Impacts and Asteroids

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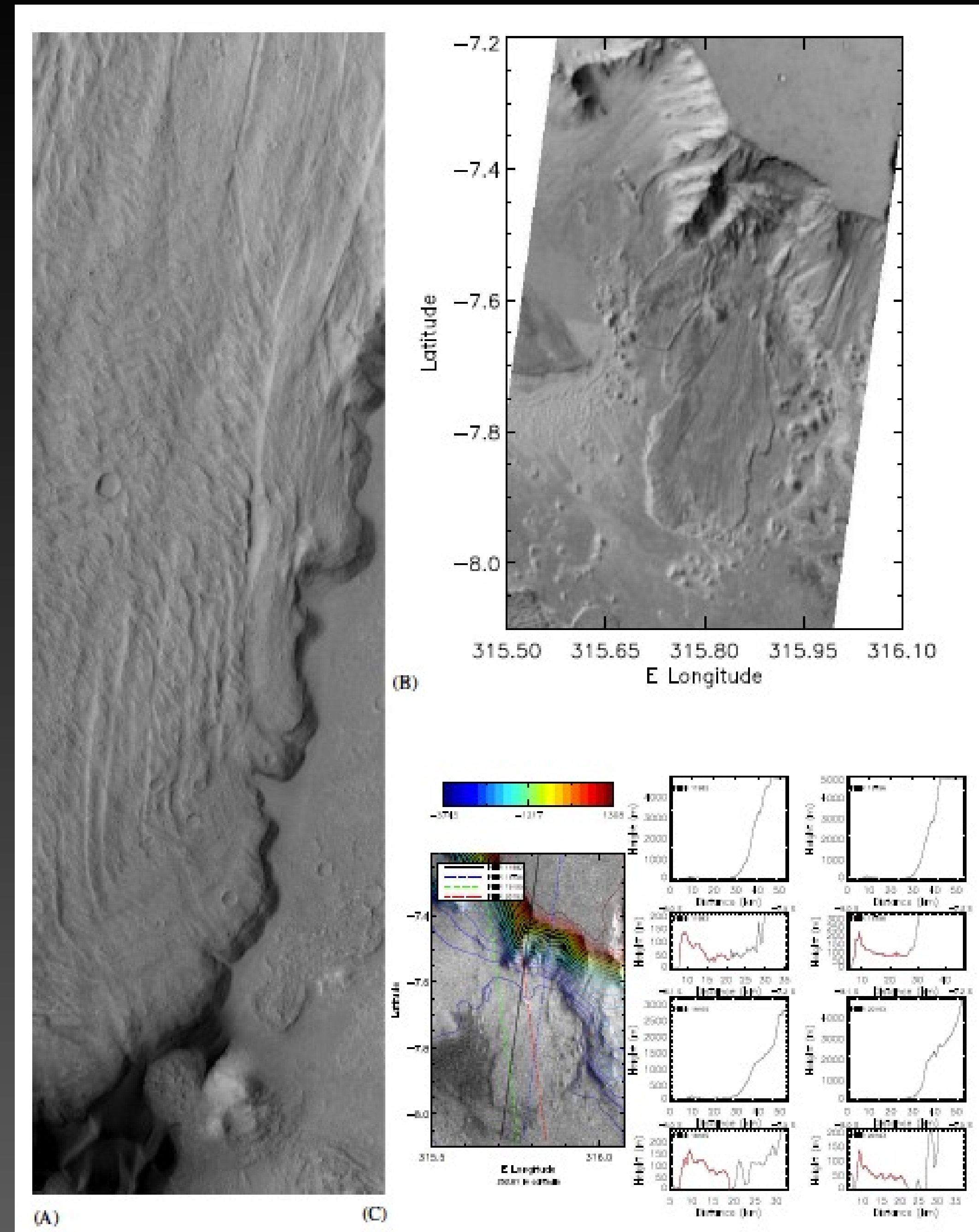
Planetary surface observations and processes

- Examine observations of granular processes in planetary environments
  - Mars: mass movements – landslides and ejecta
  - Eros: softening of terrain; destruction of craters; influence of pre-existing terrain
  - Itokawa: lack of crater; landslide
- Explore granular mechanism for observed features
- Objective: What are we learning about the origin and evolution of these celestial objects?

Martian landslides and ejecta

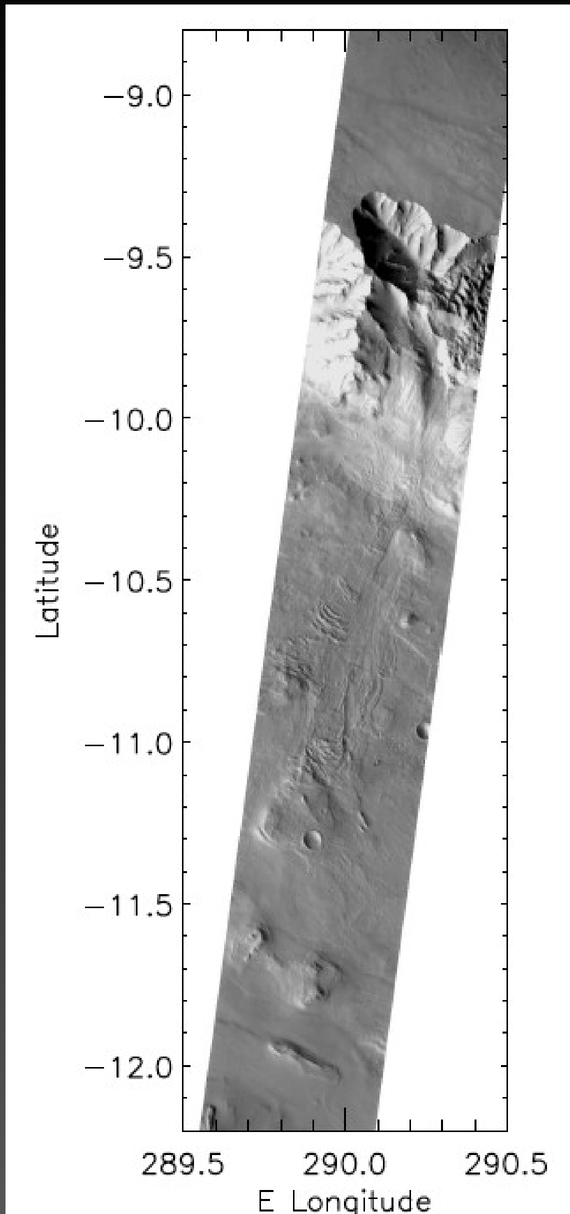
- Are landslides and fluidized ejecta indicators of water?
  - If yes:
    - How much?
    - When in geological history?
- Step 1: Can a dry granular make these structures?

Lunae Planum D~30km



Ganges Chasm

Mars long run-out landslides – resemble terrestrial ones



- Striations
- Ramparts (subtle)
- Distal boulders (sometimes)
- Water - minor contributor ?
  - Large rock masses
  - Broken rock cannot maintain high pore pressure

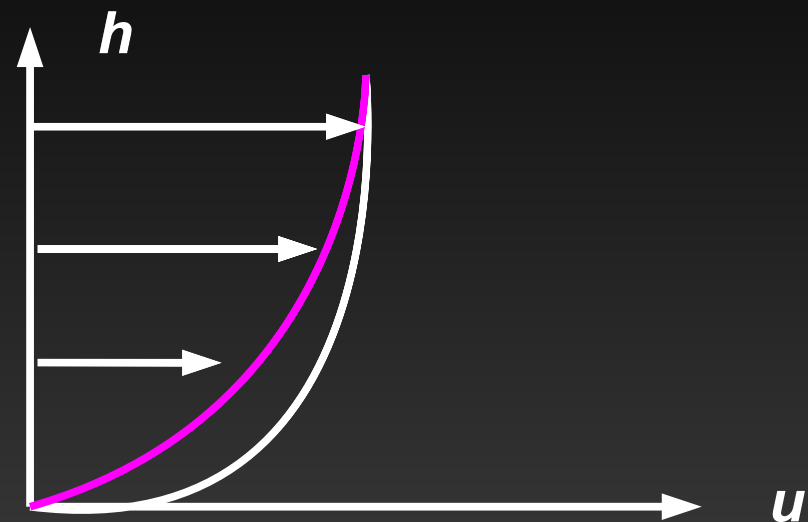
Sherman Glacier Rock Avalanche (5km across frame)

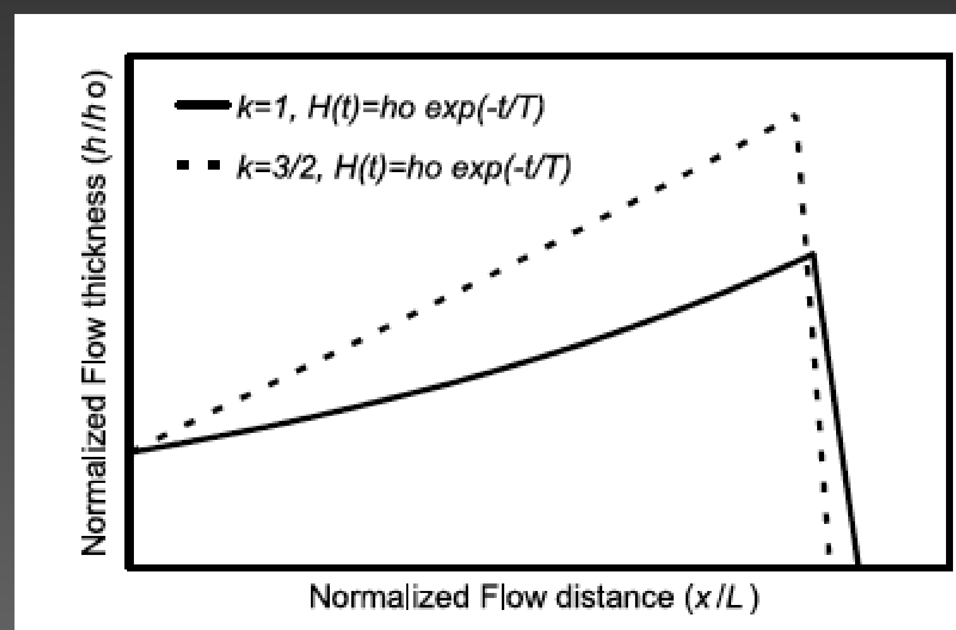
Simple continuum model

- Combine
  - Conservation of mass
  - Semi-empirical kinematic formalism

$$h(x,t)=H\left[t-\frac{x}{ku_o}\left(\frac{h_o}{h}\right)^{k-1}\right]$$

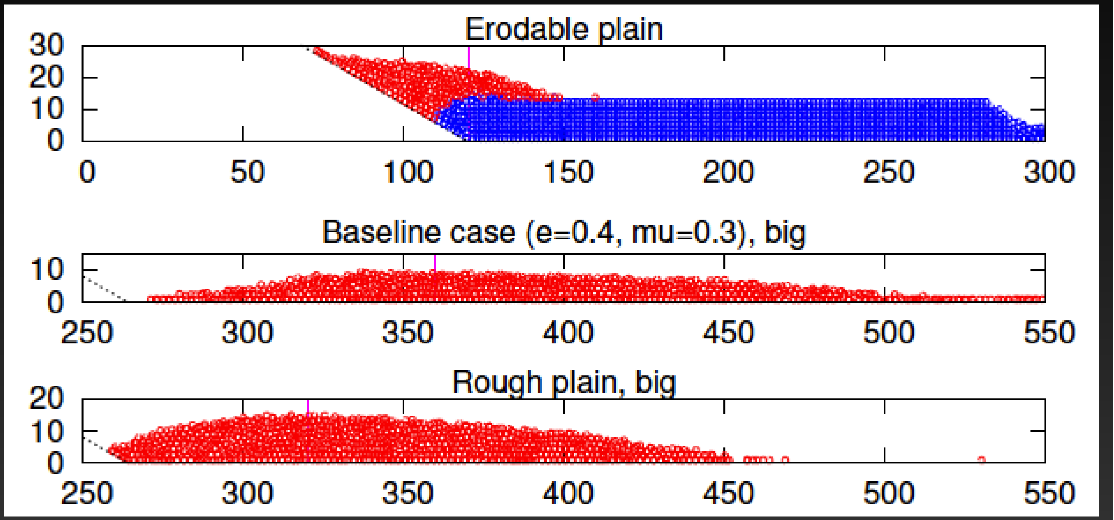
  - k = 1 basal glide -steep velocity gradient
    - Maintains stratigraphy
    - Subtle rampart
  - k = 3/2 debris flow-like velocity gradient

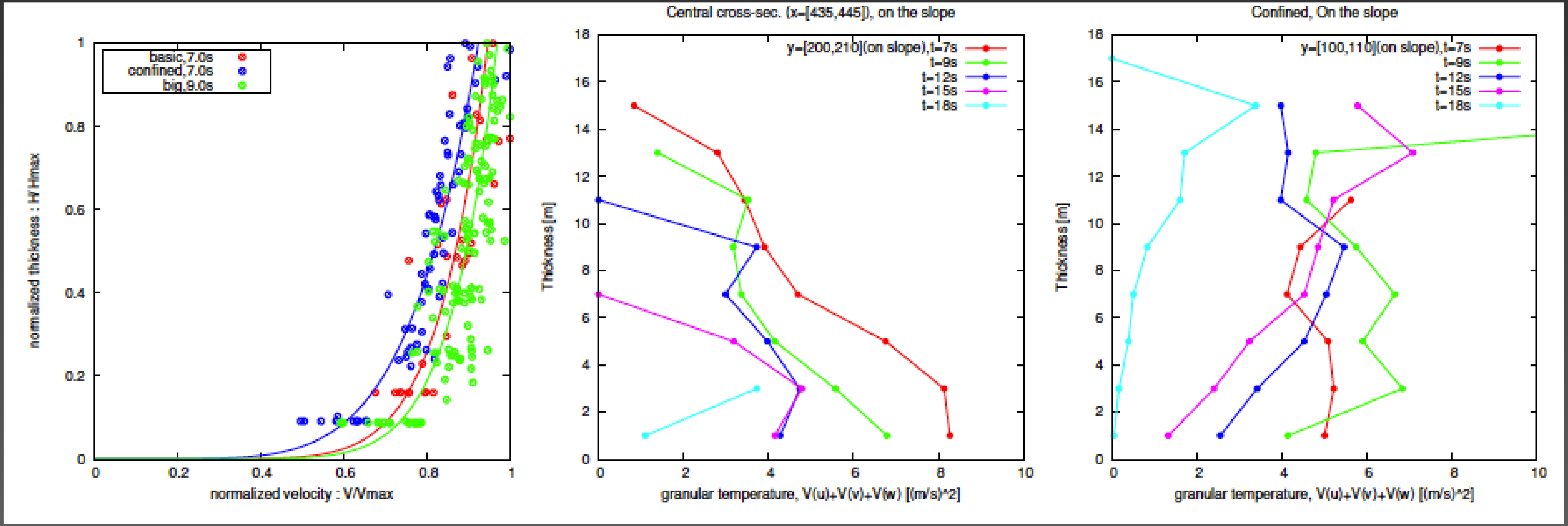




Such a velocity profile possible?

- Cambell (1989) proposed this concept
- 2-D DEM calculations – velocity profile not as steep as anticpated
- Could geometry matter?





Water still needed?

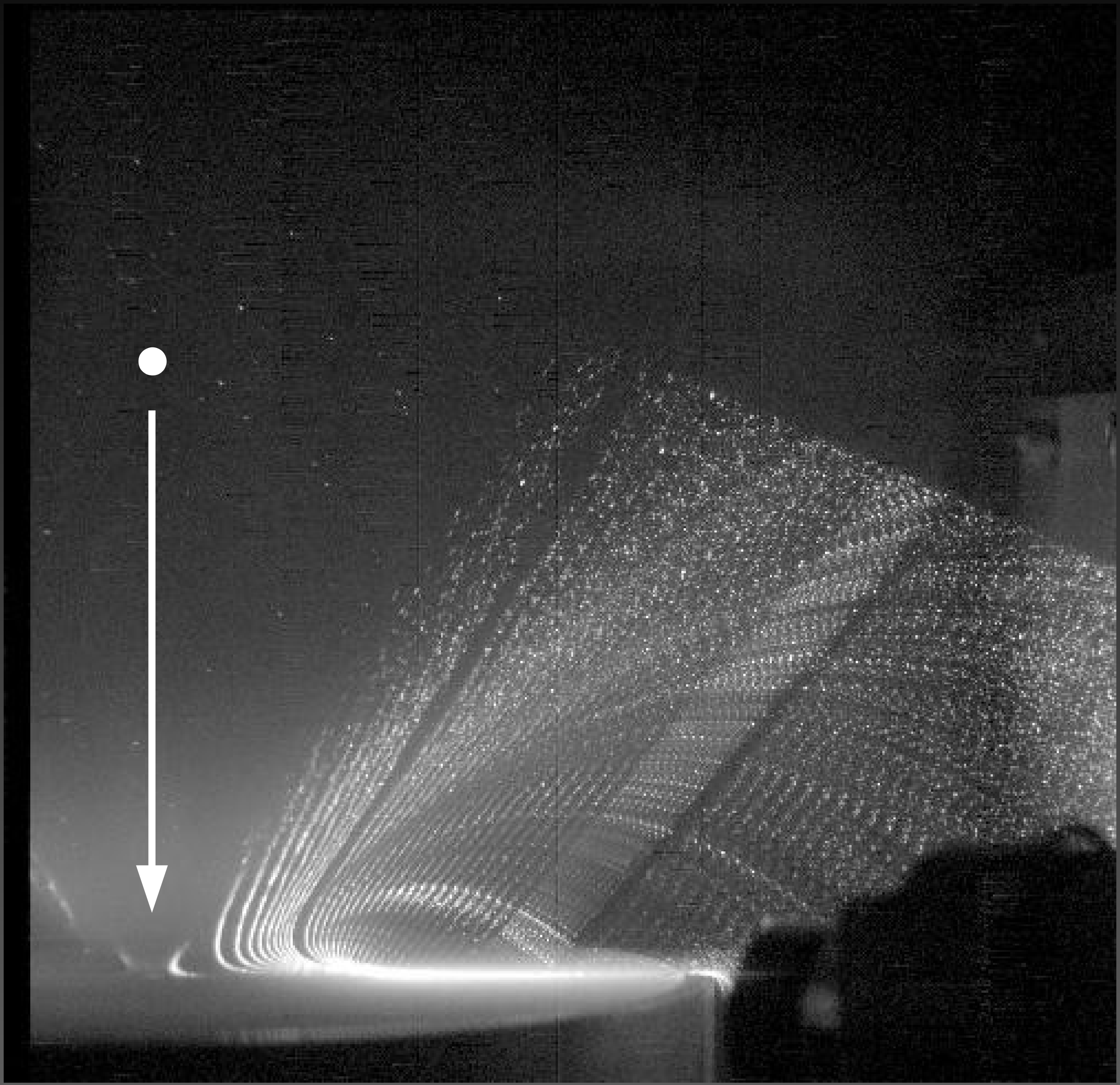
Ejecta on most planetary surfaces

- Moon, Mercury, Icy satellites
  - Hummocky inner ejecta
  - Development of radial features
  - Field of secondaries
  - Crater rays

Result of ballistic ejection and emplacement of ejecta

Image: NASA JSC Vertical Gun Range (courtesy: M. Cintala)

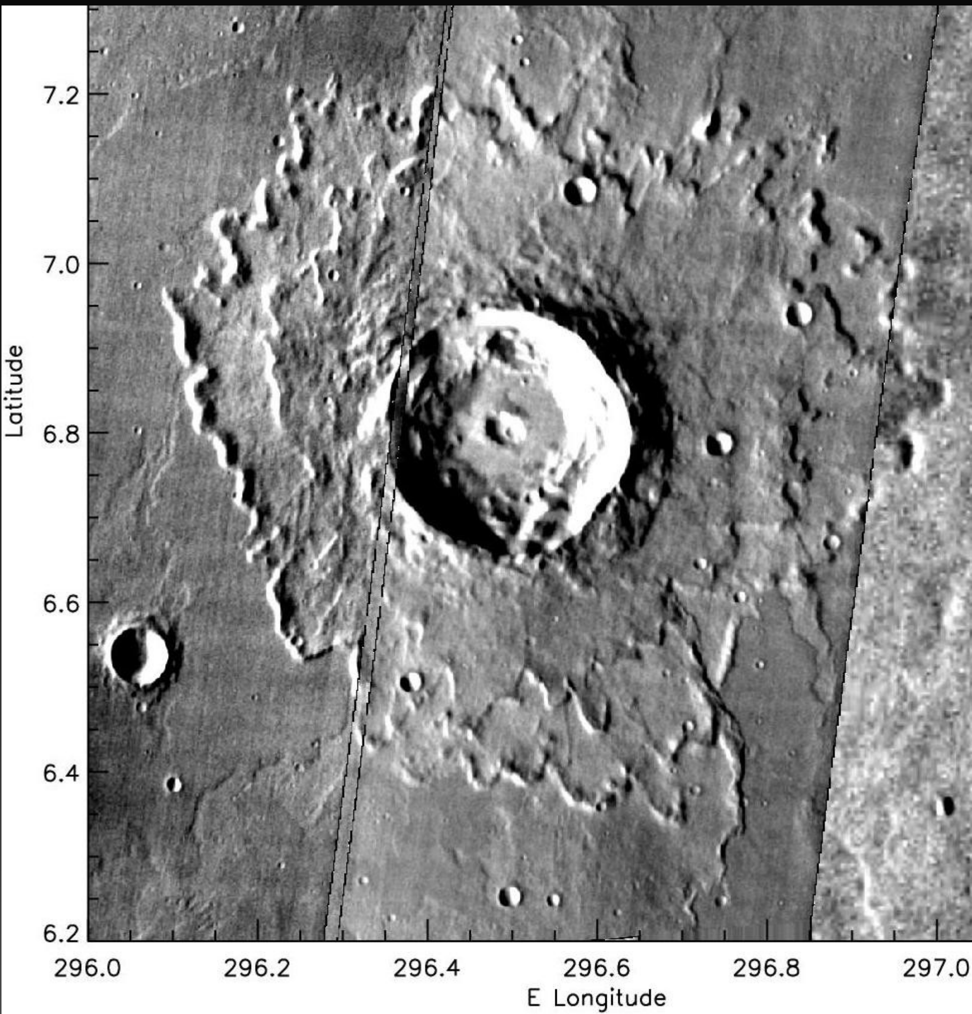
Video: Vertical Gun Range, Dept. of Complexity Science, U. Tokyo (courtesy: S. Yamamoto)

