SNOW COMPACTION DURING THE CHELYABINSK METEORITE FALL

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Introduction

Facts of **Chelyabinsk meteorite** event:
- 20-m-diameter meteoroid
- Break up in an altitude of 40–20 km [1]
- Atmospheric shock waves
- Injuries (mainly by broken windows) and minor damage in local infrastructures

Ground Truth:
- Fragment size of collected meteorites on average 3–6 cm
- Total amount: 4 kg (450 samples) [2]
- Fragments mostly found in funnels in snow (Fig. 1)
- Irregular topology of funnels
- Funnels consist of coarse-grained snow
- Larger fragments:
  - Penetrate 70-cm-thick snow layer
  - Reach frozen ground surface
- Smaller fragments:
  - Got stuck in snow
  - Bottom 15–25 cm: Funnels narrow into a snow filled cone, forming so-called "**snow carrots**" (Fig. 1)
  - Meteorite sits at the tip of the carrots
  - Meteorite is surrounded by a dense shell of equally coarse-grained snow

Goals:
- Constrain initial conditions of fragments prior to penetration into the snow: Mass, Velocity, Temperature
- Quantify penetration into the snow and cone formation

Fig. 1: "Snow carrots". a) and c): The lowest part is shown upside down (with sunglasses for scale); b): Snow carrot in situ (Images courtesy to C.Lorenz).

Deceleration and free-fall time

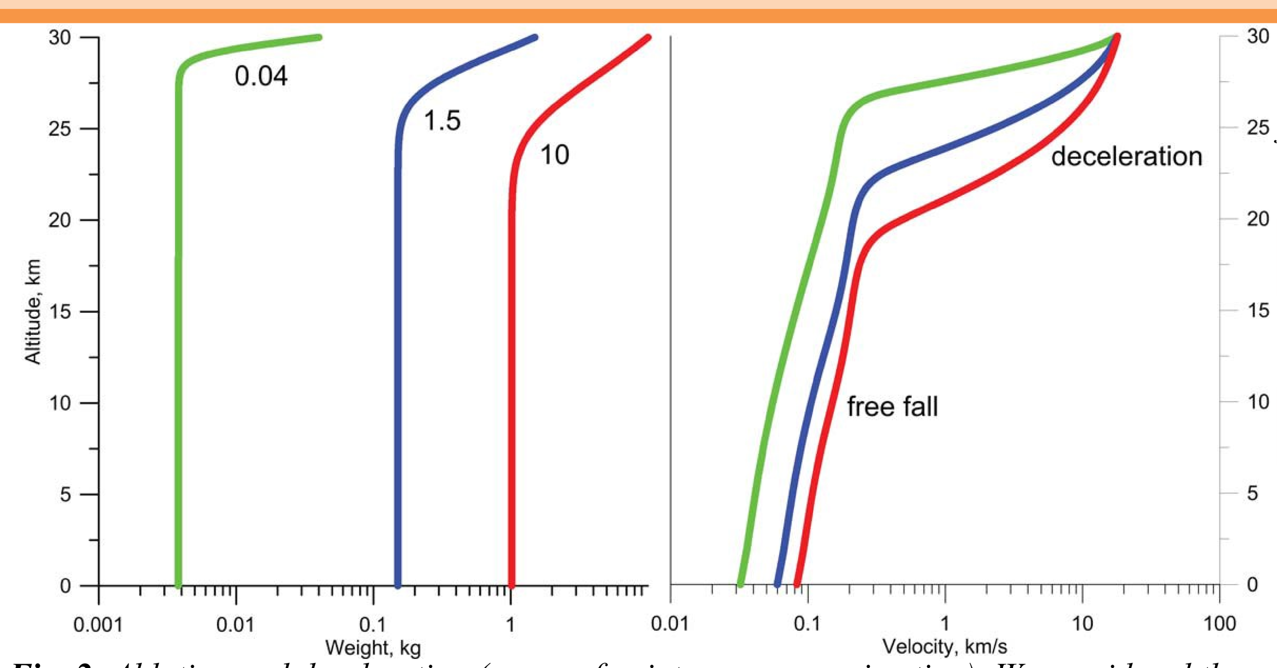

Fig. 2: Ablation and deceleration (usage of point mass approximation). We considered three initial masses of 0.04 kg, 1.5 kg and 10 kg, shown as green, blue and red curve, respectively.

***Tab. 1:** Results for three initial fragment sizes. The middle case is studied in detail for snow penetration (Fig. 4,5).*

Initial mass	4 g	1.5 kg	10 kg
Free fall time	8 min	4 min	3 min
Surface velocity (vertically)	28 m/s	60 m/s	74 m/s
Final diameter	1.3 cm	4.8 cm	8.5 cm

Shortly after catastrophic disruption (1–3.5 s):
- Individual **fragments lose 90% of their mass**
- Deceleration below 2 km/s, when ablation ceases.

