete Element Method** (DEM) [3-8].

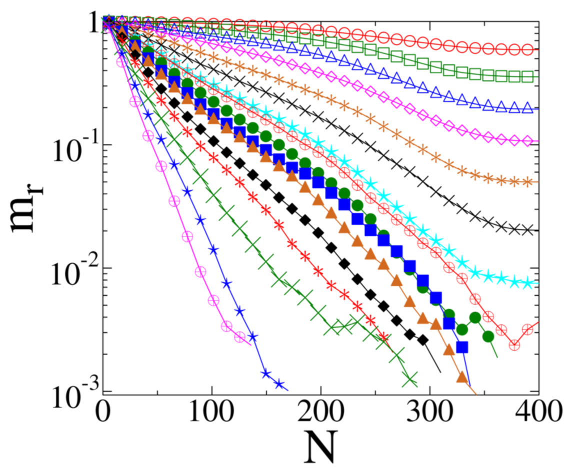
- Cubic samples with aspect ratio 1:1.2:1.4.
- Random homogeneous packing of **elastic spheres**
- **Hertz-contact** between overlapping spheres
- Cohesion is represented by elastic beams.
- Beams excert forces and torques.
- Broken beams form **cracks**
- Repeated impact against a hard wall
- **Molecular dynamic simulation**

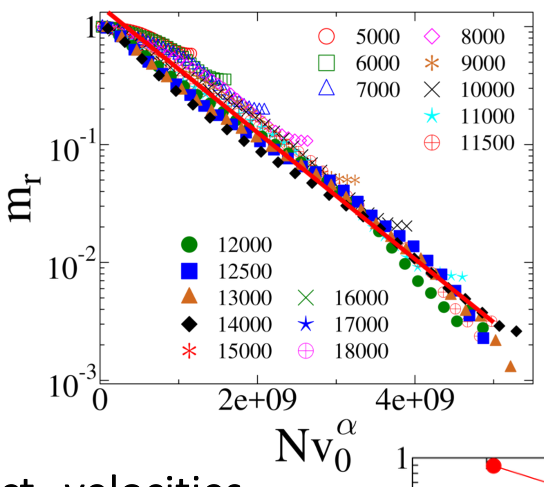




Mass reduction in repeated impacts

Simulations revealed the **existence of a new critical point v_c** separating two qualitatively different behaviours:





Basquin-law of **fragment lifetime N_c**

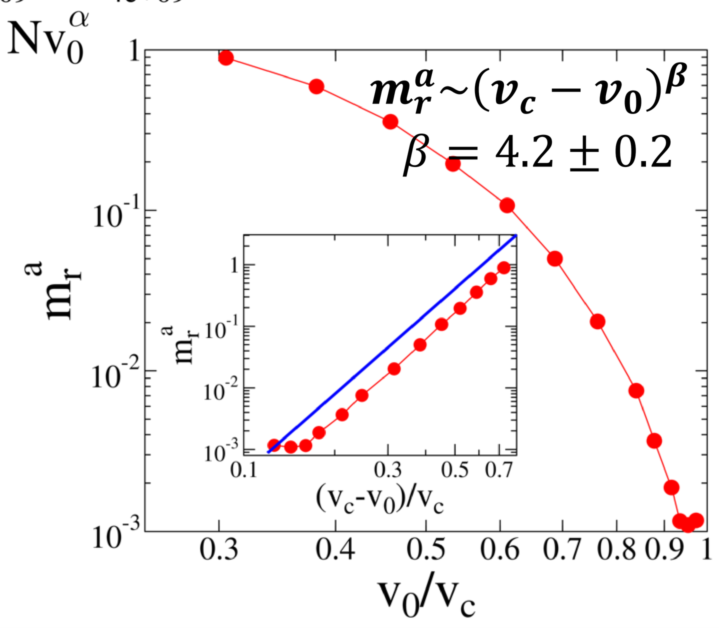
$$m_r(N, v_0) \sim exp(-Nv_0^\alpha)$$

$$N_c \sim v_0^{-\alpha}$$

$$\alpha = 2.1 \pm 0.15$$

- **Abrasion**: For low impact velocities $v_0 < v_c$ a **finite residual mass** is obtained $m_r^a > 0$
- **Cleavage**: For high velocities $v_0 > v_c$ **complete destruction** occurs with $m_r^a \to 0$