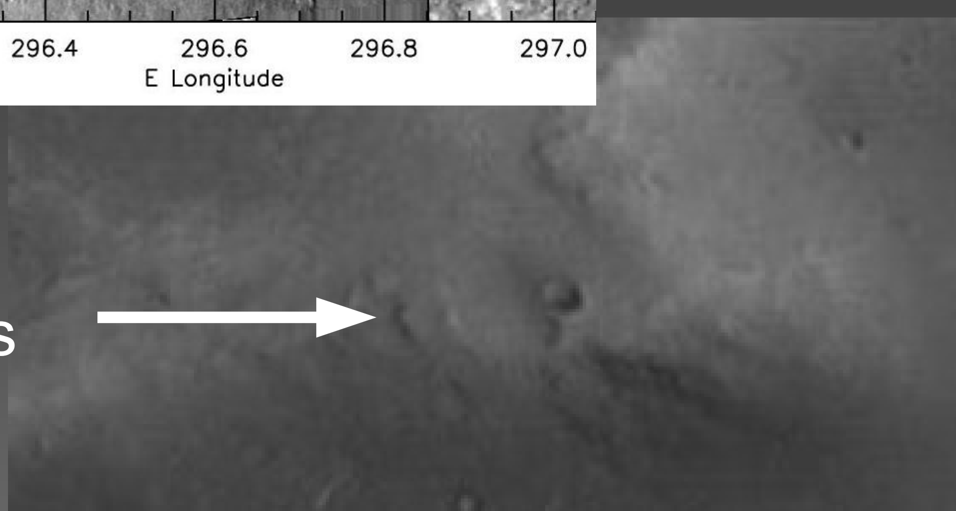


Open shutter view of ballistic ejecta curtain

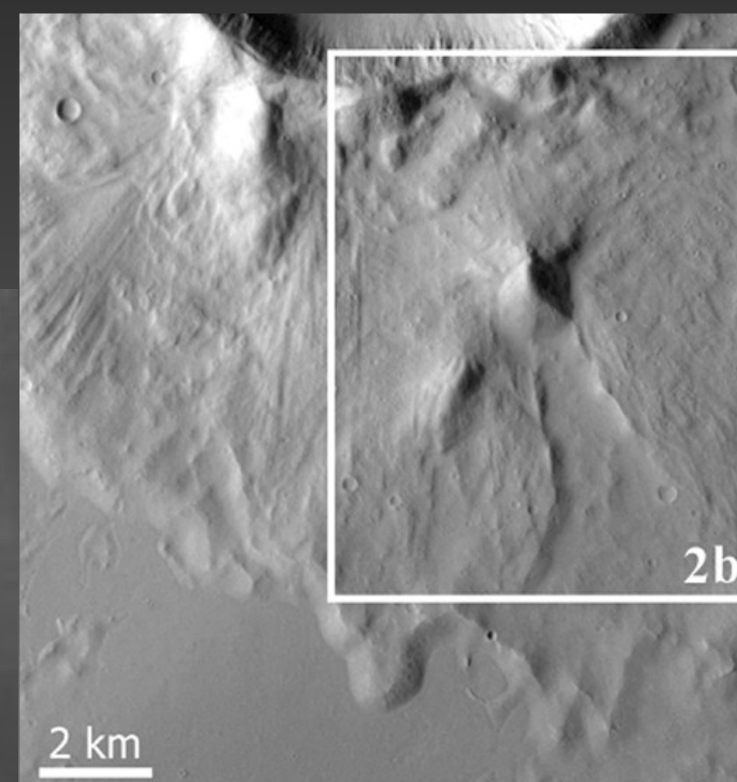
Mars ejecta look different

- Fluidized appearance
  - Distal ramparts
  - Flow around obstacles
    - Ground hugging flows
  - Boulders at distal edge



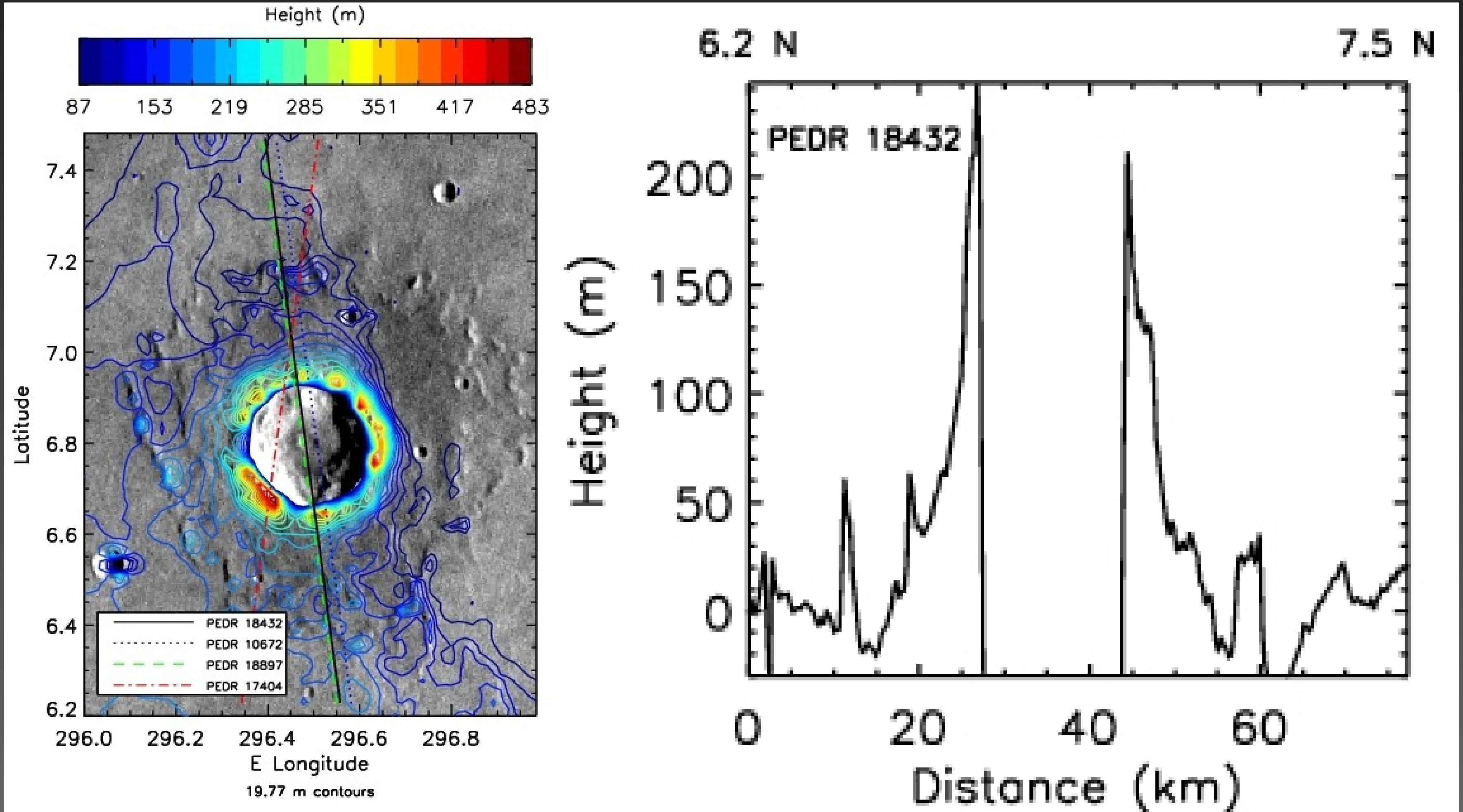


Boulders

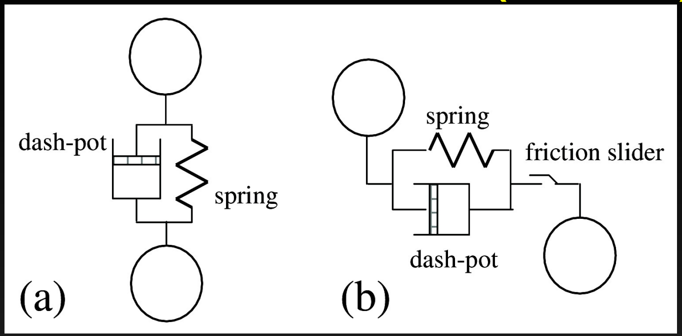


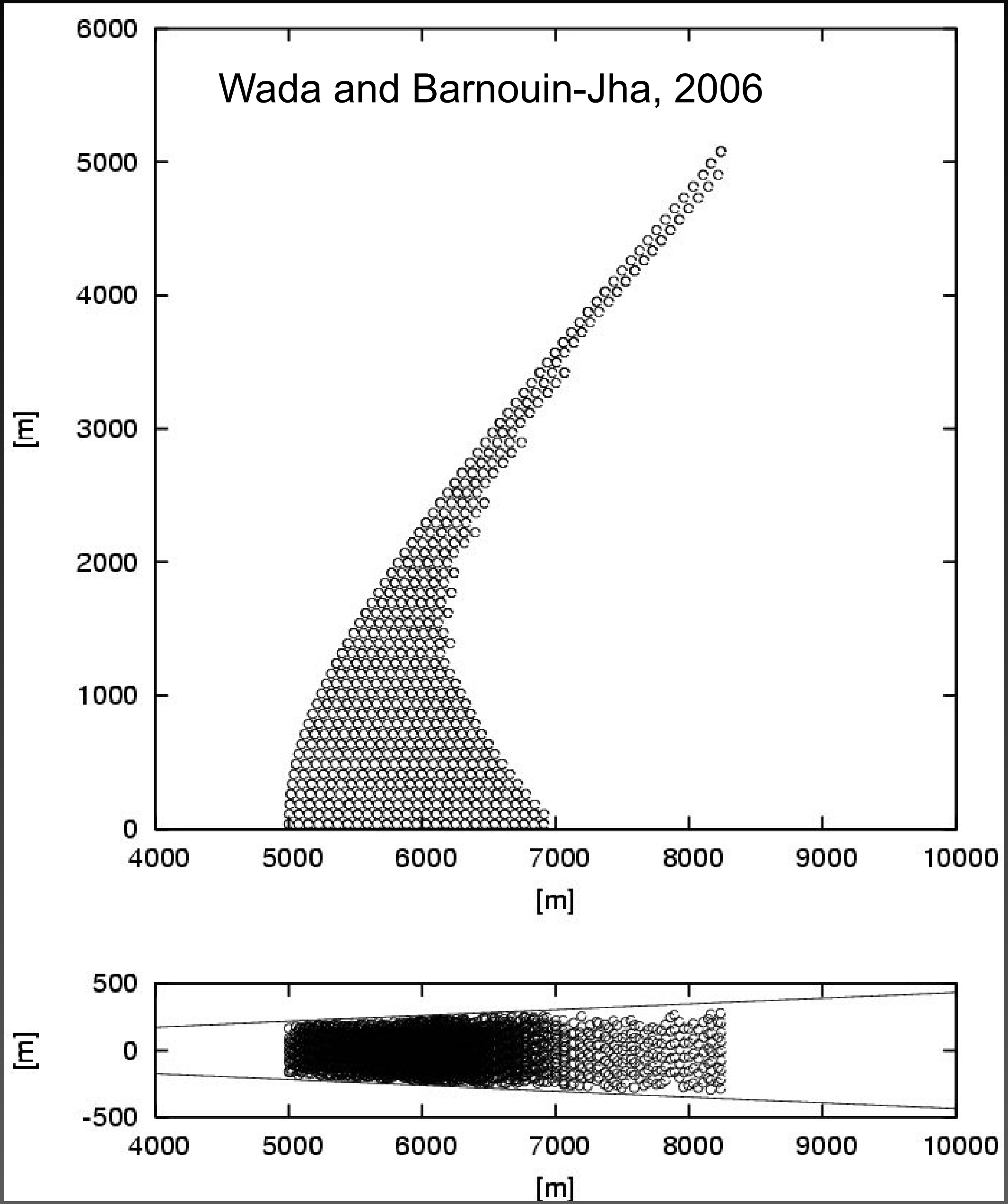
Ejecta topography

- Rampart height typically 50-200m
- Runout 1-2.5 crater radii
- Rampart width relatively narrow (1-3 km) – with moat
- A lot of ejecta volume is in rampart



Start with the basics - Discrete Element Model (DEM)

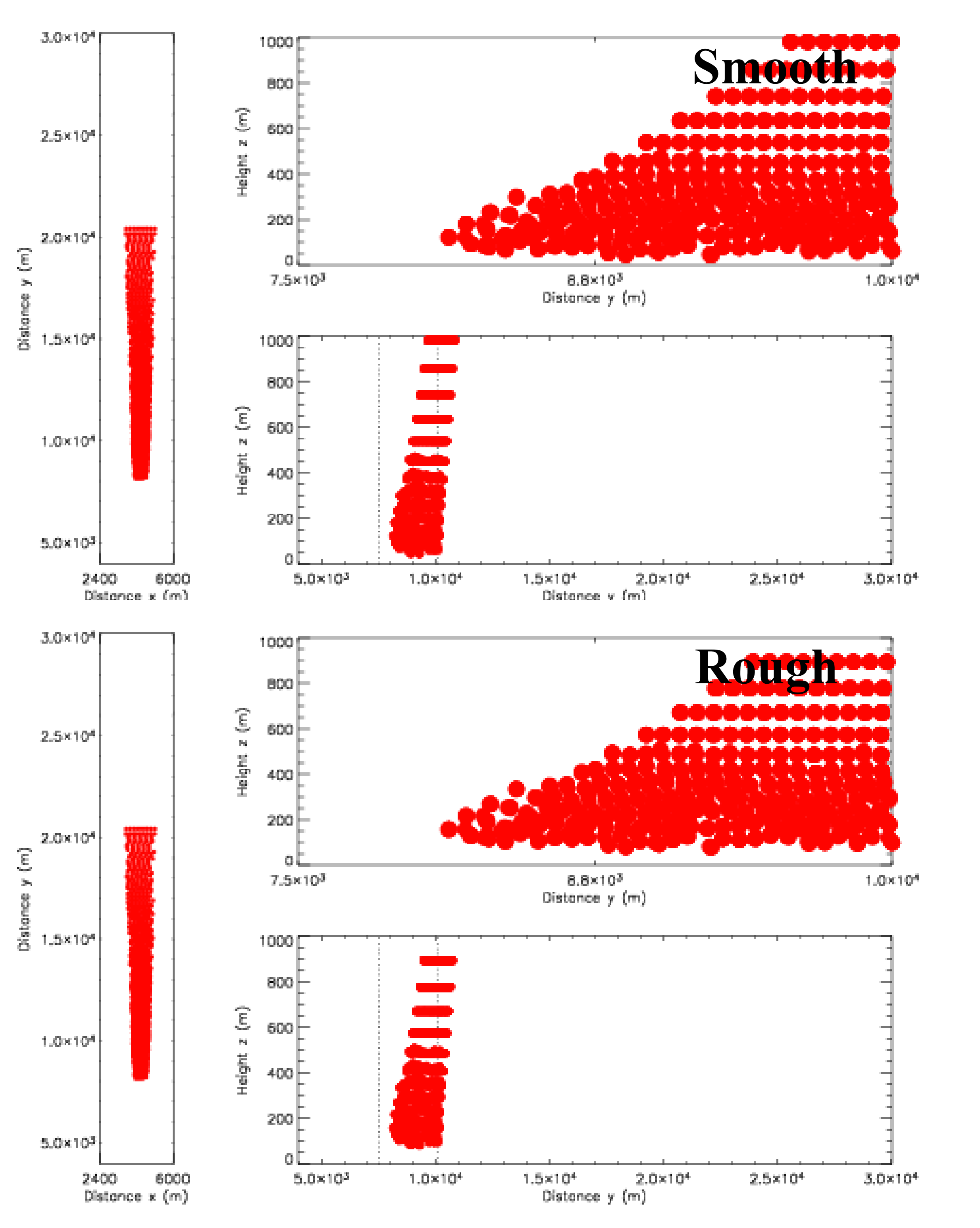




5 degree wedge

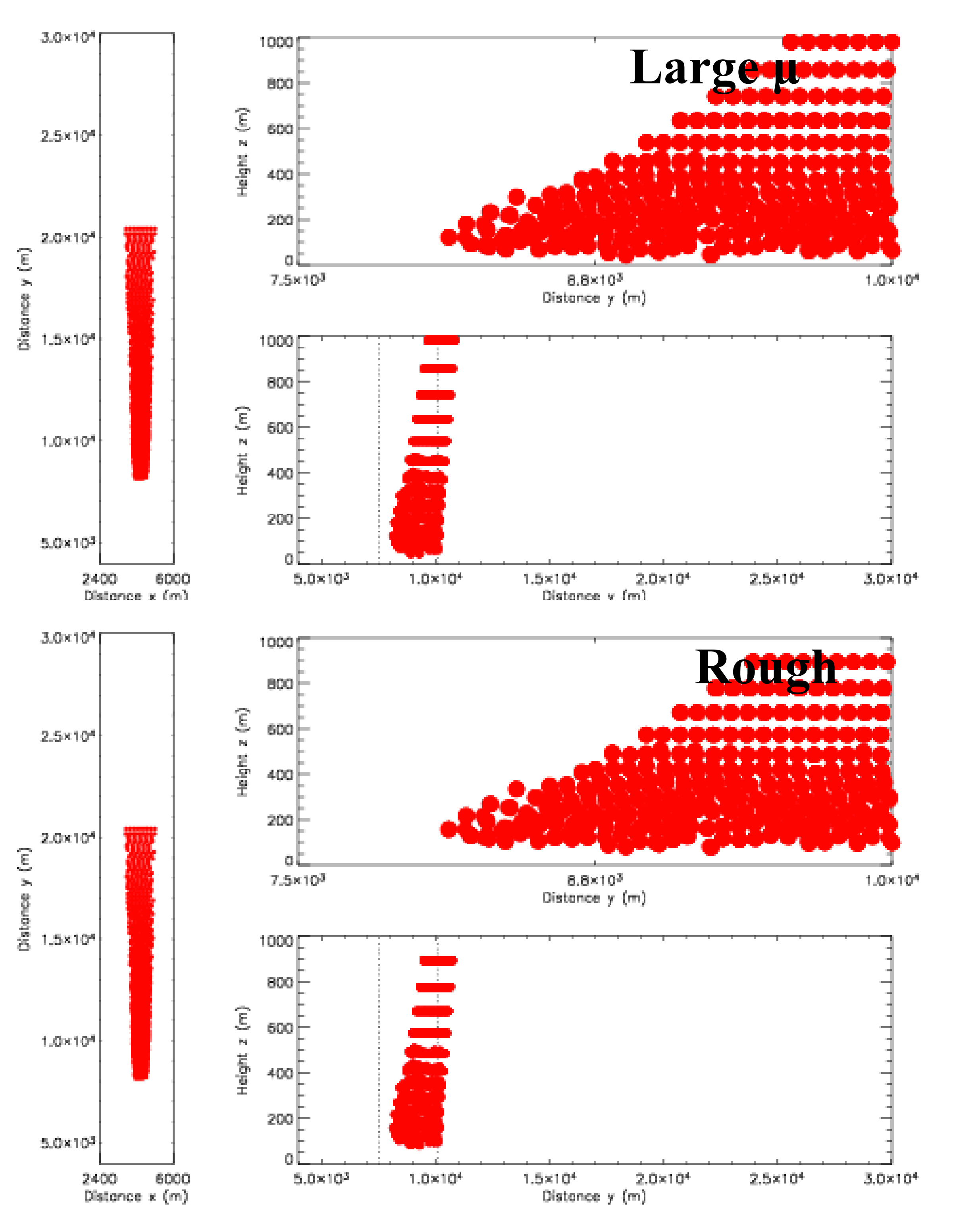
- Treat dynamics of each individual ejecta
  - Preliminary calculations
    - Uniform size (35-70m), elastic spheres
    - Transient *R* = 5km
  - Vary surface properties
    - Coefficient of restitution and friction
    - Roughness/Erodibility
  - Inter-particulate properties
    - Coefficient of restitution and friction

When do we get flow?