Thermal History

Model of the heating of fragments in the hot cloud after disruption (Solving the heat transfer equation):
- Fragment shows ablation crust of about 1 mm thickness
- Interior heated above 300 K (84 and 21% of final mass, Tab. 2)
- Assumed initial temperature distributions:
  - Fragment is heated up to the melting point
  - Cold fragment is surrounded by a molten 1-mm-thick crust
  - Gradual decrease from hot crust to cold interior (most realistic temperature distribution)
- Cooling time interval < free fall time interval; except in case of molten large sphere (Fig. 3)

➔ fragments reach the surface being at **thermal equilibrium with the lower atmosphere** (-20°C).

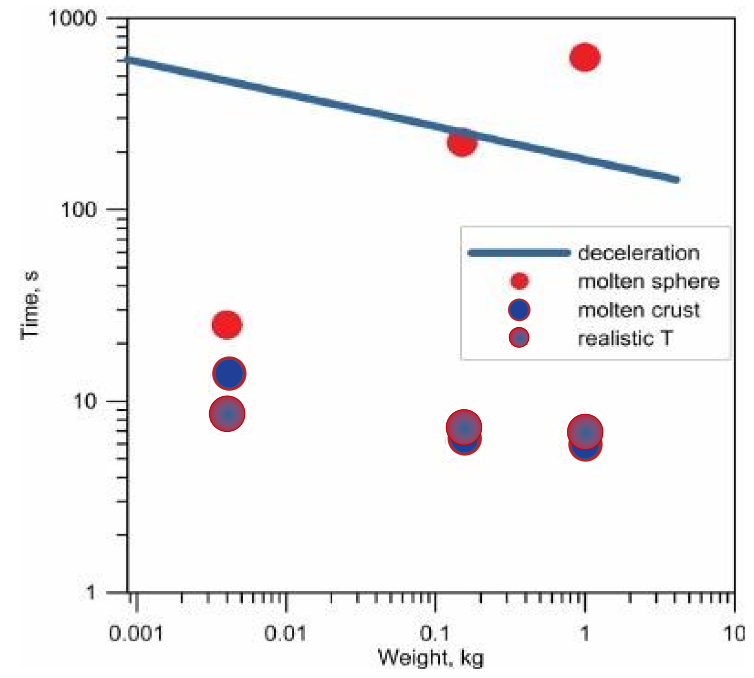

Fig. 3: Comparison of cooling time and free-fall time for 3 fragments with various final masses.

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Fragment Penetration into Snow Target

Numerical Model and Setup
- Eulerian hydrocode **iSALE 2D** [3,4,5]
- Tillotson equations of state for basalt and ice
- Porosity in snow is considered by ε-α porosity compaction model [4,6]
- Drucker-Prager rheology model for the snow
- Model Setup:
  - 70 % porosity (284 kg/m³ density) in snow
  - Snow Rheology [7,8,9]:
    - Cohesion: 1 kPa – 10 kPa
    - Coefficient of friction: 0.185 – 0.415
    - Maximum yield strength: 10 kPa – 100 kPa
  - Initial projectile mass and velocity: 150 g, 60 m/s
- 30 models evaluated

Results
- Fig. 4 shows snapshots of projectile penetration into the snow
- Density profiles (Fig. 4, black lines) show snow compaction of **up to 34 %** (380 kg/m³) in funnel walls with a thickness of **~1-2 cm**
- **Negligible increase of temperature** or internal energy
- Projectile penetration ceases at an extrapolated depth of ~55 cm (Fig. 5)