Residual mass m_r^a behaves as the order parameter of the abrasion-cleavage phase transition



Phase diagram of impact induced breakup

Depending on the collision energy, the **fragmentation** process **has three distinct phases** separated by two critical velocities v_c and v_f:

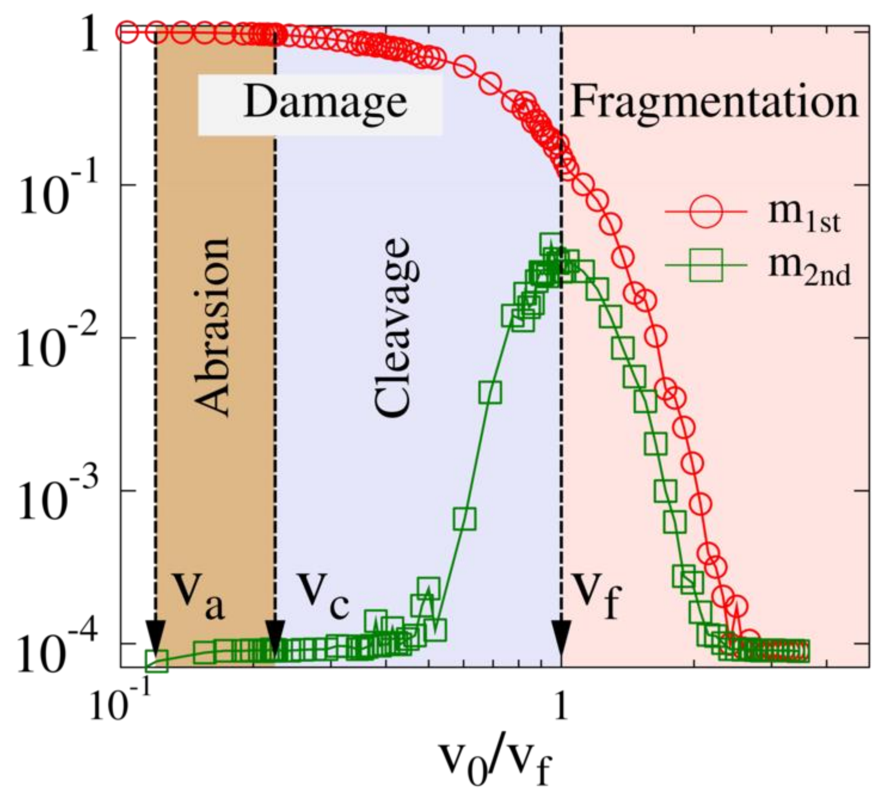


Figure: The mass of the largest and second largest fragments as a function of impact velocity.

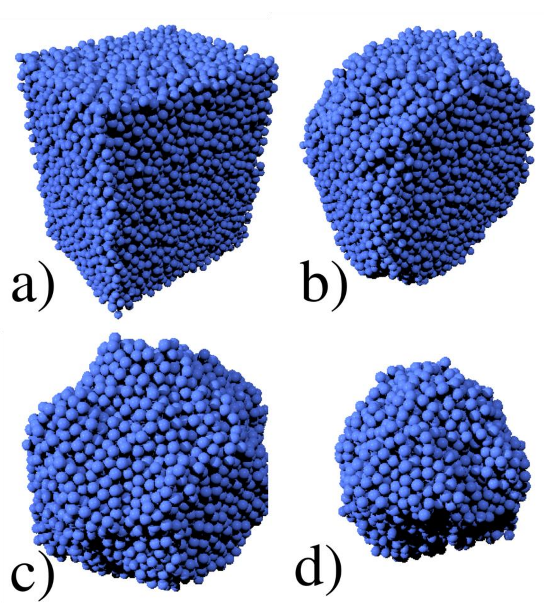
- **Fragmentation**: instantaneous breakup at high impact velocities. $v_0 > v_f$
- **Cleavage**: contact damage in single impact, **complete destruction** with repeated impacts. $v_c < v_0 < v_f$, $m_r^a \to 0$
- **Abrasion**: finite residual mass in repeated collisions, $v_a < v_0 < v_c$, $m_r^a > 0$