Smooth-hard versus rough-hard surface

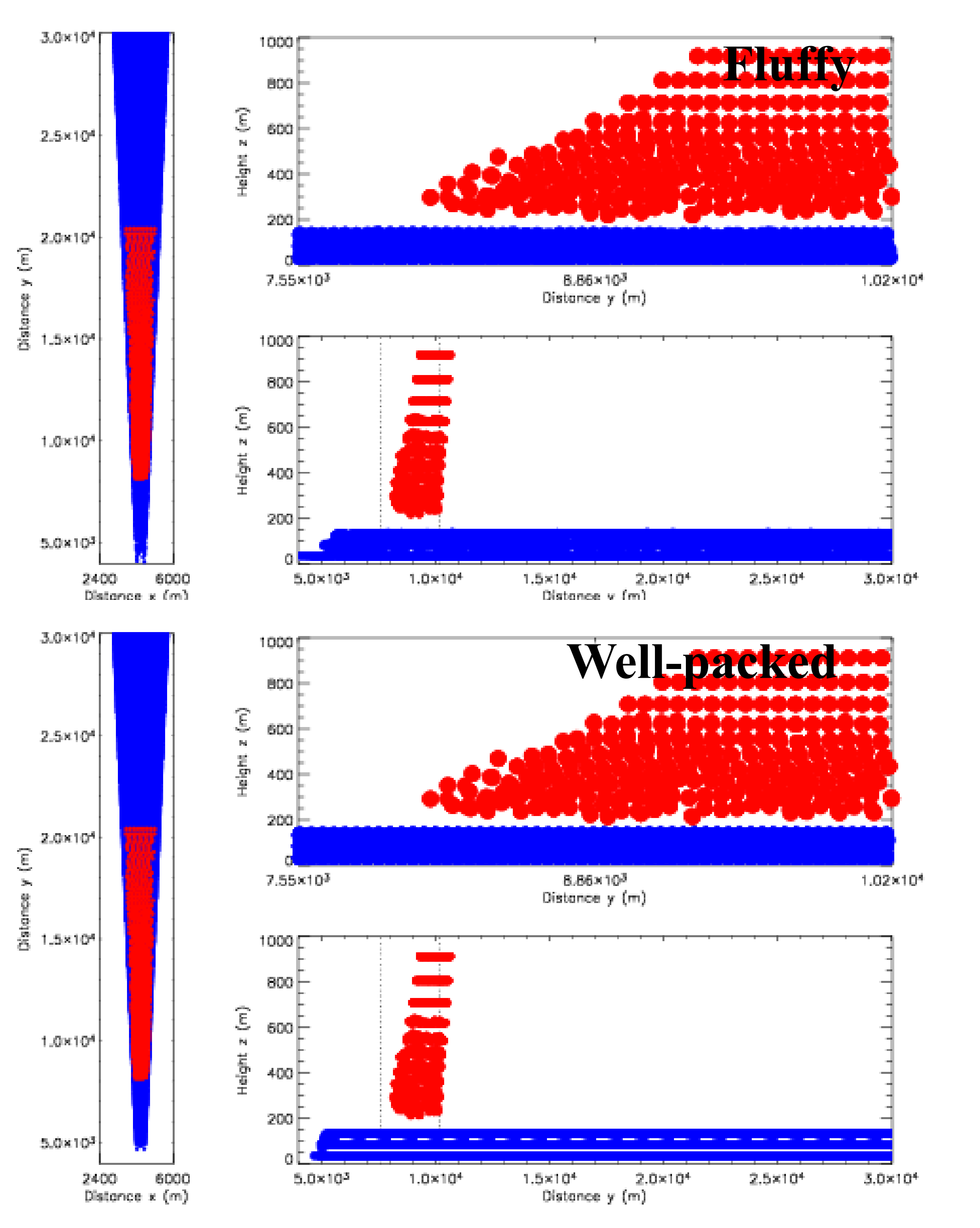
- Efficient flow for smooth case
  - Small near-rim structure
  - No rampart
  - Steeper velocity profile
    - Less shear
- Distal surge formed
  - Could be responsible for rampart



Rough-hard versus smooth with high internal friction coefficient, μ

- Behave similarly
  - Large near-rim structure
  - No rampart
  - Shallow flow profile
- Distal surge differs
  - Greater in rough case due to surface roughnes

Fluffy versus well-packed erodible surface



- Fluffy surface
  - Greater run-out
  - More impressive surge
- Well-packed surface
  - Harder to display material

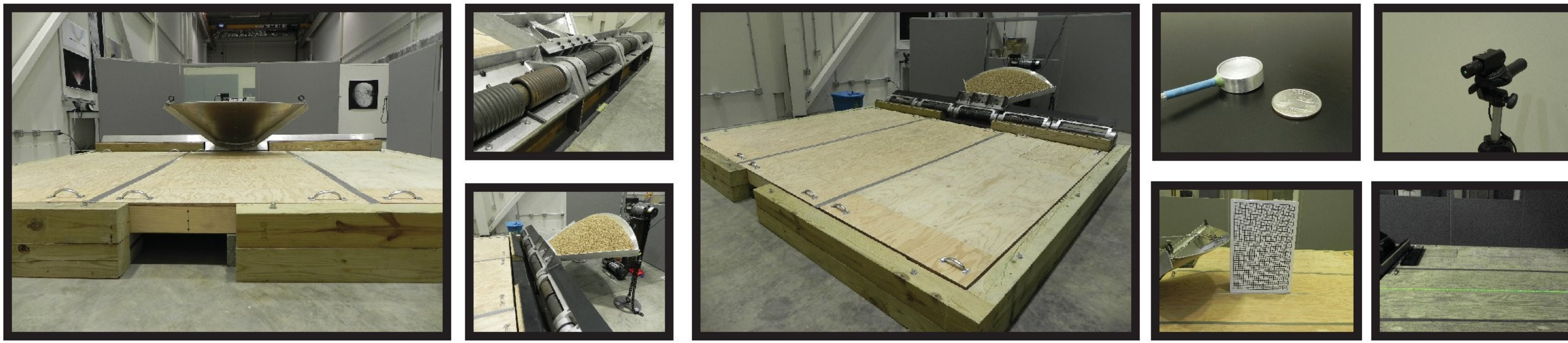
Granular flow summary

- Easy to initiate ejecta flow
  - Harder-smooth or slightly erodible surfaces
    - Result of water related sedimentation processes
  - Martian northern plains (increased ejecta run-out)
    - Sediment rock on which ejecta can easily slide
  - Crater that are not fluidized on Mars (and Mercury)
    - Very soft broken-up/dense/rough megaregolith
- But why no rampart?
  - We make some simplifying assumptions
    - No rolling friction, uniform grain size distribution
- Does not exclude low viscosity due to volatiles or atmospher
  - BUT NOT REQUIRED

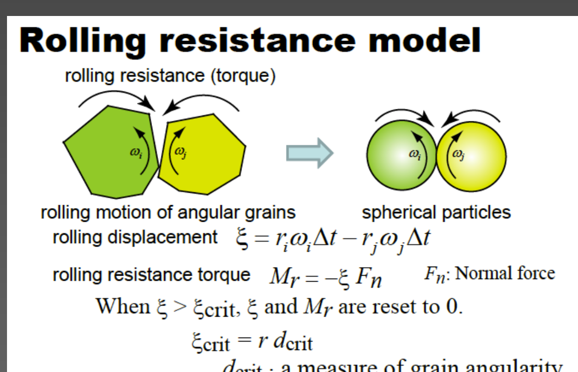
Eros – terrain softening and interior heterogeneity

- Observations that might be the result of granular processes operating on Eros?
  - Association of bright regions with bright slopes
  - Removal of craters
  - Terrain softening
- Consequences of interior heterogeneity and impact cratering

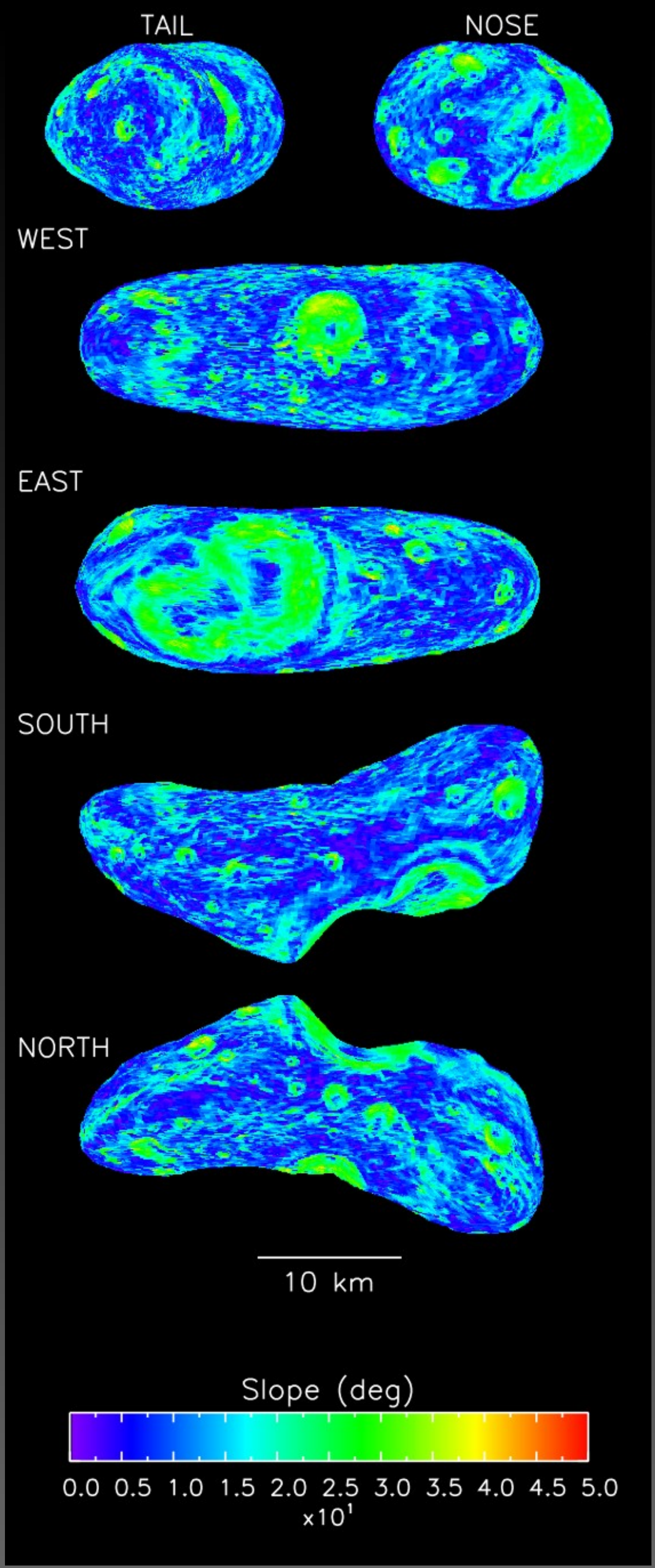
Why no ramparts?
Rolling friction – Insufficient grains



- Two pronged approach
  - Experiments
  - Discrete element model



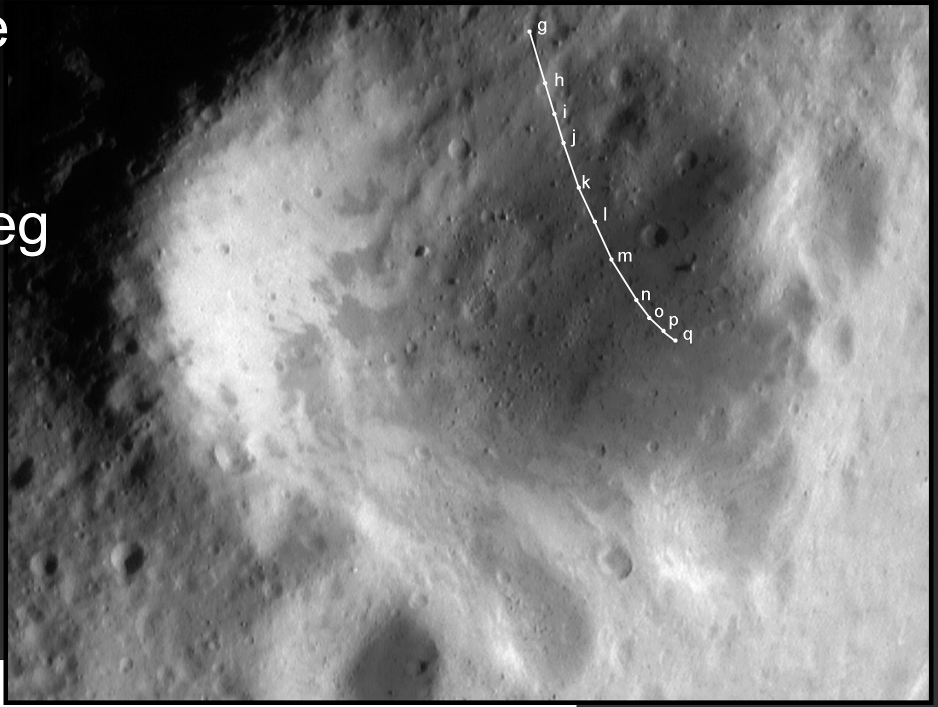
Bright albedo terrains

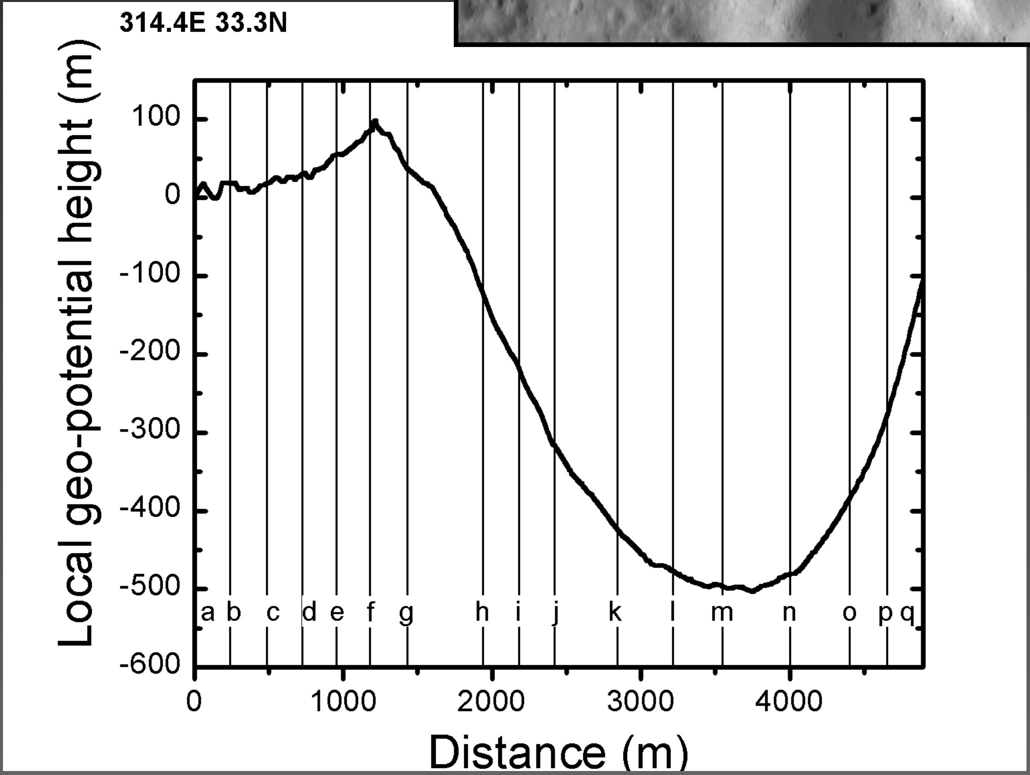


Evidence for slope failure

Usually ~ 30-32 deg

If non-cohesive grains: angular grains sand-sized (500 microns)



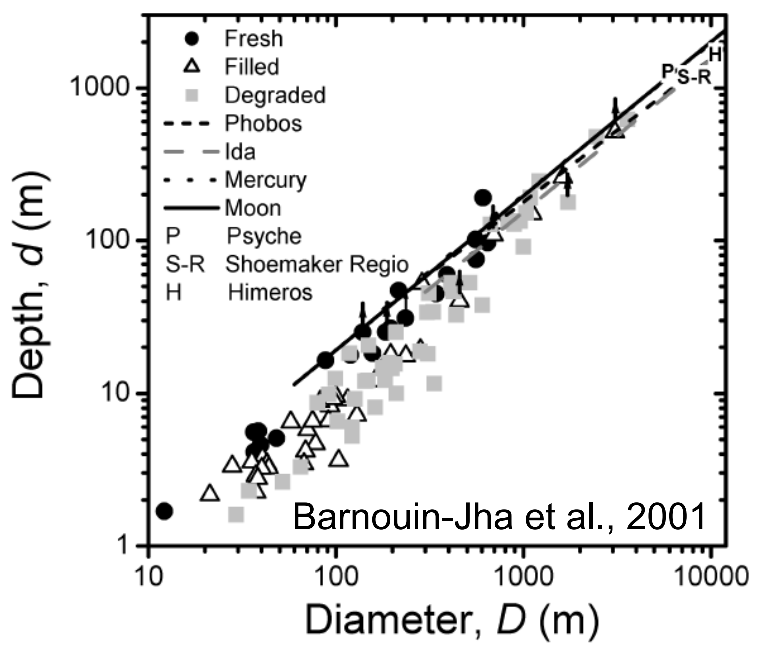


Accumulations are sometimes substantial

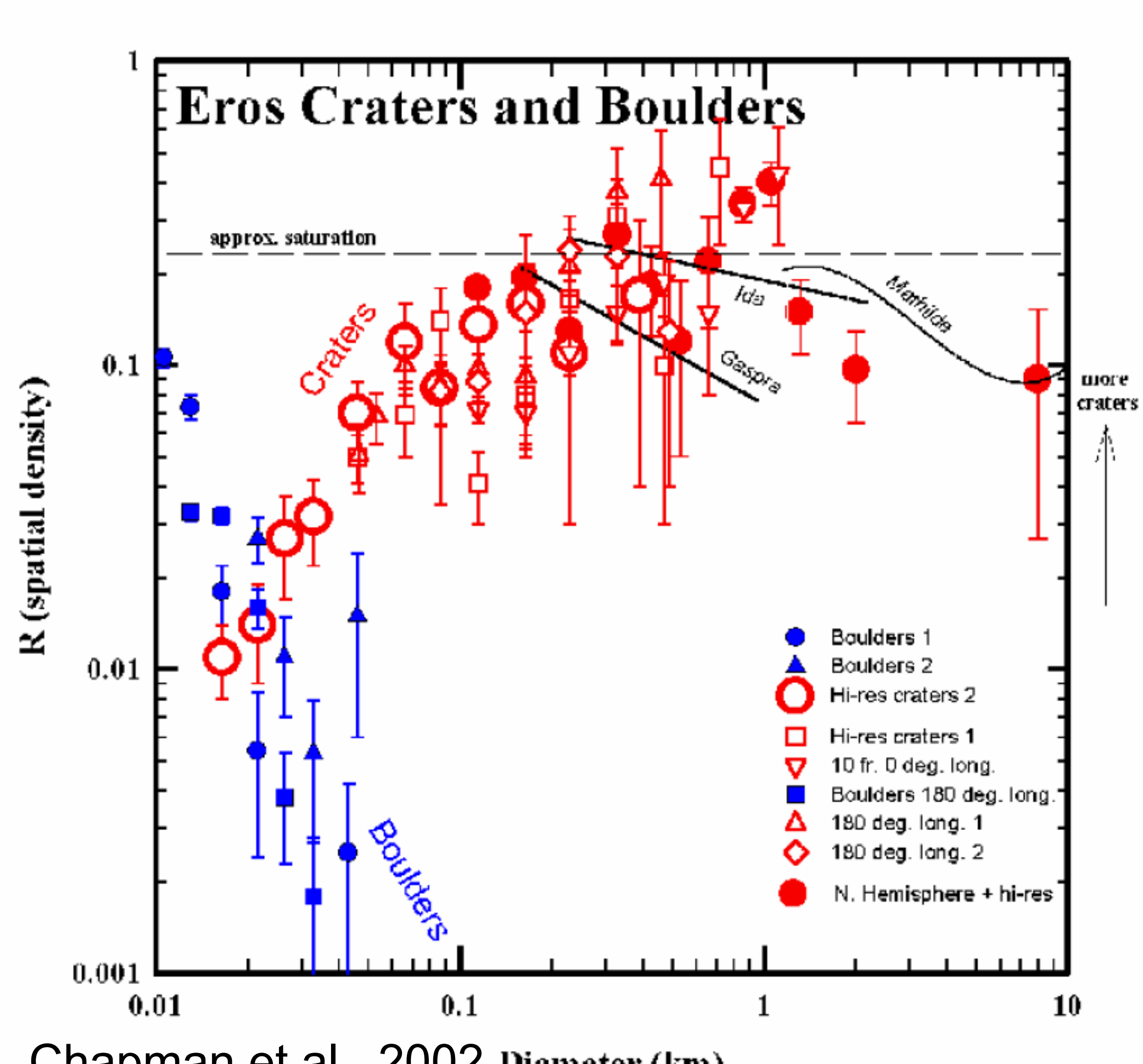
With evidence of crater infilling.

Destruction of craters by seismic shaking of regolith?