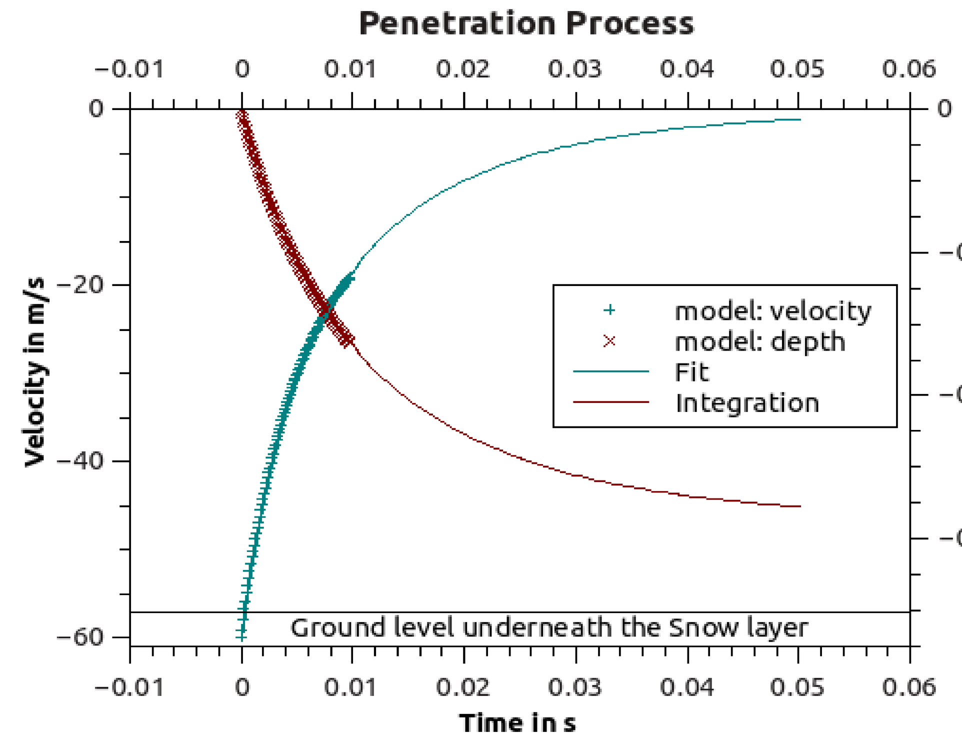

Fig. 5: Comparison between model and analytical solution for the deceleration of the meteorites in snow. The Deceleration corresponds to a drag coefficient of ~1 for the fragment and a viscosity of ~21 Pa s for the snow (Stokes law).