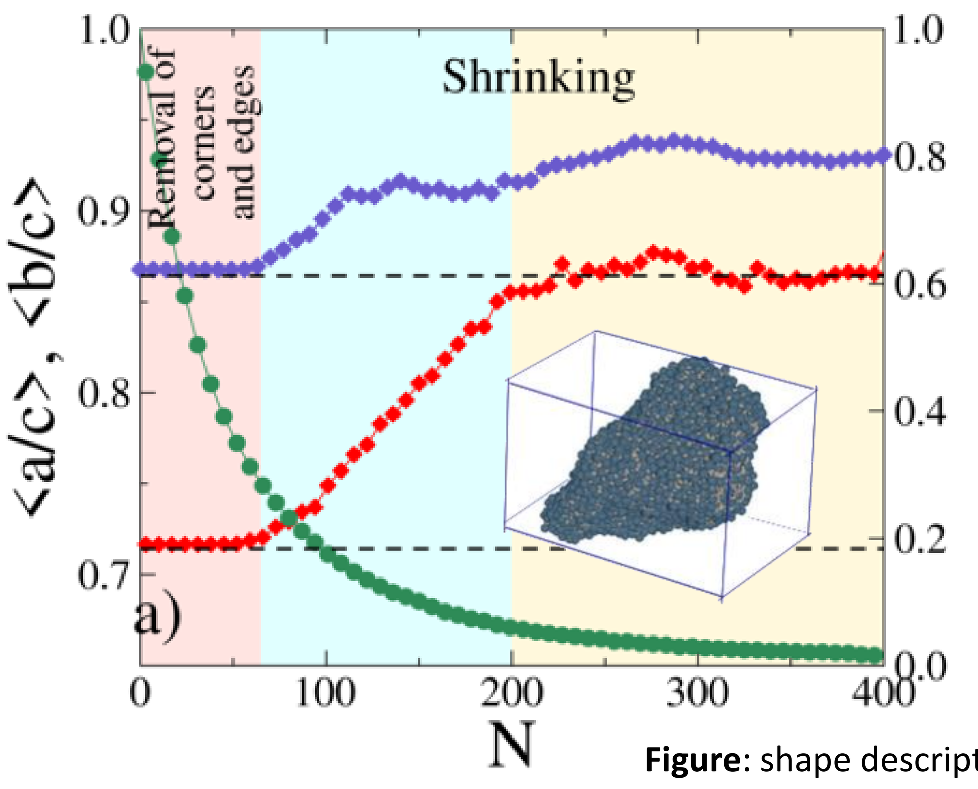
Abrasion is responsible for the **shape evolution** of rocks in nature e.g. the shape of pebbles in riverbeds and sea coasts.