- Average regoliths ~ 15 to 20 m
  - Crater diameter to depth ratios
  - Observed accumulations
  - Pit chains width

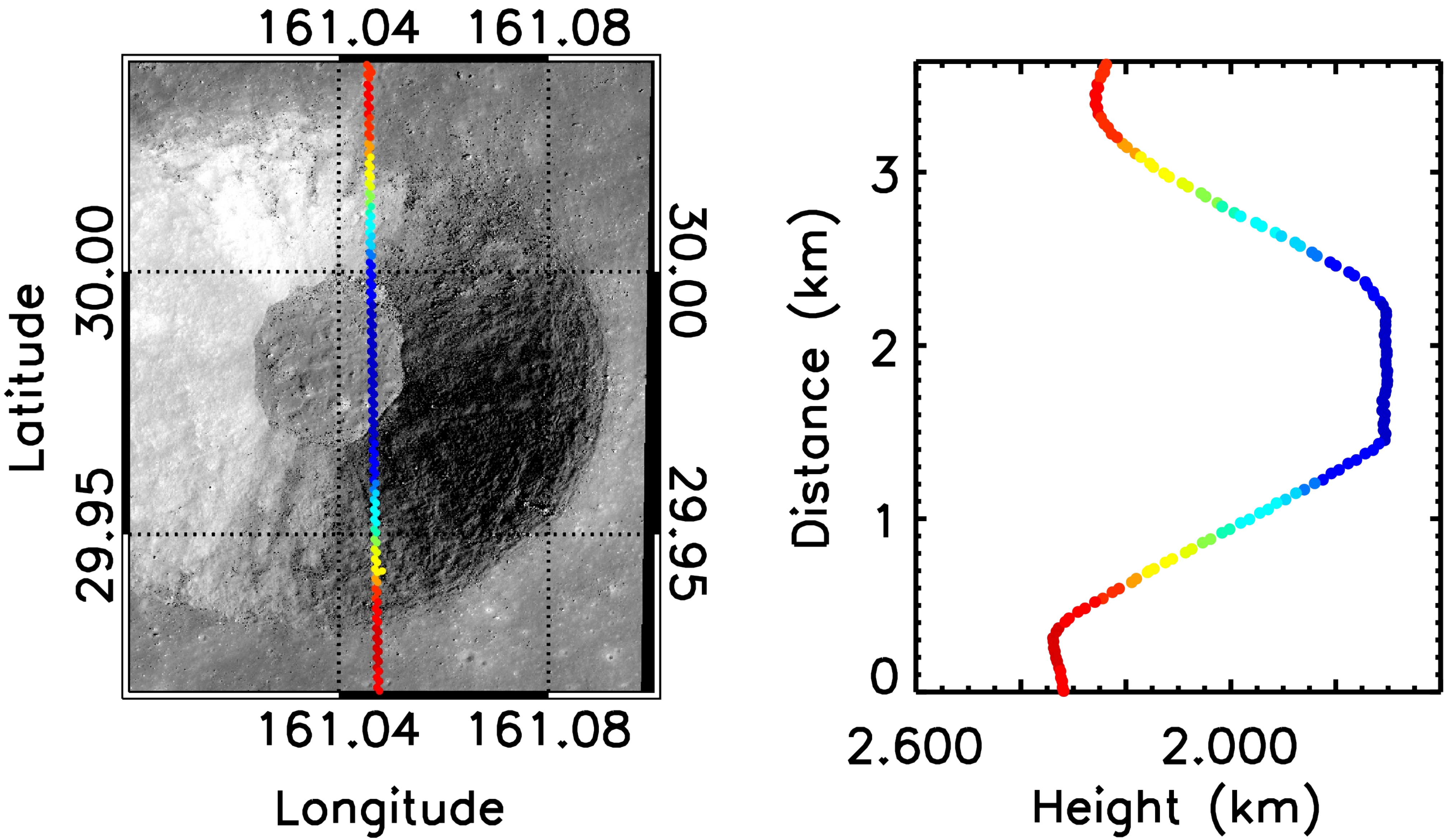


Barnouin-Jha et al., 2001



Chapman et al., 2002

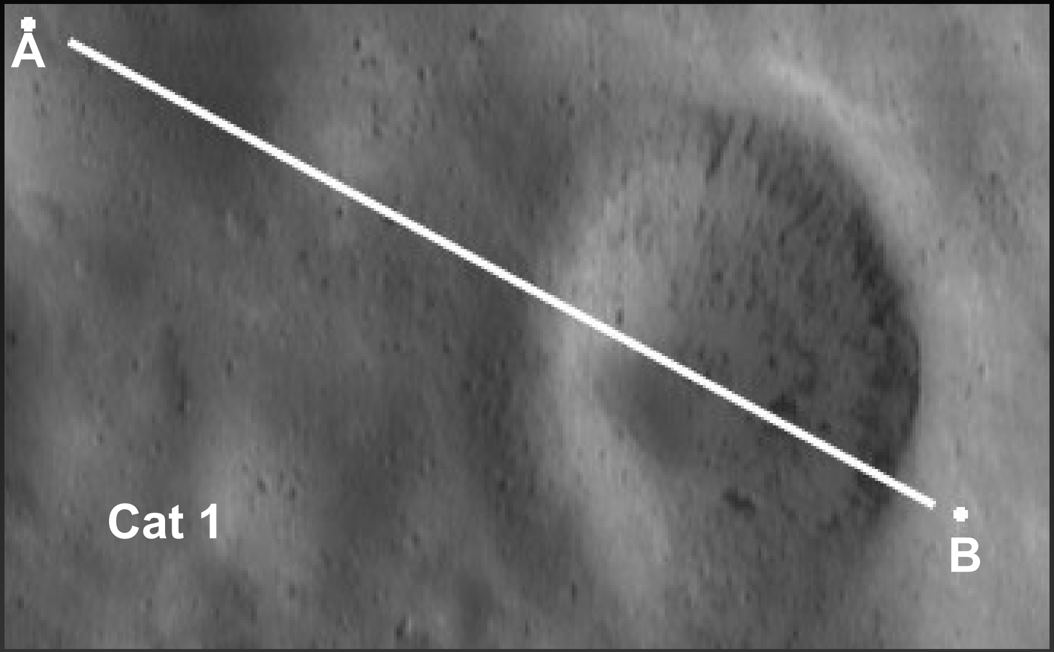
Most Eros craters are subdued

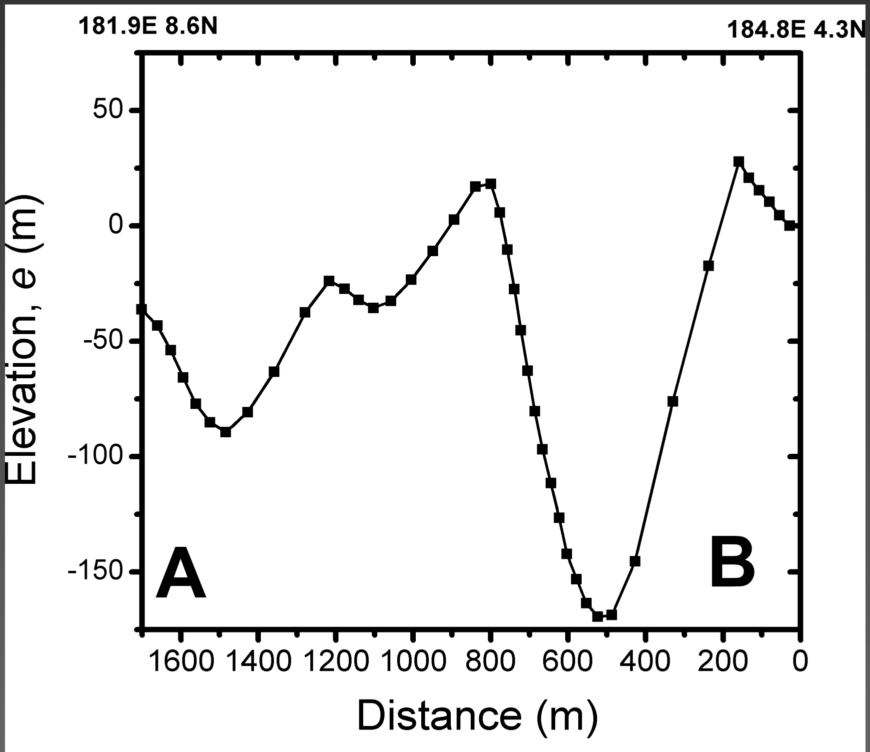


LROC image of a very fresh lunar crater

Eros comparison

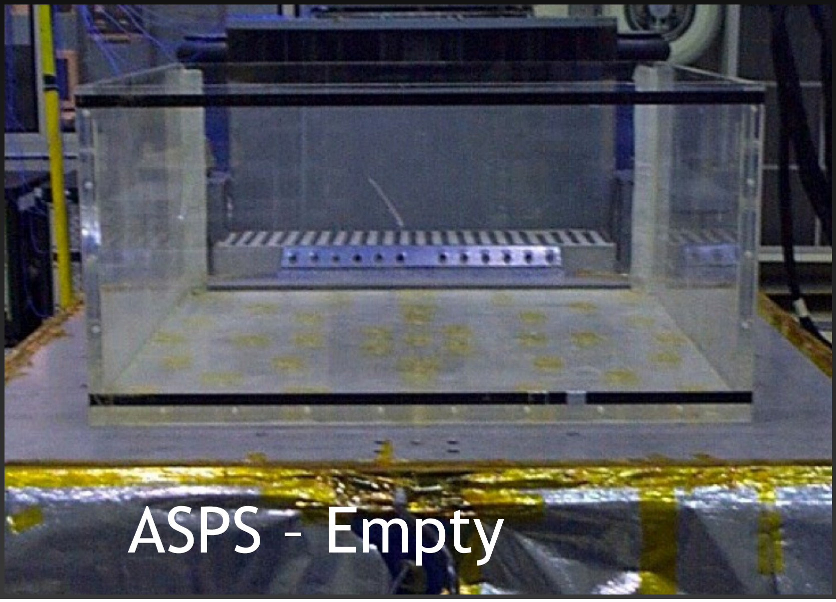
- Fresh Eros crater
  - Few or no visible superposed craters
  - Well defined rim but often a little subdued
  - Little or no obvious fill
- Most are
  - Subdued appearance
  - Few superposed craters

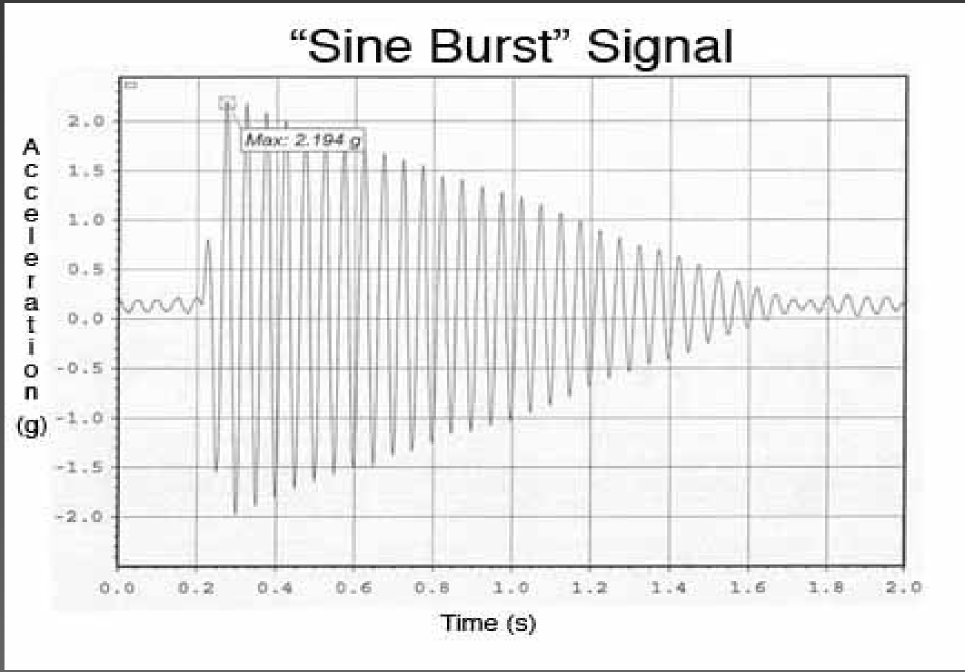




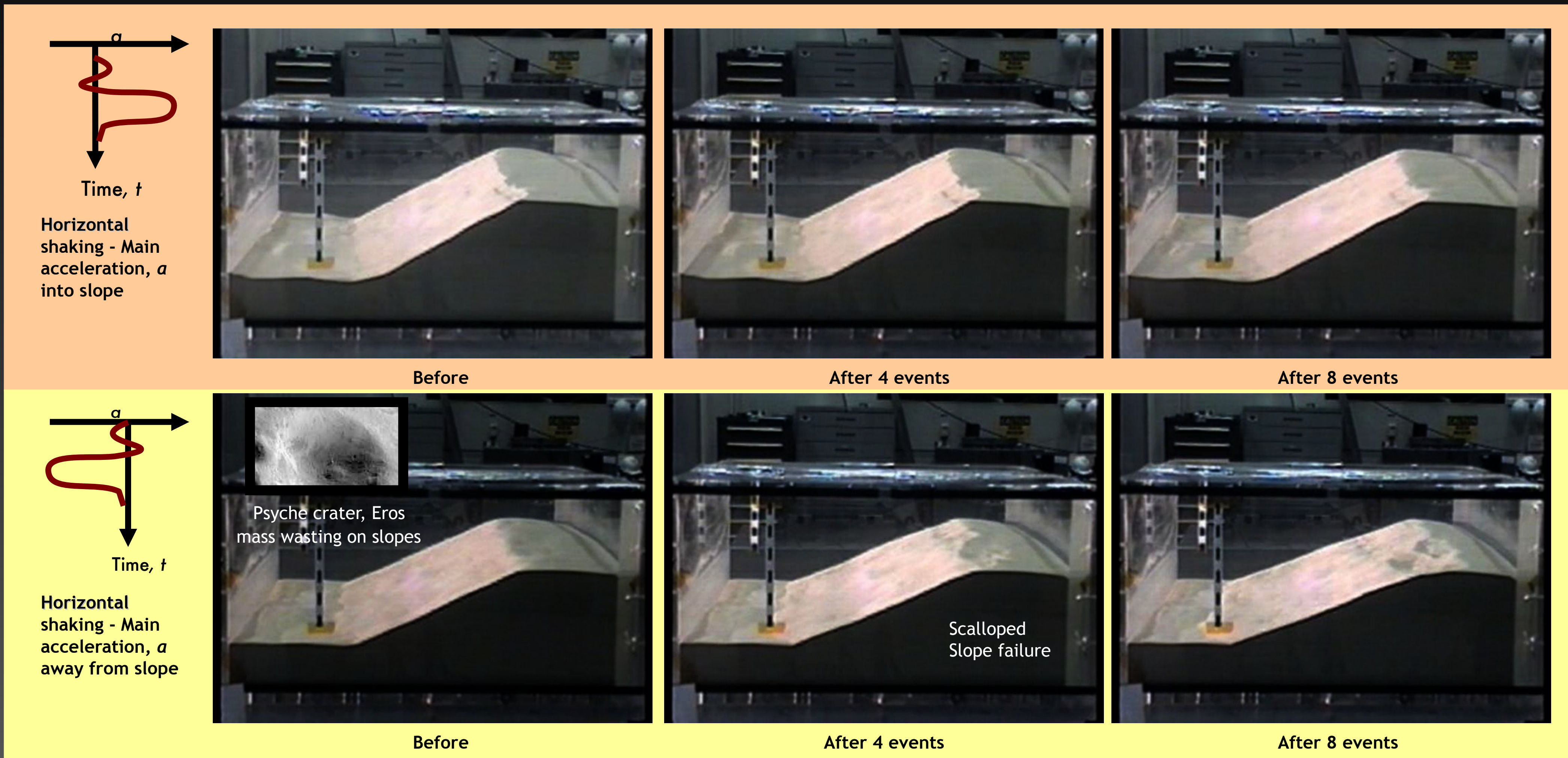
A possible explanation: seismic shaking

- **ASPS – Asteroid Surface Process Simulator**
    - **Izenberg and Barnouin, AGU 2004.**
- 1 x 1 x 0.4 m Plexiglas box, bolted to a shake table
- Regolith simulants – Sand, pebbles, etc.
- High speed camera (up to 4000 fps)
- Considered seismic accelerations:
    - Jolts or uniform shaking
    - Horizontal or vertical shake direction
    - Accelerations up to few gravities
    - Amplitudes of a few centimeters
- Resemble impact induced P-waves, surface waves
- Multiple slope orientations, landforms



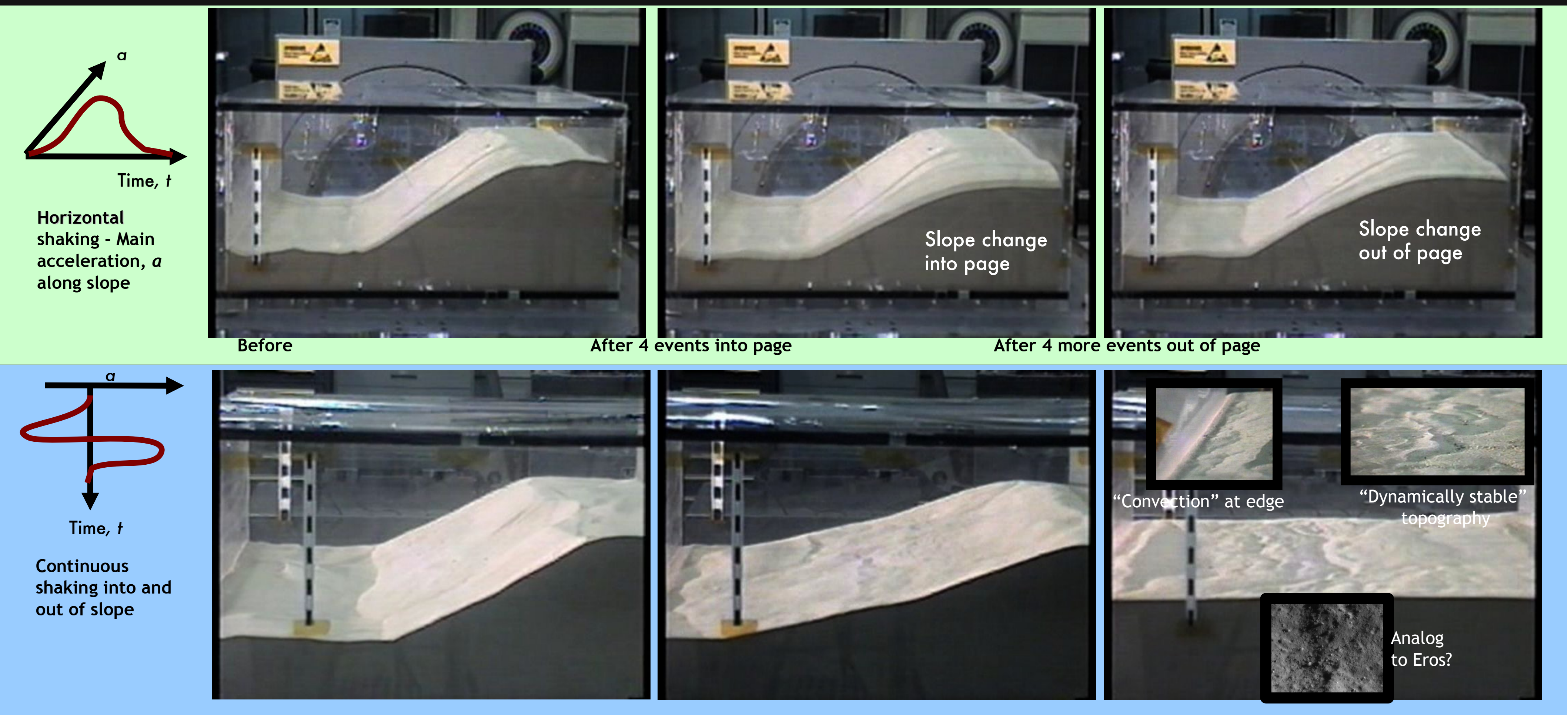


ASPS Experiments - 1



- Horizontal shaking, effects on regolith slopes

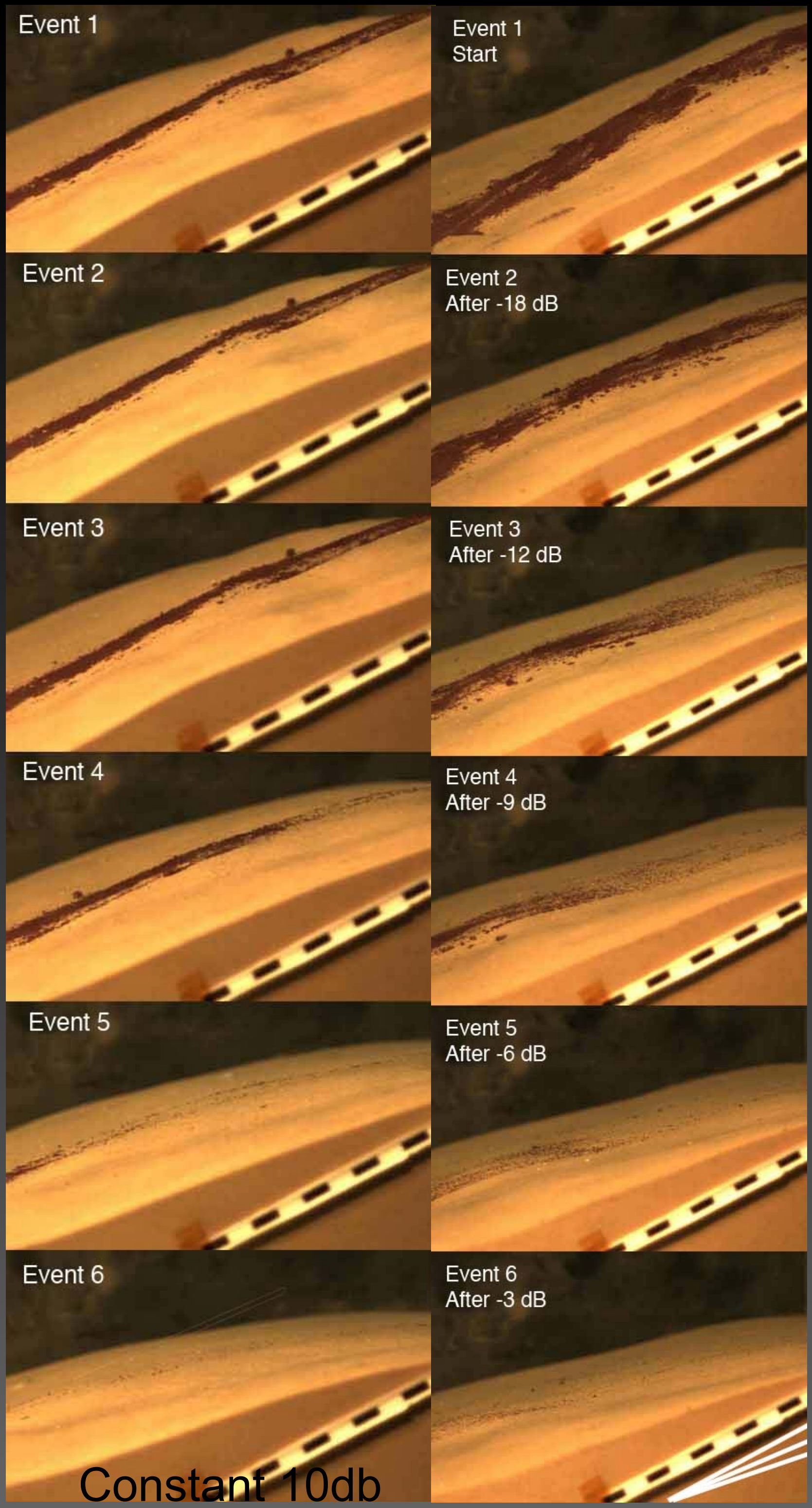
ASPS Experiments - 2



- Horizontal shaking, effects on regolith slopes

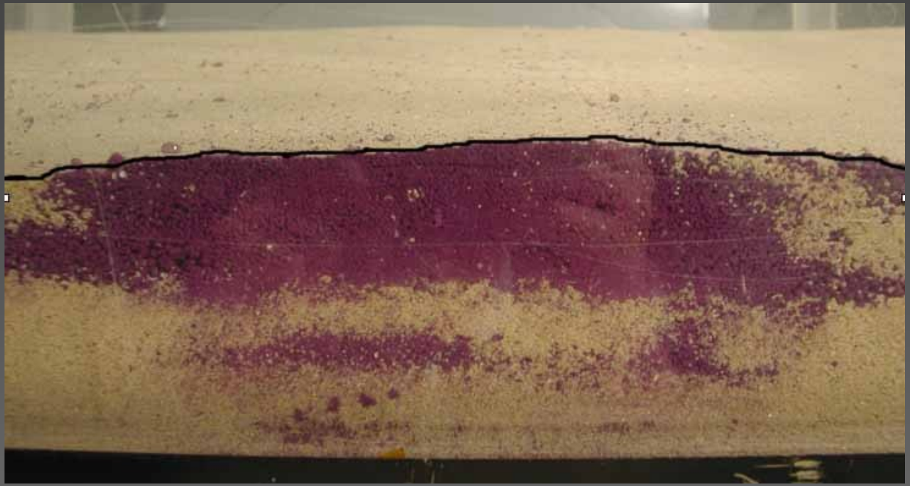
ASPS Experiments - 3

- Horizontal Shaking, effects on crater forms
- Small seismic jolts, both individually and in aggregate, can induce slumping of crater walls, migration of boulders, smoothing of regolith topography.
- Single large jolts may induce larger scale changes more quickly, and result in significant horizontal transport of regolith in ballistic trajectories if the mobilizing acceleration is at an angle to local gravity.