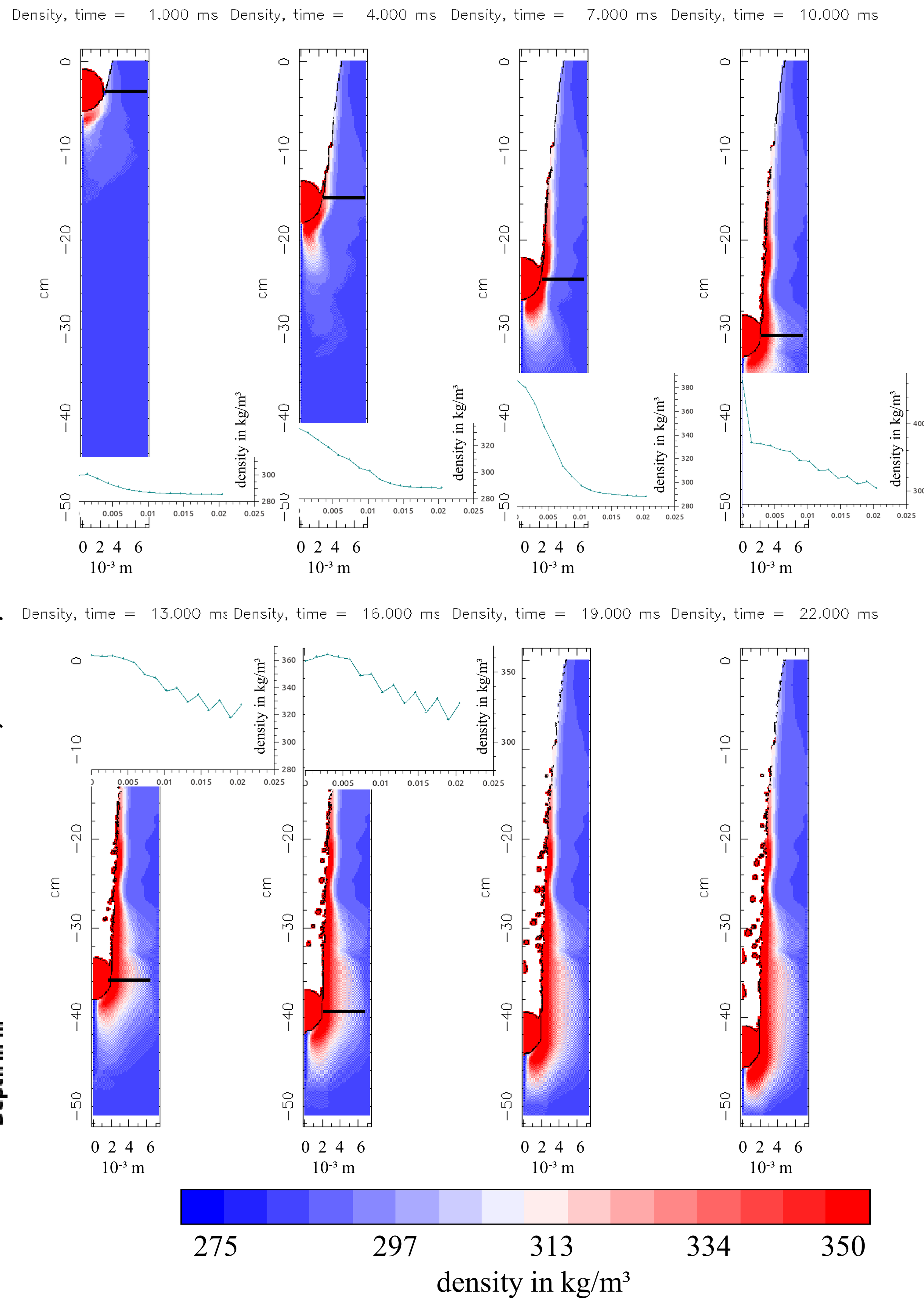

Fig. 4: Model of penetration and funnel formation. Timesteps from 1 ms – 22 ms. The color represents the density in kg/m³. Inserts: Density profiles for the first six steps (profile of black line).

Discussion and further application

- most fragments reach the ground cold (-20°C) and in thermal equilibrium with the lower atmosphere
- penetration into snow and snow compaction does neither lead to a significant increase of temperature nor to partial melting

➔ **Funnel formation is a cold compaction process**

The formation of a funnel disturbs the prior temperature gradient of the snow layer by the cold air entering the funnel. A new, strong, lateral temperature gradient evolves (Fig. 6, iii):

➔ Snow morphology changes due to **kinetic metamorphism**: Water vapour moves along the temperature gradient and deposits in the (colder) areas with lower vapour pressure [10]. Over time, ice grains and thus the density of the already denser (and heavier) funnel wall grow further. However, ice grains that grew due to kinetic metamorphism show **weak bonds**. Probably, the snow walls partly collapsed on top of the projectile after some time while ice grains are growing (Fig. 6, iv).

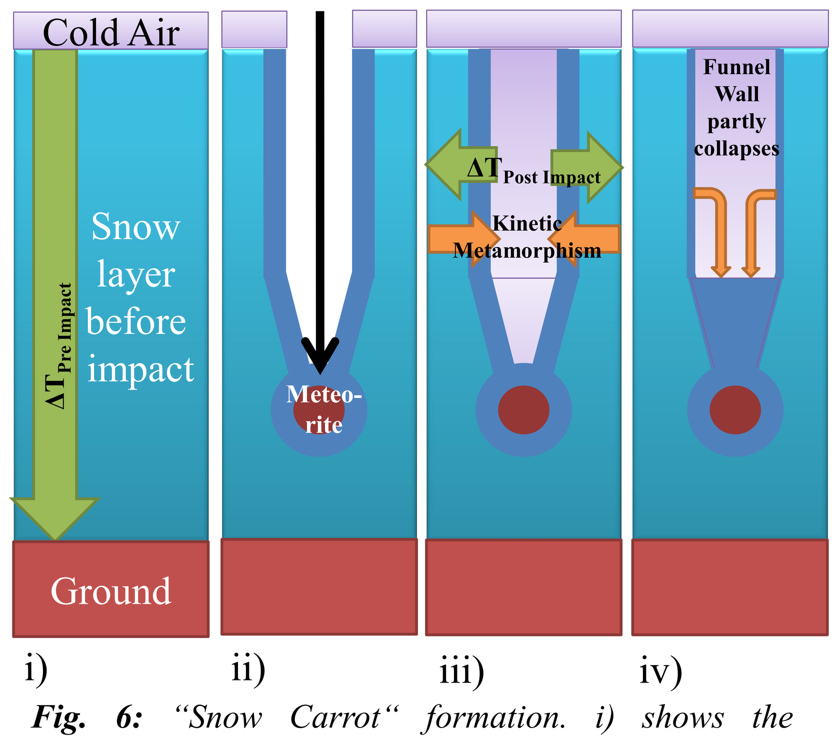

Fig. 6: "Snow Carrot" formation. i) shows the undisturbed snow layer with temperature gradient (green arrow). ii) shows the projectile path (black arrow) and the funnel after penetration. iii) shows the new temperature gradient (green arrows) and the direction of water vapour diffusion (orange arrows). iv) shows the partial funnel wall collapse of grown heavy ice grains after kinetic metamorphism.

Importance of impacts into highly porous targets:
- StarDust aerogel catchers for cometary dust [11]:
  - The observed tracks resemble the "snow carrots"
  - Accurate interpretation may provide additional information about properties of the collected particles (e.g., initial strength and porosity) prior to the capture
- Rosetta mission:
  - Craters in highly porous cometary nucleus of Churyumov-Gerasimenko

➔ Simulation of Snow Funnel formation in Chelyabinsk allows for successful validation study of the iSALE hydrocode modelling of impacts into highly porous targets

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