Shape evolution in the abrasion phase

The **stages** of the evolution of the fragment shape:

- $N < N_R$: removal of corners and edges, intact face centers
- $N_R < N < N_S$: rounding and shrinking
- $N_S < N$: shrinking sphere

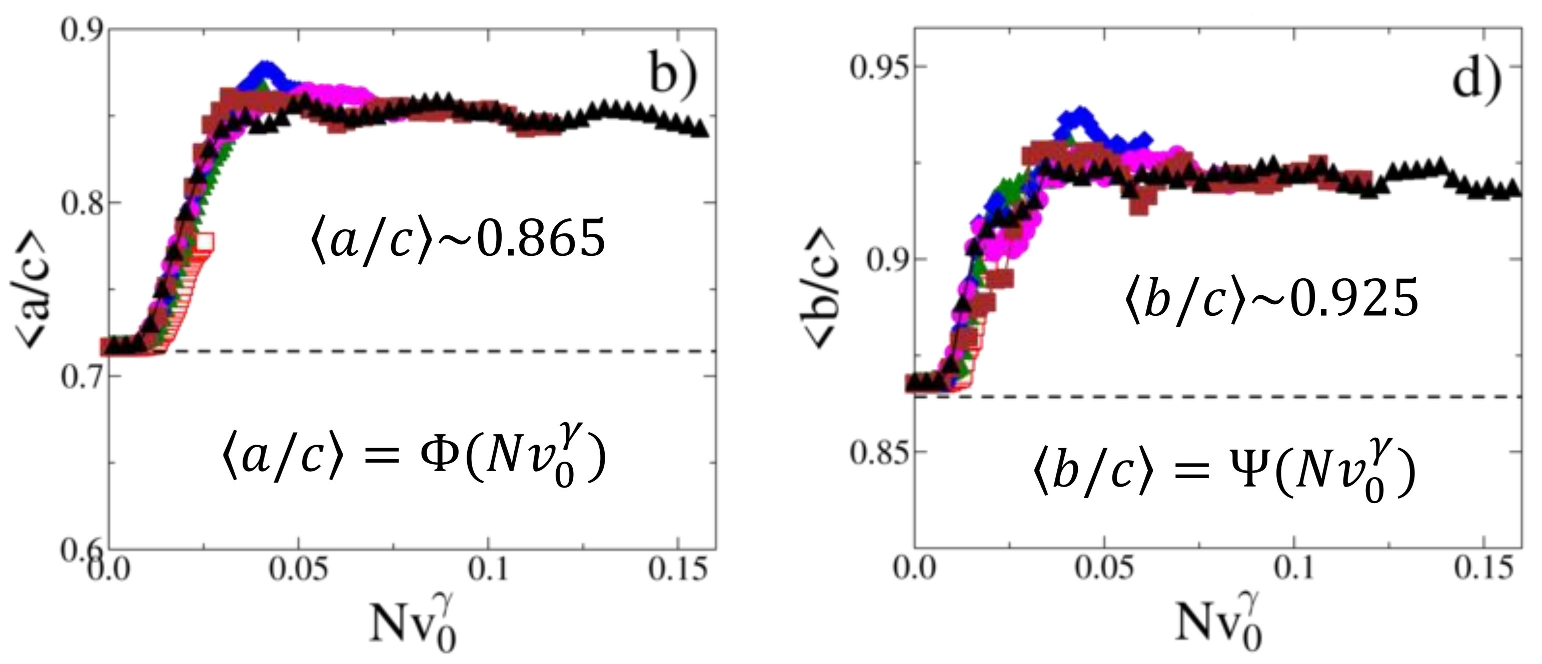




Shape descriptors:
Side length of the bounding box
$a < b < c$
$< a/c >$: Flatness
$< b/c >$: Elongation
c : Linear extension

Figure: shape descriptors as a function of impact number N

Scaling structure of shape evolution



With increasing impact velocity v_0, a faster mass removal indicates an accelerated shape evolution. Rescaling with the γ power of impact velocity, the curves of the side length ratios can be collapsed onto a master curve with good quality. The **characteristic impact numbers N_R** and **N_S** both can be described by a power law of the initial impact velocity.

$$N_R = Av_0^{-\gamma} \qquad N_S = Bv_0^{-\gamma} \qquad \gamma = 3 \pm 0.07$$

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