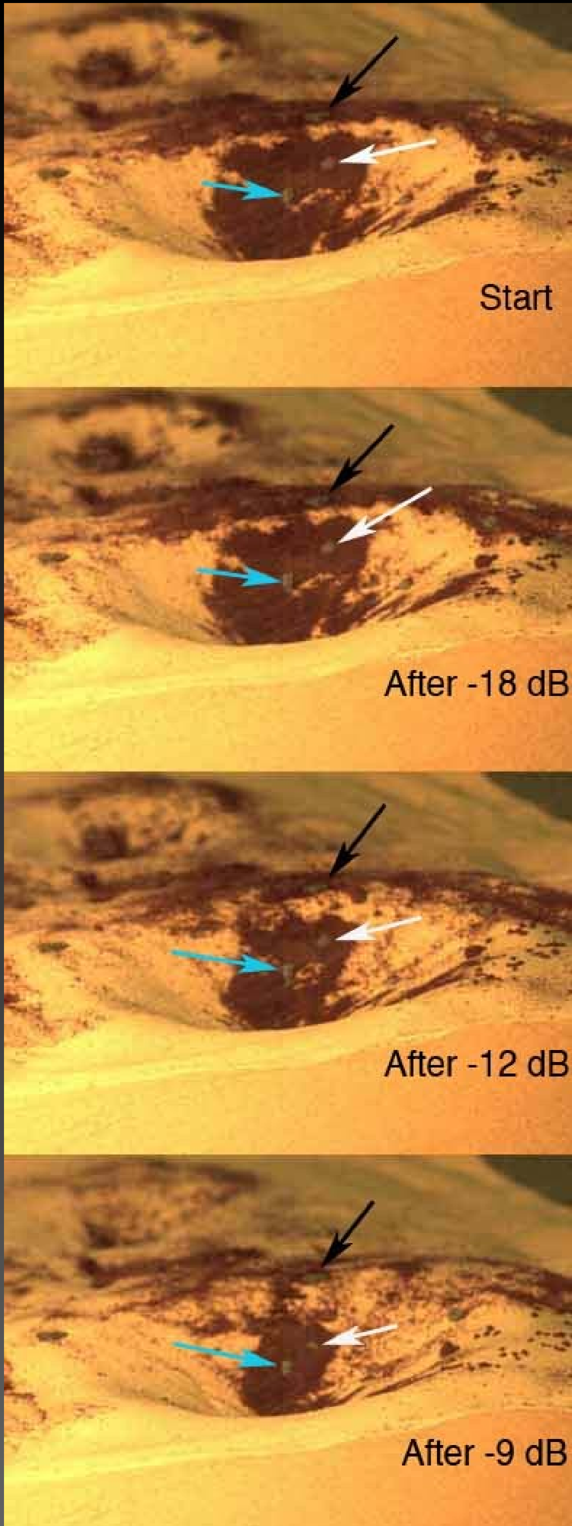


ASPS Experiments - 4

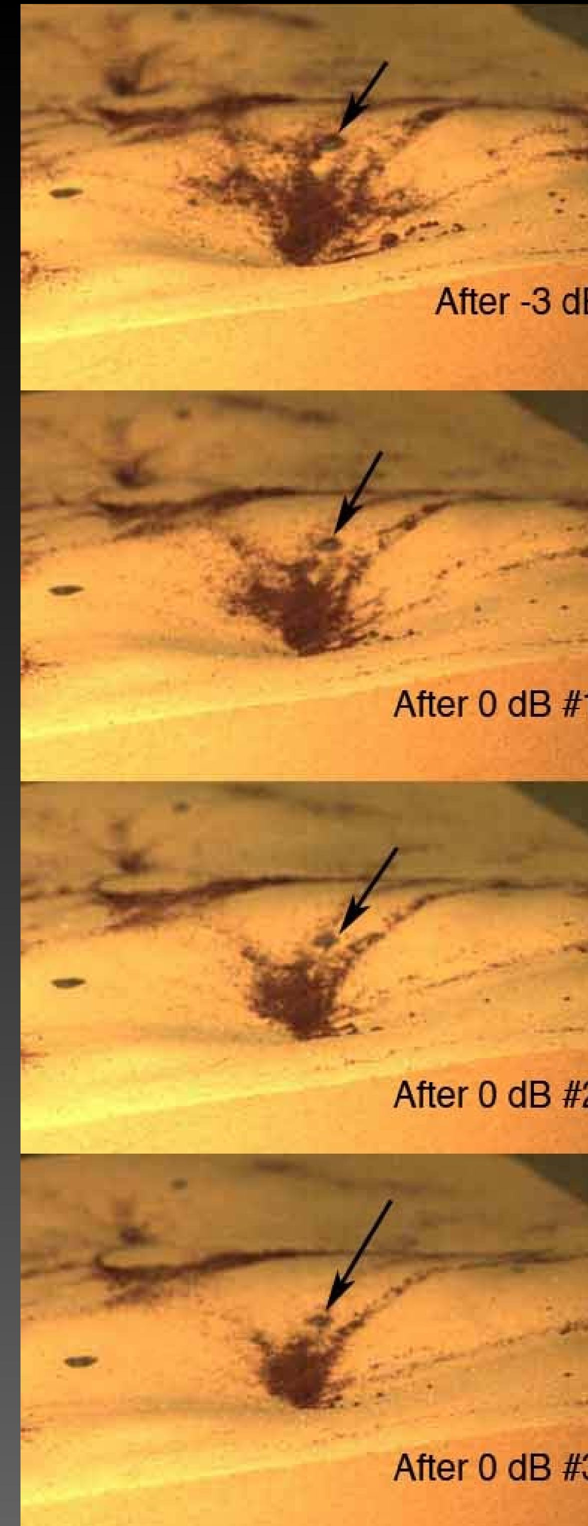
- Horizon shaking on slopes
- Slope modification and mass-movement experiments.
- Burial of material at slope bottoms



Crater modification

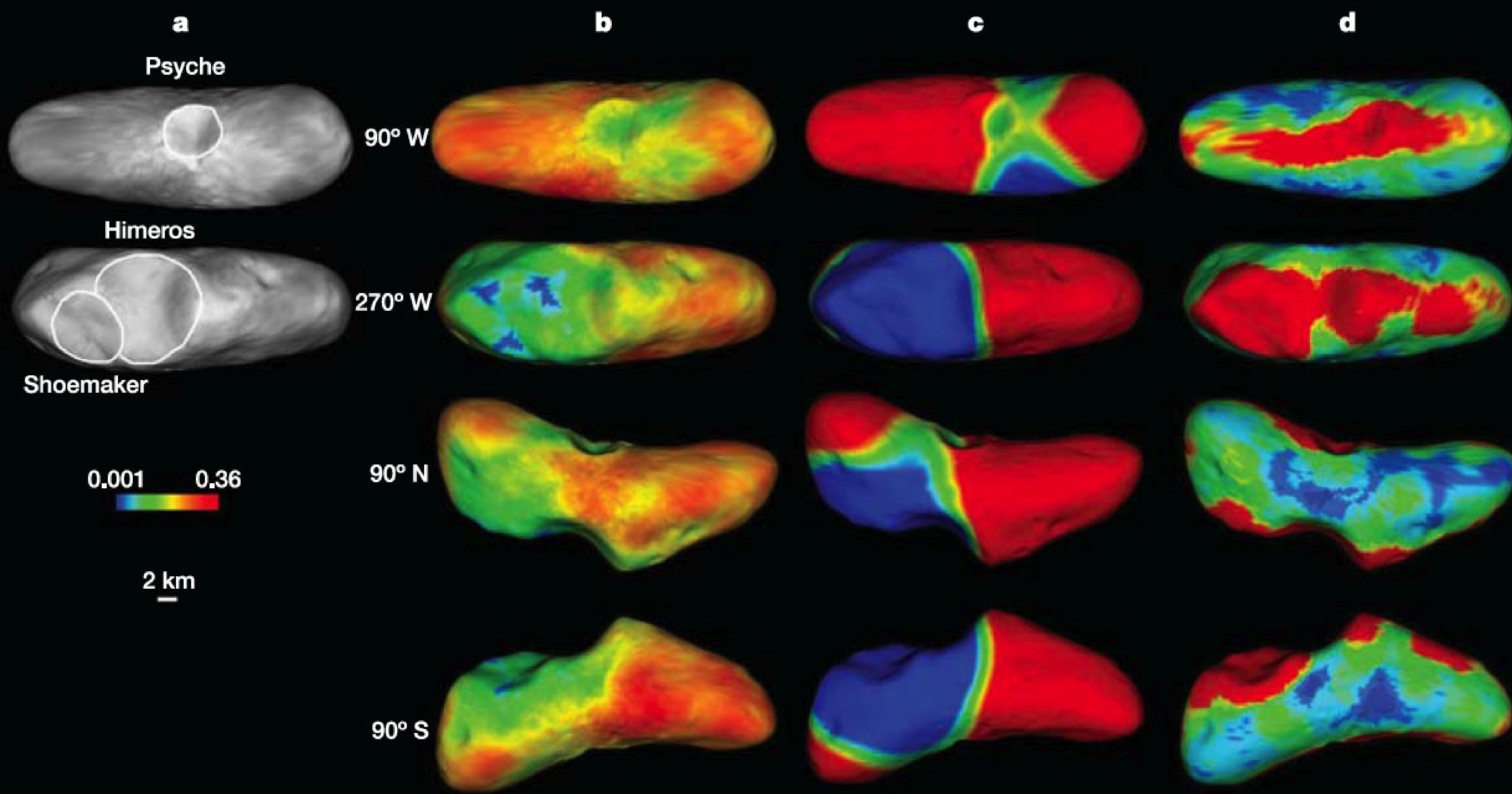


- Crater form softening
- Mass wasting
- Boulder movement
- Burial of material



Seismic shaking – another line of evidence

Thomas and Robinson, Nature, 2005



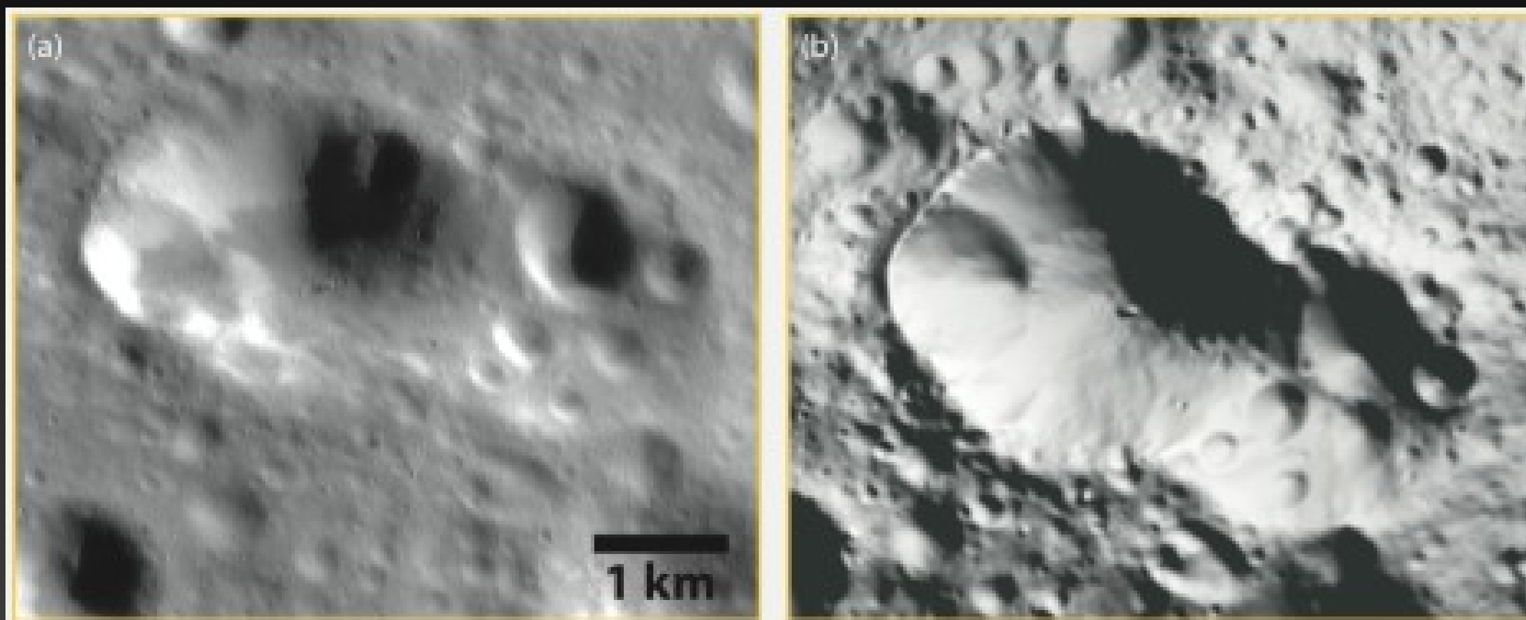
Crater density
0.17 km< D < 2km

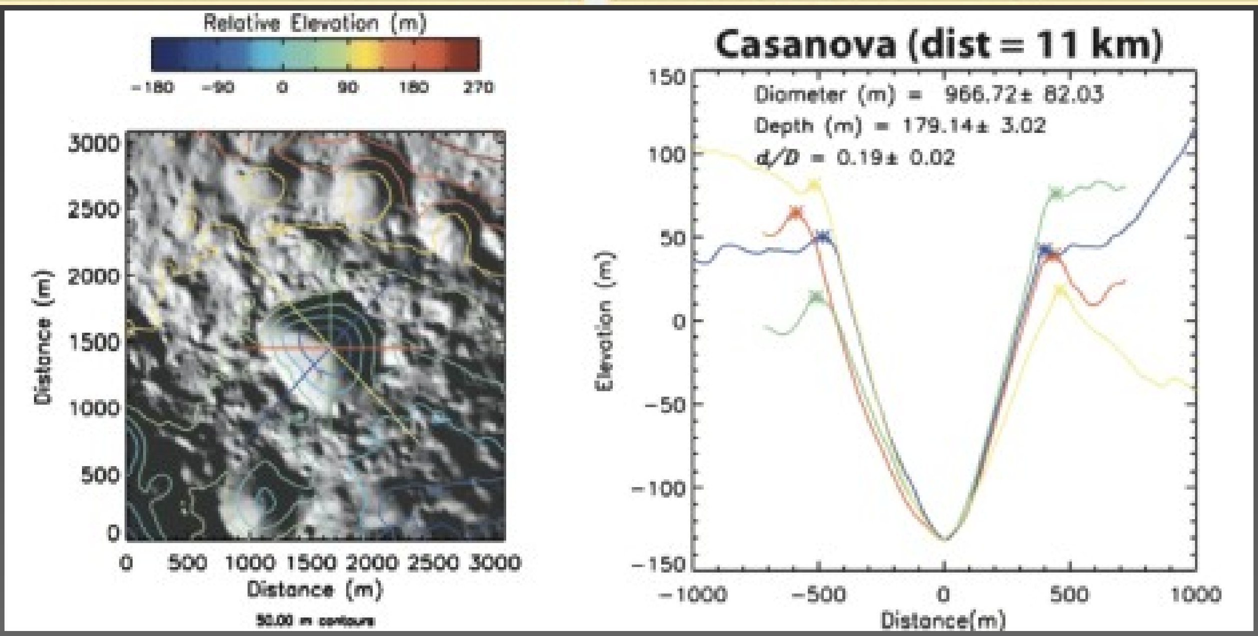
Straight line
distance

Ejecta

Trying to quantify the effect

- Measured crater depth to diameter ratio as a function of distance from Shoemaker

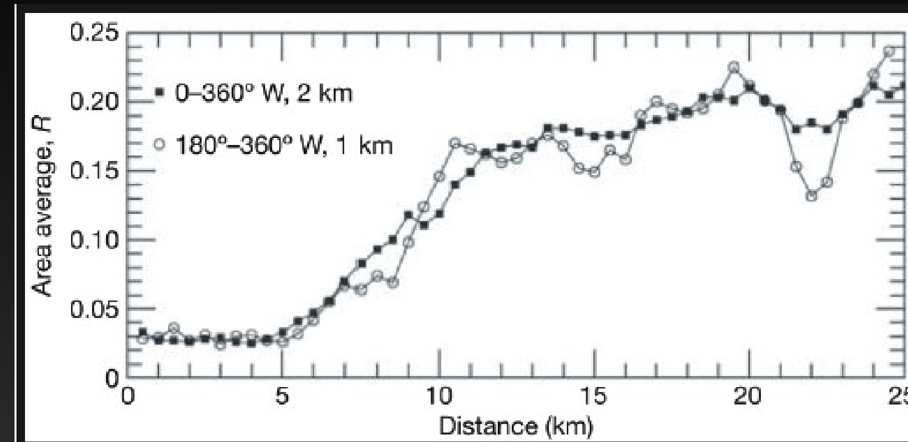


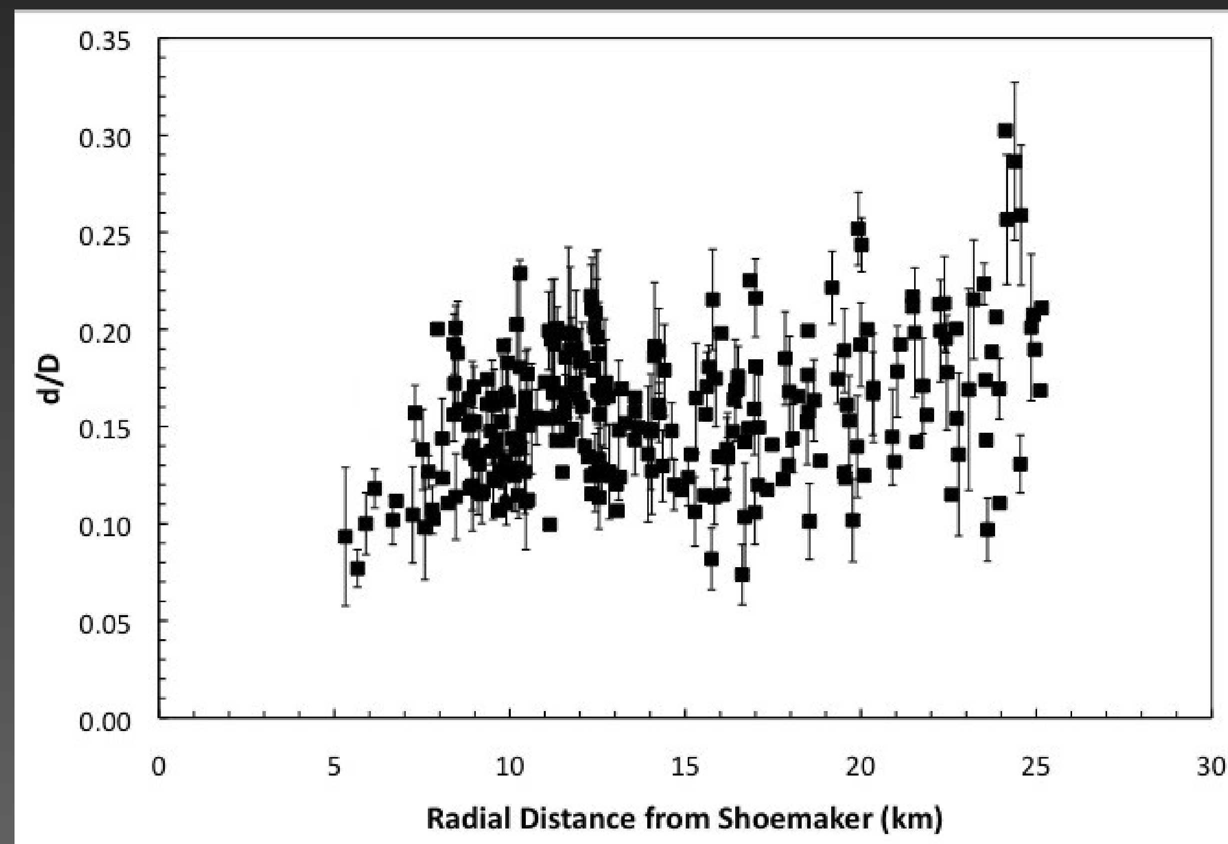


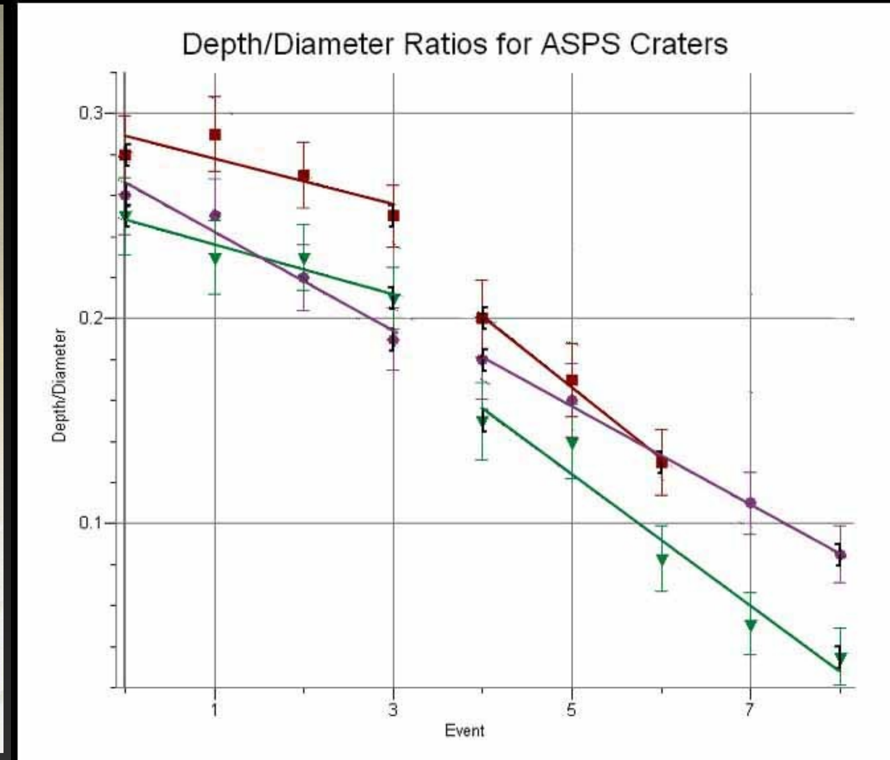
Ernst et al, in prep.

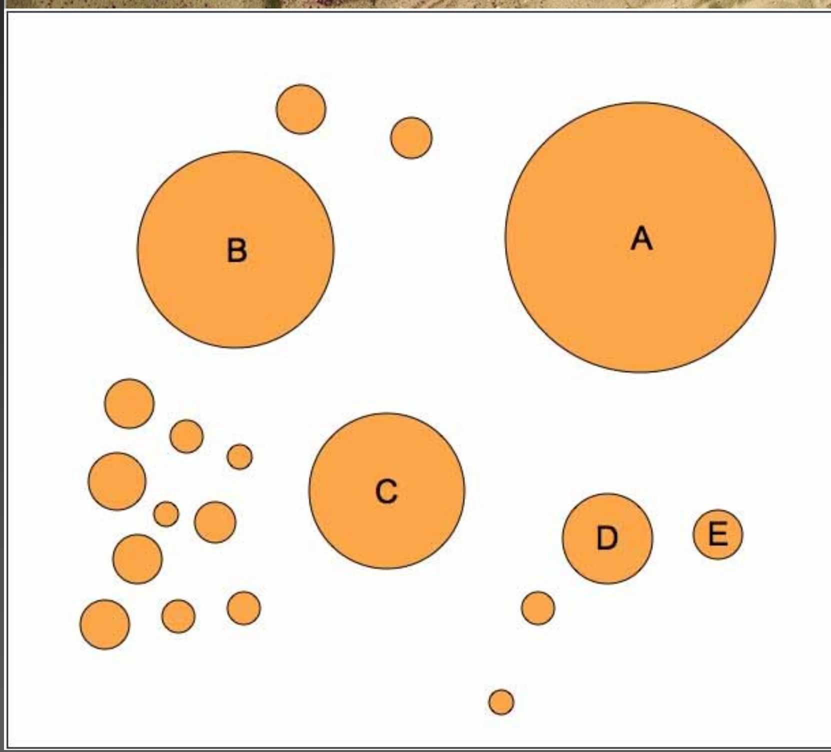
Shallow crater near Shoemaker

- Not seen relative to other large craters
- Not limited to regions where ejecta is found
- Strong seismic effects within 1.3 *D*







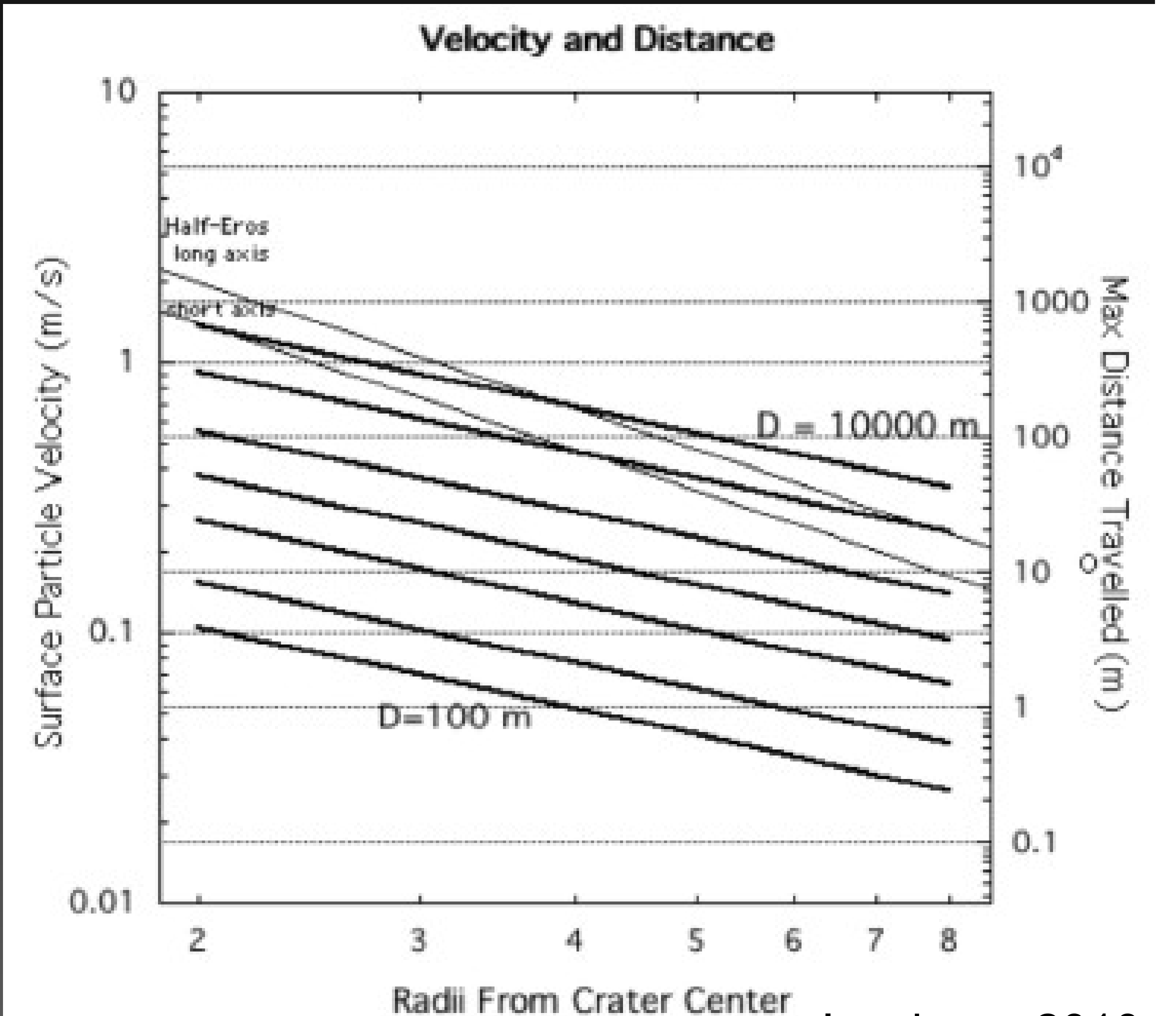


- Depth/diameter decrease with increased cumulative seismic effect.

Malanoski et al., LPSC, 2007

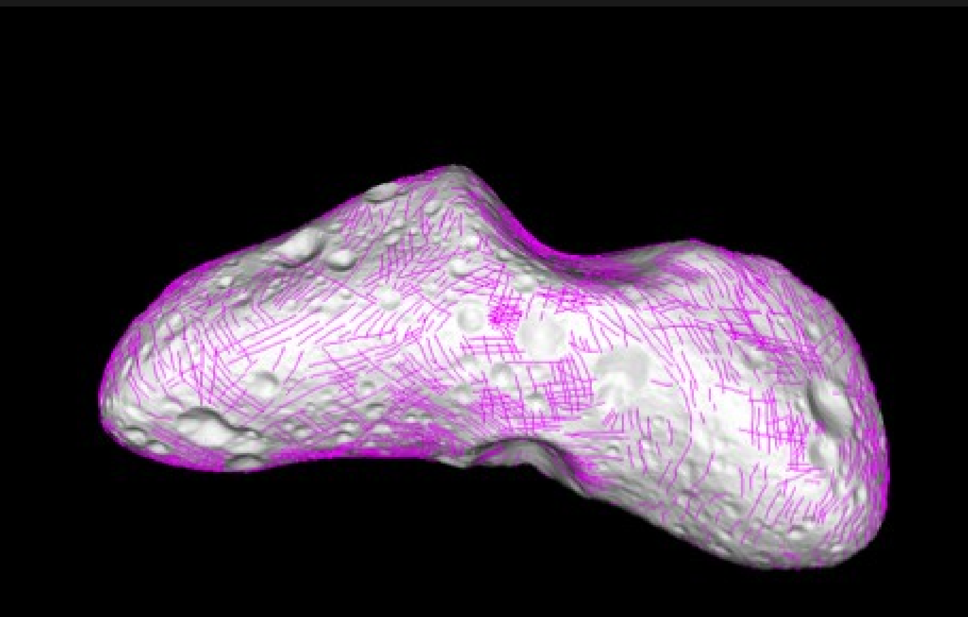
Model exist to estimate accelerations due to seismic shaking

- Semi-empirical results
  - Schultz and Gault, Moon, 1975 investigated seismic shaking from Imbrium basin
    - Apollo Saturn 5 impact
      - McGarr et al. JGR 1969; Latham et al. Science 1970.
  - Richardson J. et al. 2005 and 2006



Izenberg, 2010

Another approach – Numerical investigation



Buczkowski et al., Icarus 2008

Crawford and Barnouin-Jha, LPSC, 2003

Heterogeneity common in planetary settings

Earth – Ries crater

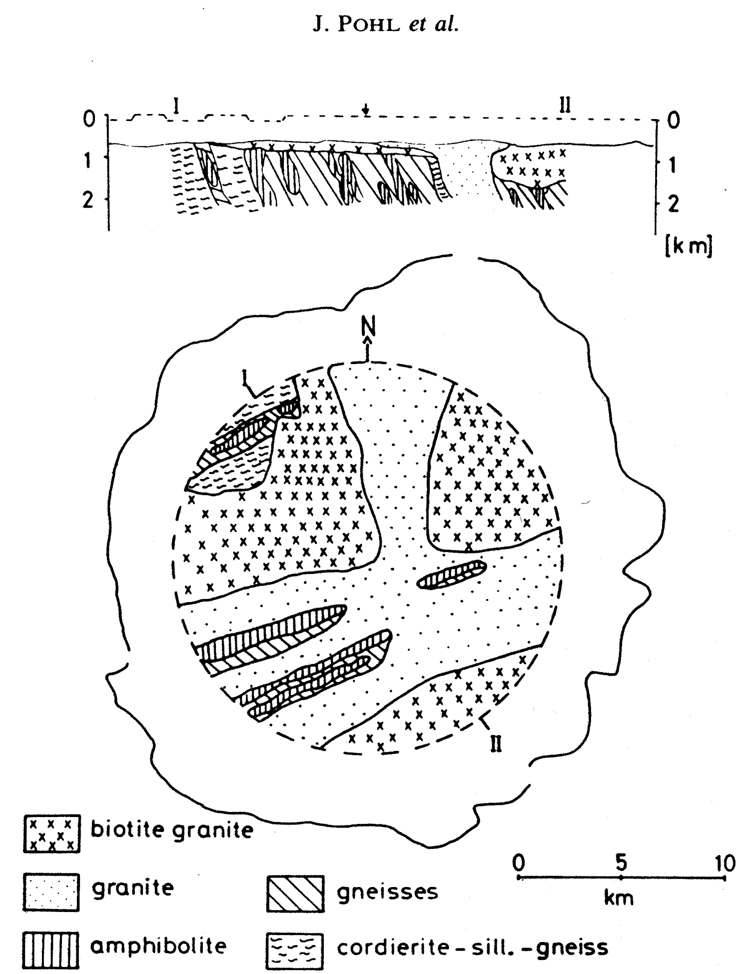
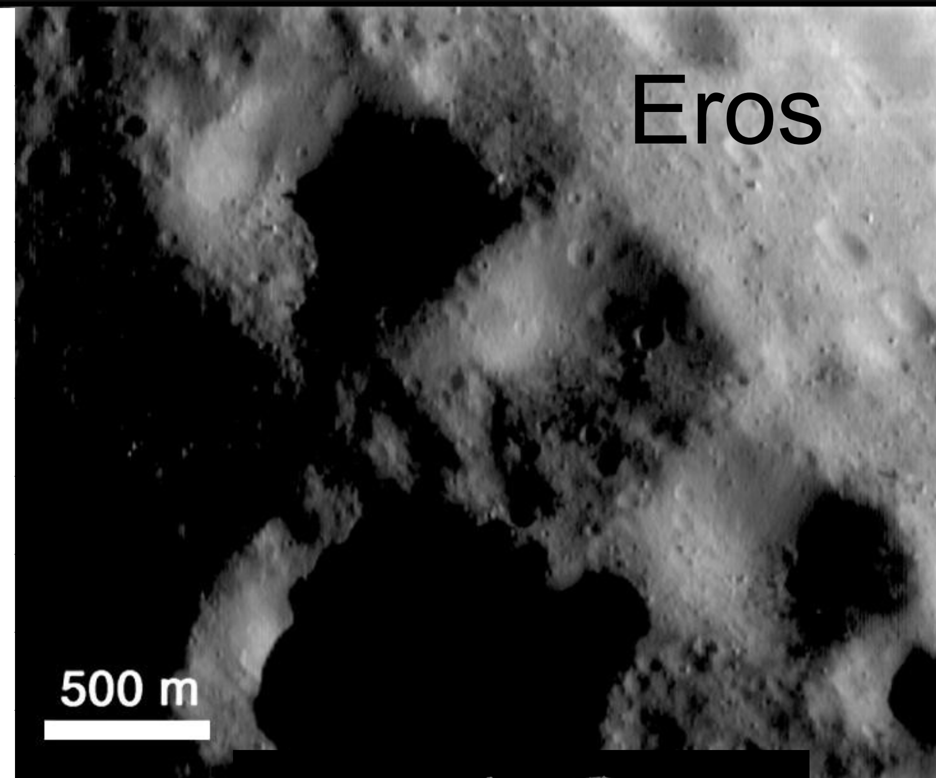


Fig. 4. Geological map and vertical cross section of the crystalline basement of the Ries crater area reconstructed by Graup (1975); modified after Graup (1977); irregular circular line = tectonic rim of the crater; I–II indicates the position of the cross section.

Asteroids

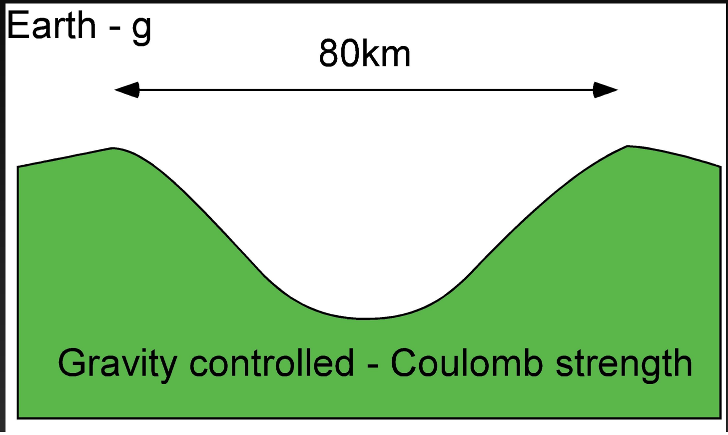


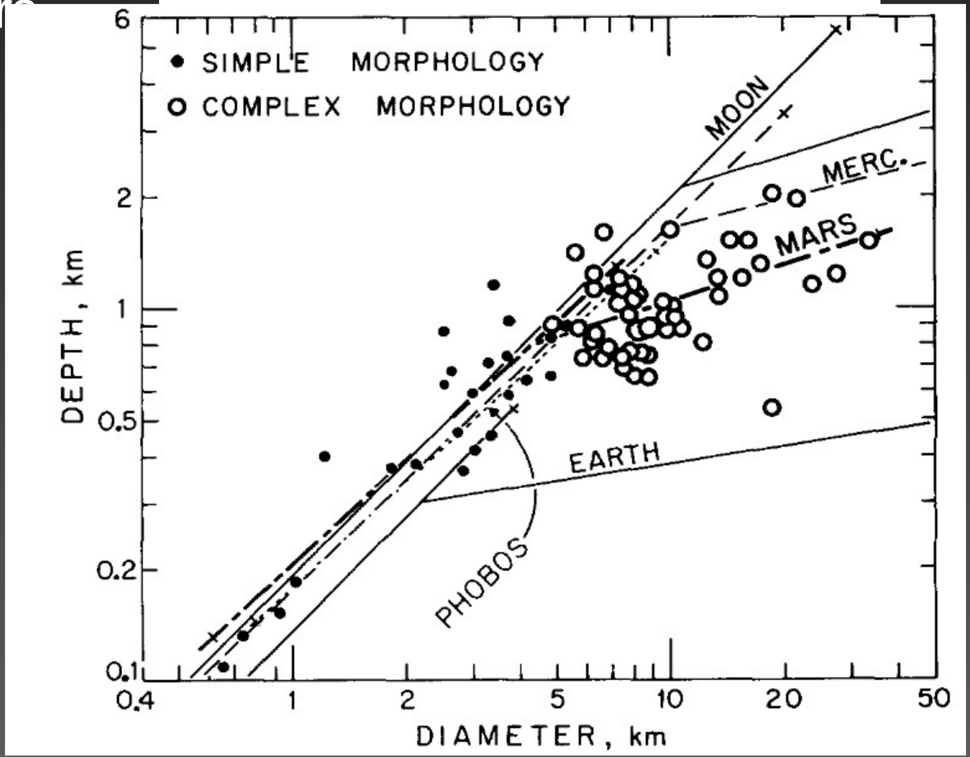
Pre-existing target structure influences cratering process

- Observational evidence
  - Meteor crater: Heterogeneity influences melt generation and crater shape (Kieffer, 1971; Shoemaker, 1963)
- Experimental evidence
  - Coarse targets : Heterogeneity influences excavation (Cintala et al., 1999, Barnouin-Jha et al., 2005)
    - Discrepancies with previous results (pore space collapse, attenuations at free-surfaces, initial coupling)
  - Asteroid fragmentation: Pre-fractured targets do not fragment further; instead ejecta speed increases (Martelli et al. 1994)
- Numerical evidence
  - Agglomeration of large boulders
    - Faster ejecta and greater shock attenuation near impact point relative to a solid target (Asphaug et al., 1998)
  - Porosity and strength
    - Influences excavation rates (Collins and Wunnemann, 2007)

Target heterogeneity, target strength and crater modification

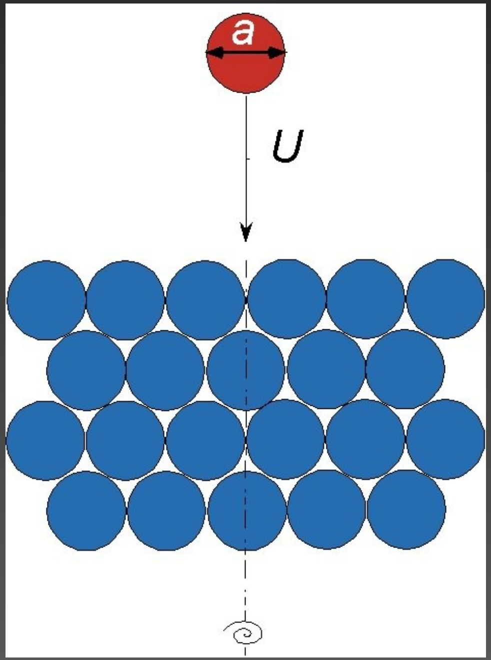
- Heterogeneity may influence target strength
  - Models of gravity controlled cratering with pressure dependent strength model
    - Produce large simple craters
  - But data reveal collapse of craters at far smaller scales!





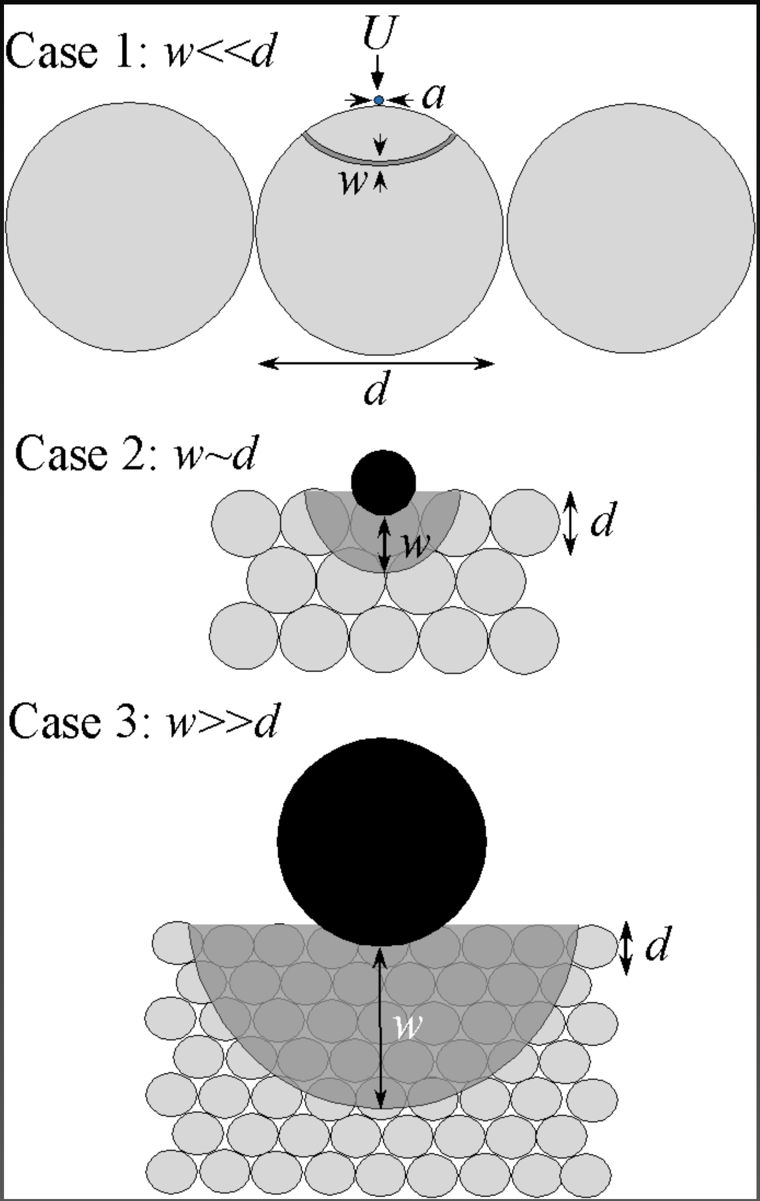
Gain additional insights using experimental and numerical approaches

- Investigate shock decay and crater growth in simple granular targets
  - Variables:
    - Ratio of projectile diameter, *a,* to target grain size, *d*
      - Initial shock pulse thickness, *w*
    - Target strength
    - Pore space
    - Target geometry and coupling
  - Slow speeds (*U*<5km/s) – Prevents complicating factors
    - Vaporization and phase changes



How do *w* and *d* possibly interact?

- *w* << *d*
  - Shock wave interact primarily with individual grain until edge
    - EOS and porosity of target grains controls
      - **Shockwave decay**
      - **Excavation velocity and crater growth**
    - Significant losses at edges
- *w* ~ *d*
  - Shock wave should interact with individual target grains
    - Rapid decay of shock wave
    - High initial excavation velocity
    - Rapid decay in crater growth rate
    - Rapid decay in ejecta excavation rate
- *w* >> *d*
  - Shock wave will not see individual grains
    - Slower wave decay
    - Slower crater growth and ejecta excavation rate approaching rate defined by EOS and porosity for target

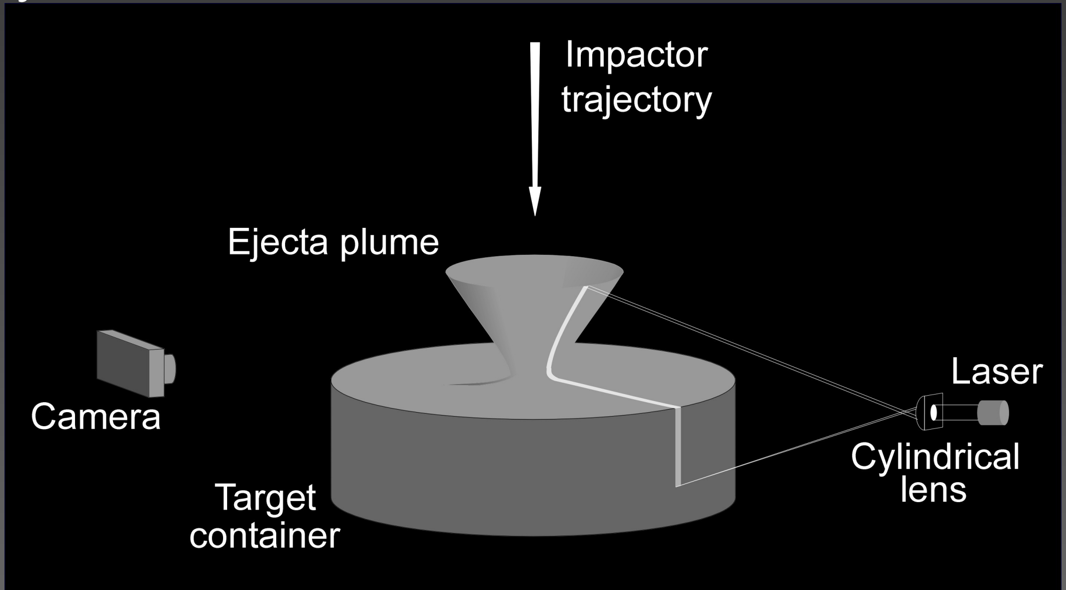


Impact experiments – focus on crater growth and excavation as proxy for shock decay

- Performed at various facilities (NASA JSC, AMES and U. Tokyo)
  - Assess crater shape as a function of time
  - Measure ballistic trajectory of individual ejecta

$$\frac{v}{\sqrt{gR}} = k\left(\frac{x}{R}\right)^{e_x}$$

- Types of target, impact velocity and projectile sizes vary
  - Projectile: 4.8mm Al; 0.9 cm Pyrex; 3.175 mm glass
  - Target: Glass beads – 220μm, 3.175 mm glass; angular sand - 0.5-2mm
  - Velocity - between 0.3 and 5km/s



Cratering efficiency assuming pt. source

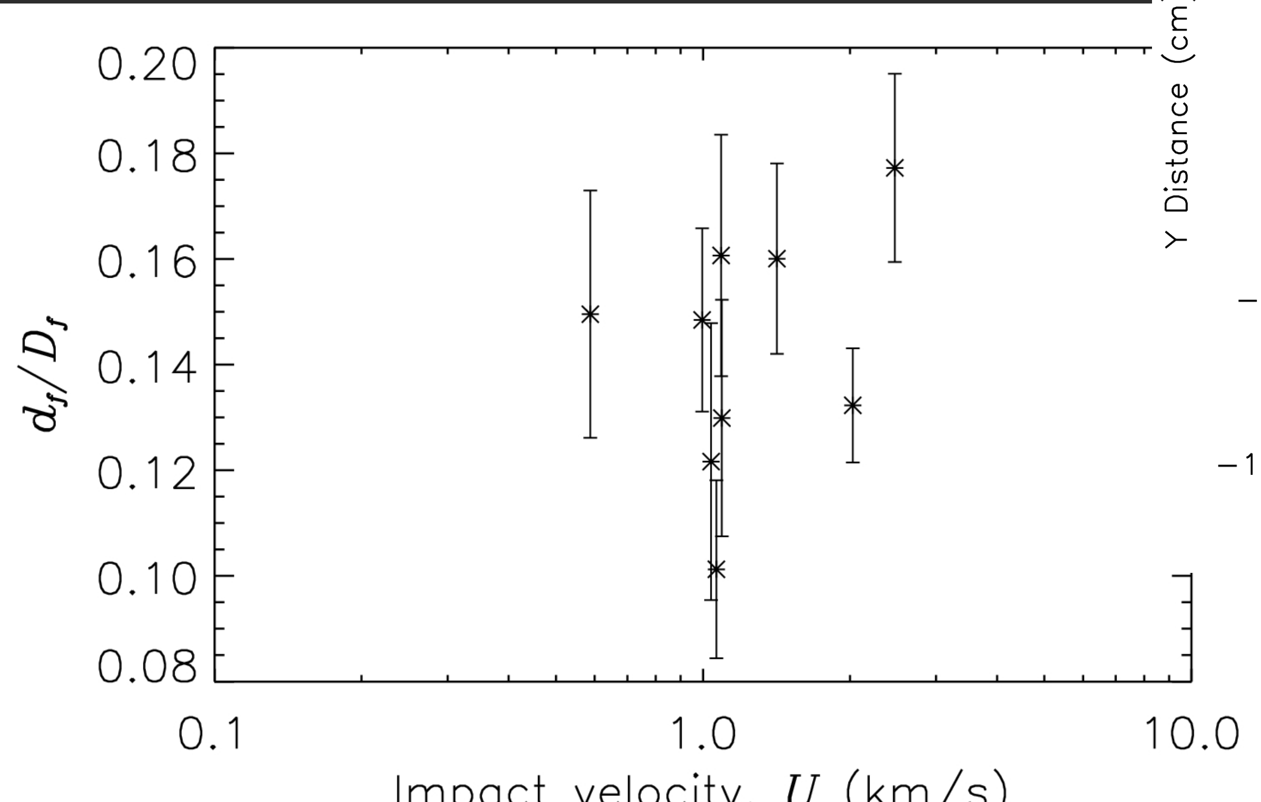
- Dimensionless radius is given by
  - $R/a = k\, \pi_2^{-\alpha/3}$
- Dimensional analysis
  - $\alpha = 3/7$ » momentum
  - $\alpha = 3/4$ » energy

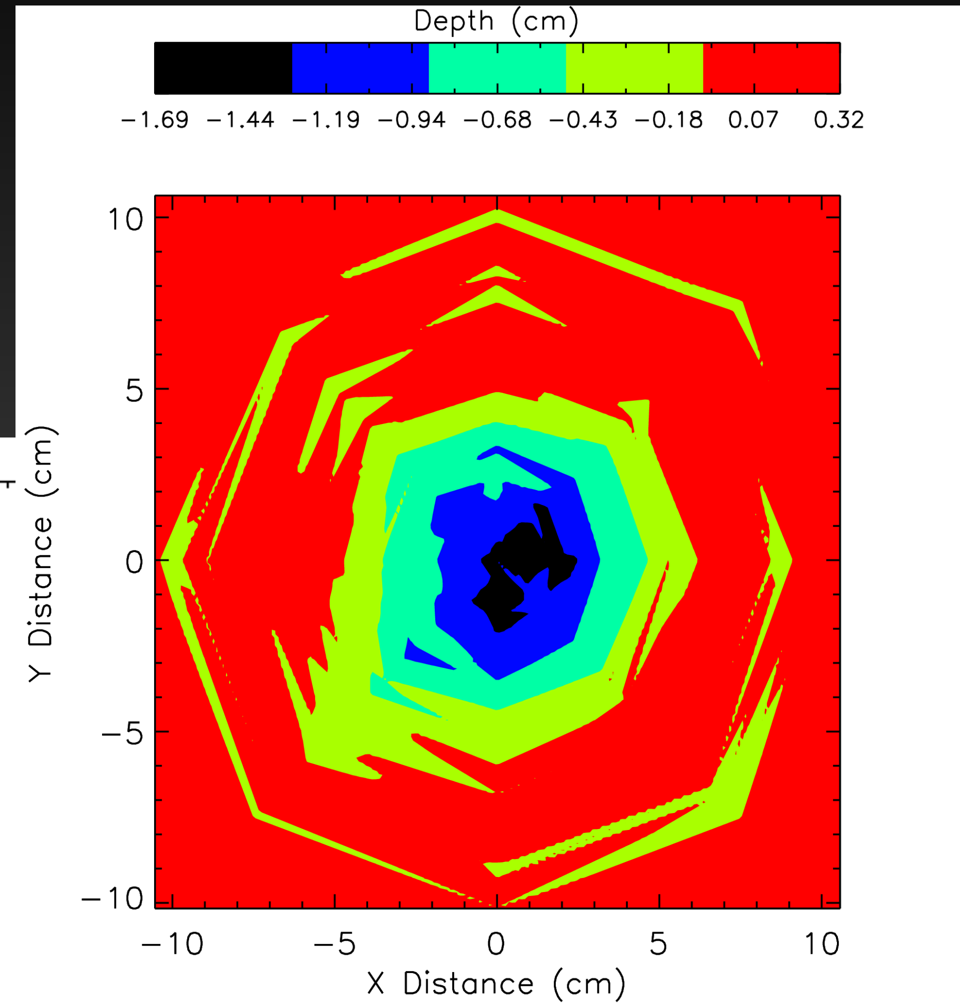
Despite substantial differences in grain size, efficiency are comparable!!!

Target type	Projectile size, a (cm)	Grain size, d (cm)	Impact Velocity, U (km/s)	Porosity, φ	Angle of repose*	Scaling parameter, α	Ref.
Coarse glass spheres	0.318 Gl	0.318	0.5-2.5	0.36	26	0.60±0.08	[8]
Fine glass spheres	0.9 Px	0.022	0.08-0.3	0.36	25	0.58±0.05	[7]
Coarse sand	0.476 Al	0.1-0.3	0.9-2.0	0.44	38	0.45±0.01	[5]
Coarse sand	0.318 Gl	0.05-0.1	0.3-1.7	0.44	34	0.45±0.01	[5]
20- 40 Sand	0.635 Al	0.0457	~1.0	0.38	32	0.46	[6]
Ottawa sand	0.318-1.22	~0.01	1.77-7.25	0.33	35	0.51	[14]
Water	0.318-1.22	NA	1.0-3.0	0	0	0.65	[14,15]

Crater shape in coarse spheres

- Asymmetric top-view
- Depth-to-diameter (d/D) ratio
  - 0.1 to 0.18
  - No systematic trend with impact velocity





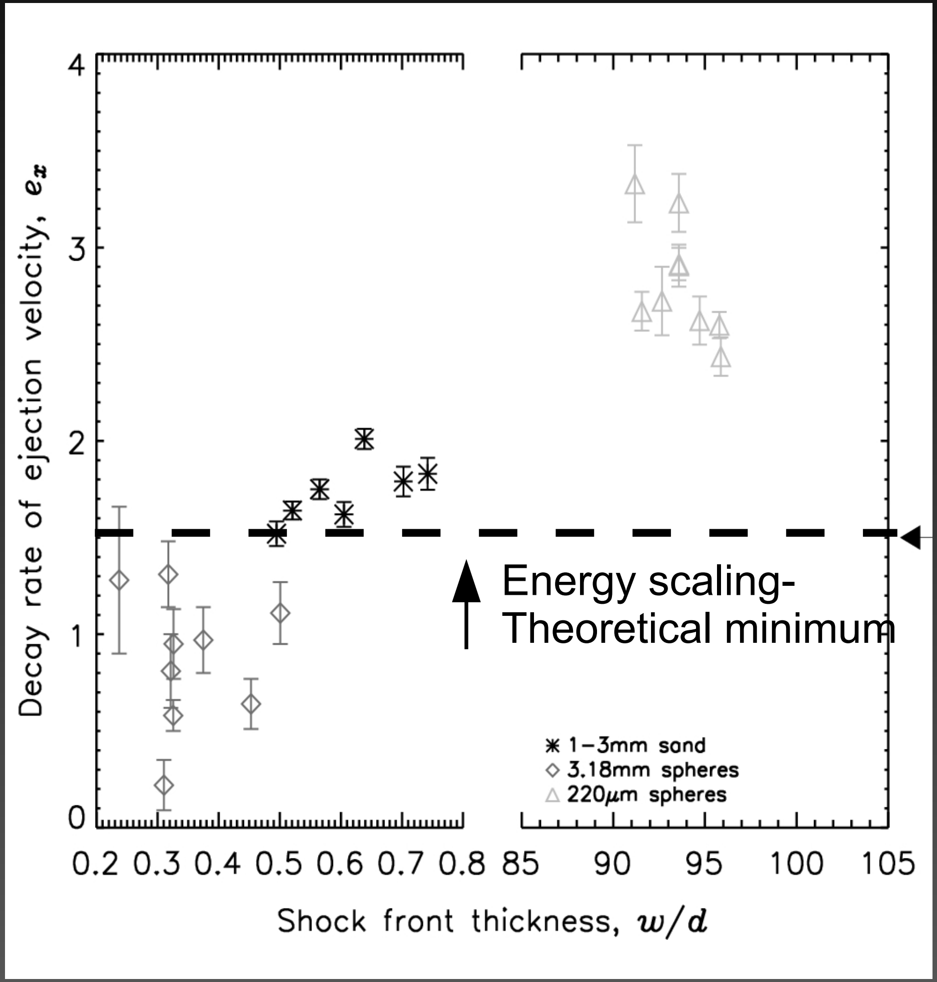
Shock front thickness and e_x

- Use 1-D hydrodynamics

$$w/d \sim 2a(U_t - u_t)/U_p$$

a=projectile diameter; U_t, U_p = shock front velocity in target, projectile; u_t=target material velocity

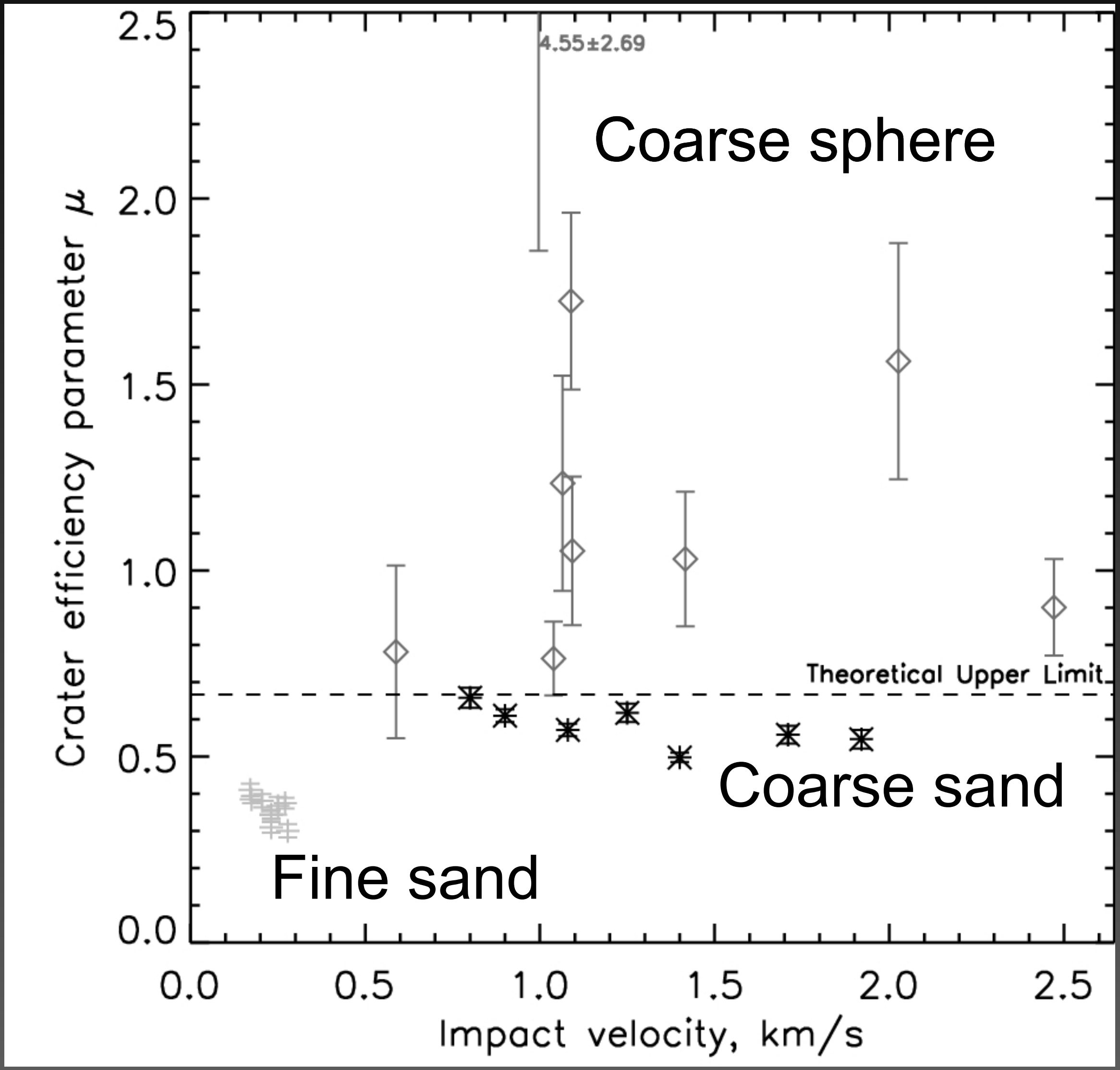
- Regardless of target
  - No obvious dependence
  - Coarse sphere
    - All measured values less than theoretically permitted by point source model

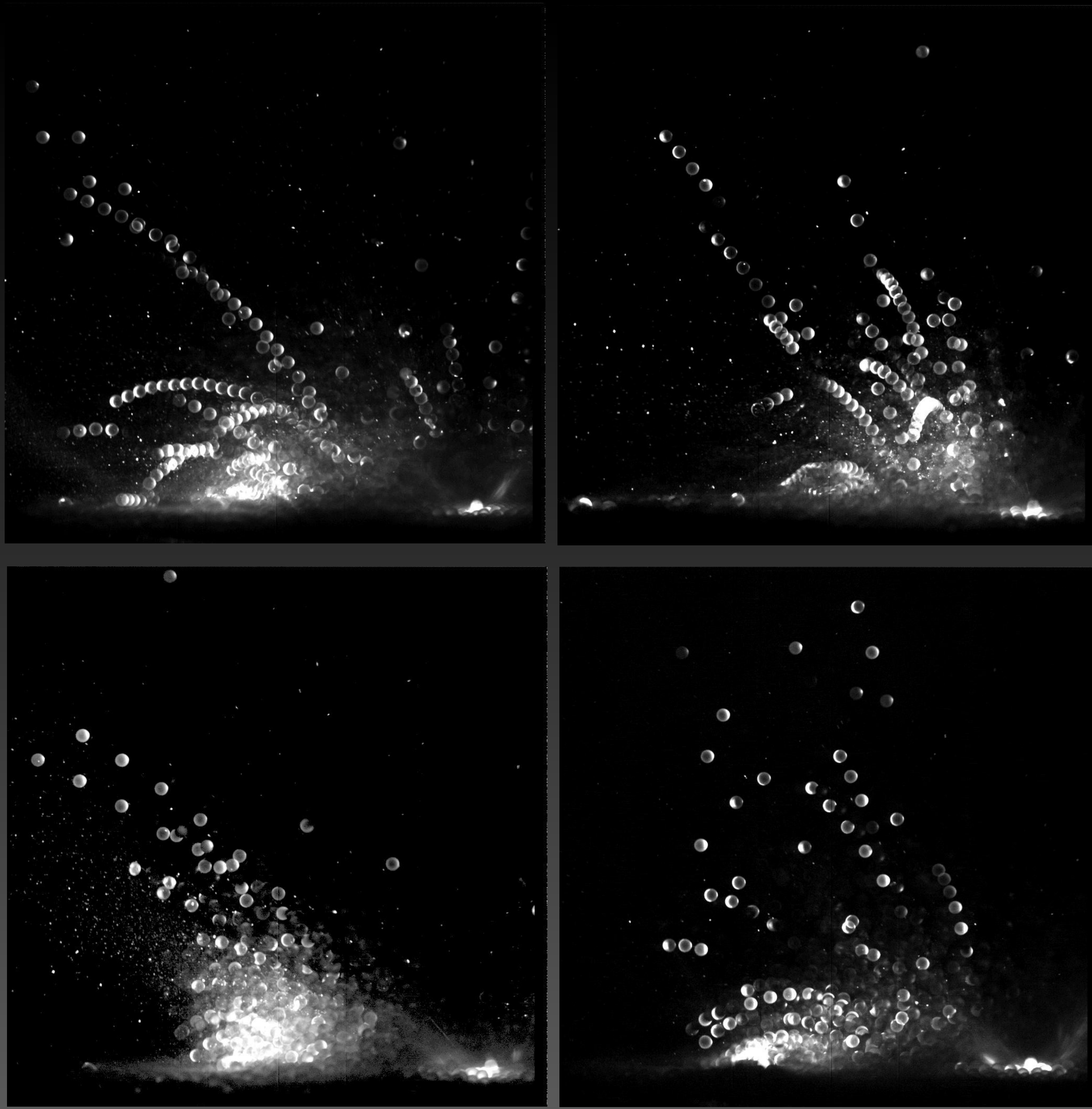


Weak projectile – shatters immediately regardless of velocity

Efficiency μ derived from crater growth or excavation and impact velocity

- Within theoretical limits (point source assumption)
  - Efficiency decreases with velocity
    - Frictional effects
    - Fragmentation of projectile
- Outside of theoretical limits
  - Coupling process between projectile and target dominates





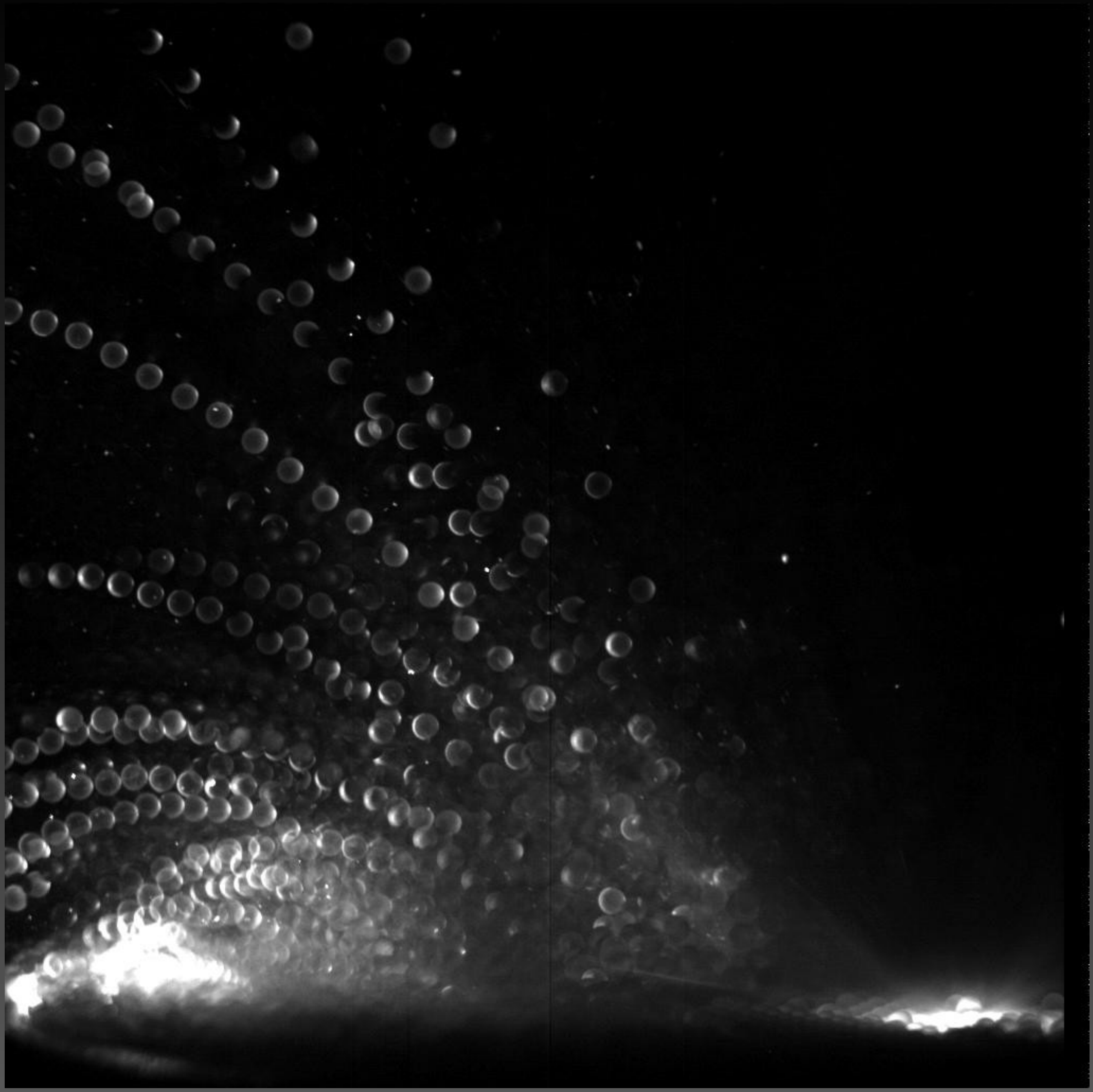
Case w~d

Glass sphere impacts

V~1 km/s
a = 3.175mm
d = 3.175mm

Collisions

Coupling is critical



Case *w~d*

Glass sphere impacts

V~2 km/s
a = 3.175mm
d = 3.175mm

Collisions

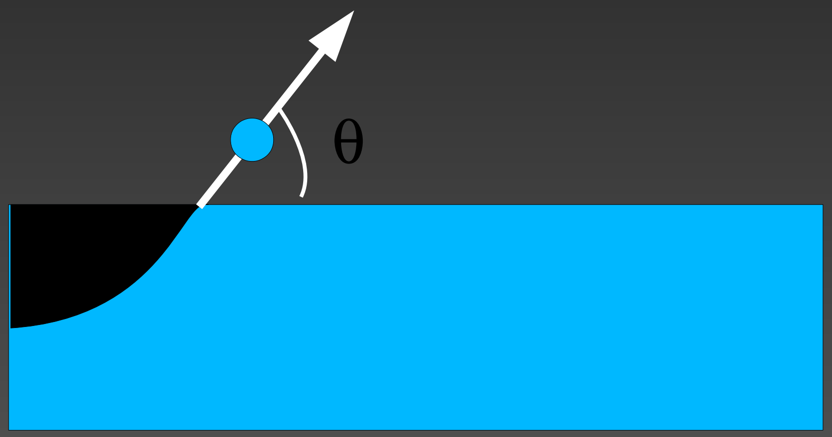
Coupling is less important

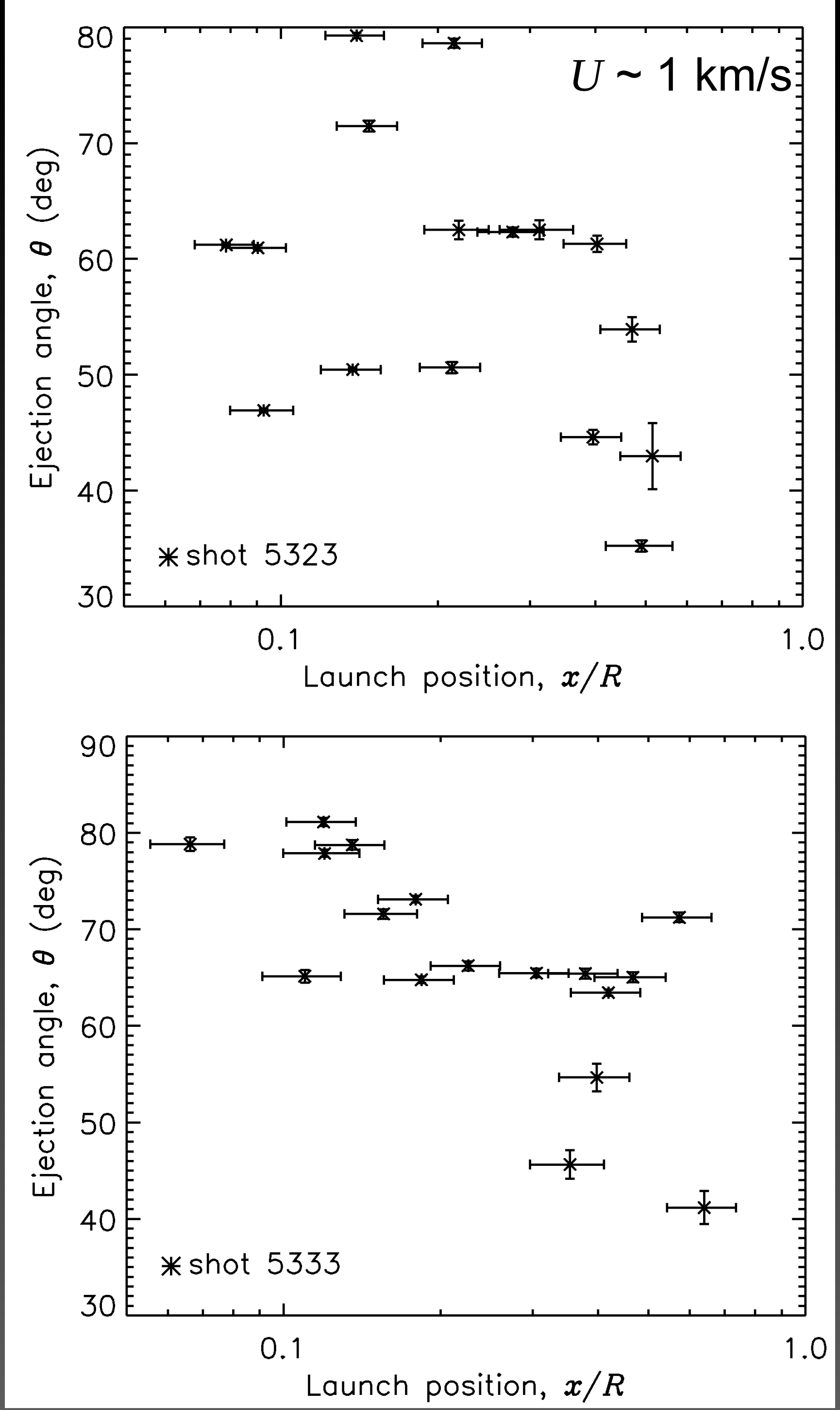
Less so even at 5 km/s

NASA AMES vertical gun range

Ballistic trajectories - coarse spheres

- Excavation angles
  - 30°-80°
    - Generally angles tend to decrease with x/R



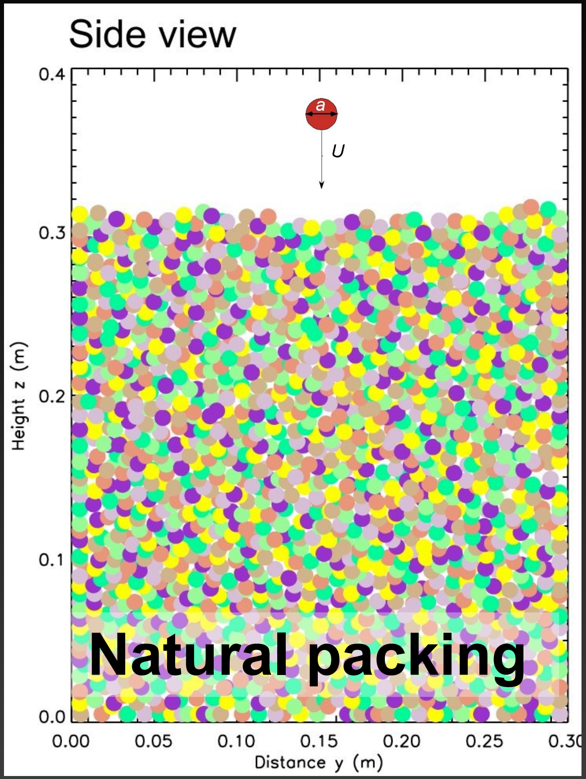


Summary of laboratory experiments

- Projectile coupling becomes very important when target is heterogeneous
  - Yields a wide range of crater shapes, ejection angles and velocities => derived cratering efficiency μ
- w:d ratio may be important but difficult to assess
  - Effects may be offset by coupling
- Collisions and comminution (frictional losses) exist and could play a role during cratering
- Surprise
  - Coarse target cratering remains efficient - why?

Description of numerical model

- Idealized hydrodynamic calculations
  - CTH with on-the-fly grid refinement
    - Minimum 8 cells (usually 20) per target ball
  - Used Mie-Gruneisen EOS for quartz
    - No phase changes
    - Low impact velocity U = 5 and 10 km/s
  - Various target properties and strength
    - Like target 'spheres' - weld together and flow
      - No strength
      - Coulomb model – pressure dependent yield strength
      - Elastic-perfectly plastic
    - Strong spheres slide past each other (3D)
      - Elastic-perfectly plastic spheres with no cohesion
  - No porosity within target ‘spheres' and no gravity
  - Impact geometry: Axisymmetric, 2Dr and 3D
- Measure and observe
  - Shock attenuation rates
  - Crater shape
  - Rate of crater growth decay



Housen et al., 1983

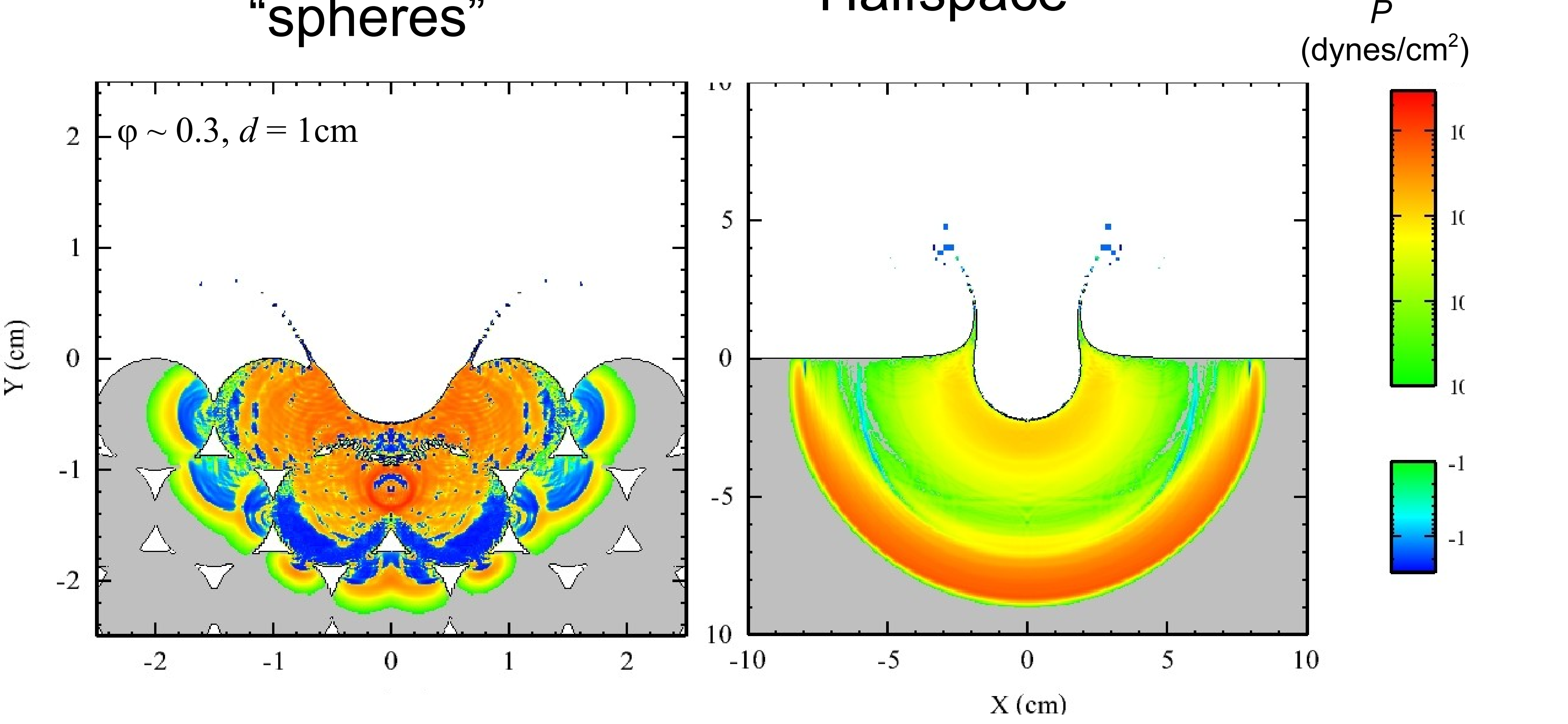
$$\frac{v_e}{\sqrt{(Rg)}} = k\left(\frac{x}{R}\right)^{e_x}$$

2D shock wave attenuation and crater growth for *w* < *d*

a =0.25 cm
U = 5 km/s
No strength
t/(*a*/*v*) ~ 10
X/*d* ~ 20

Close-packed "spheres"

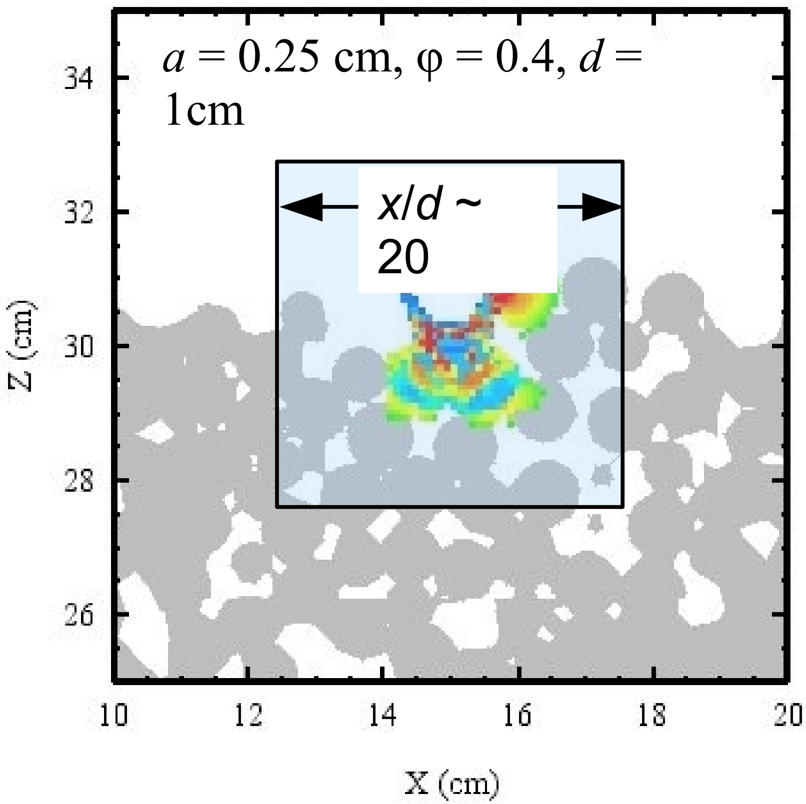
Halfspace



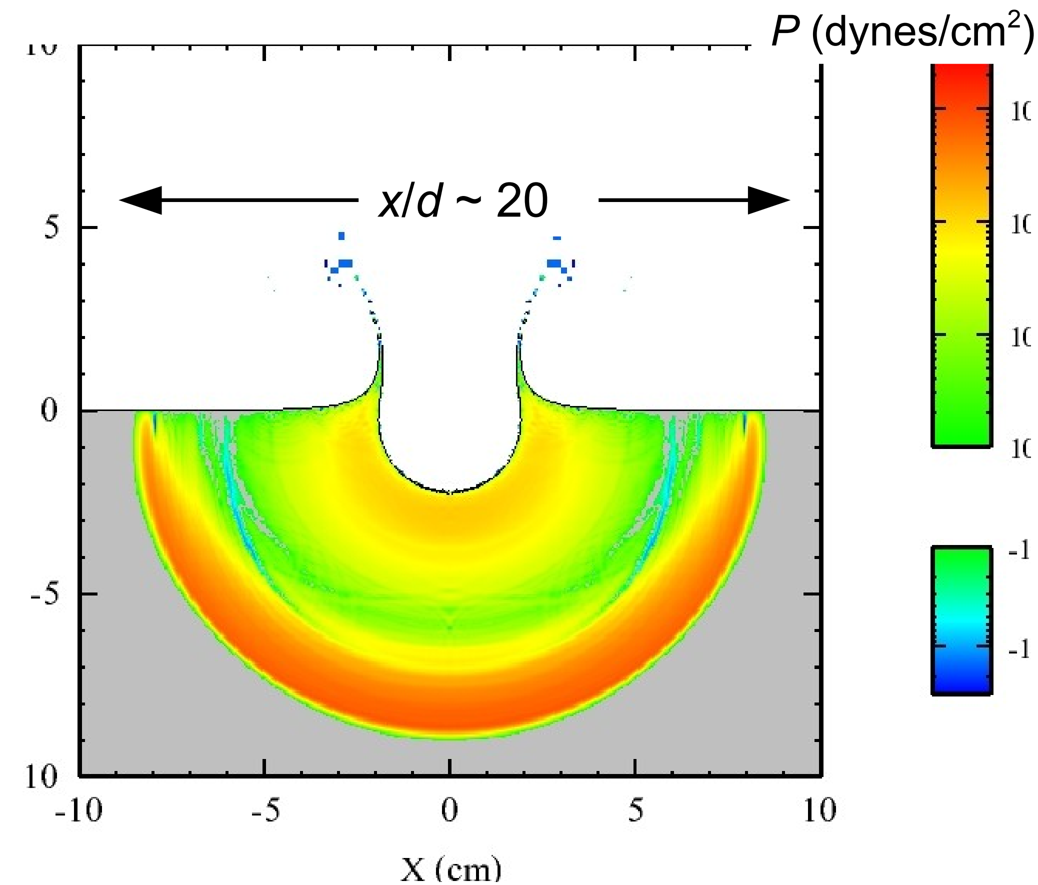
3D shock wave attenuation and crater growth for *w* < *d*

a =0.25 cm
U = 5 km/s
No strength
t/(*a*/*v*) ~ 10
X/*d* ~ 20

Natural packing of spheres



Halfspace

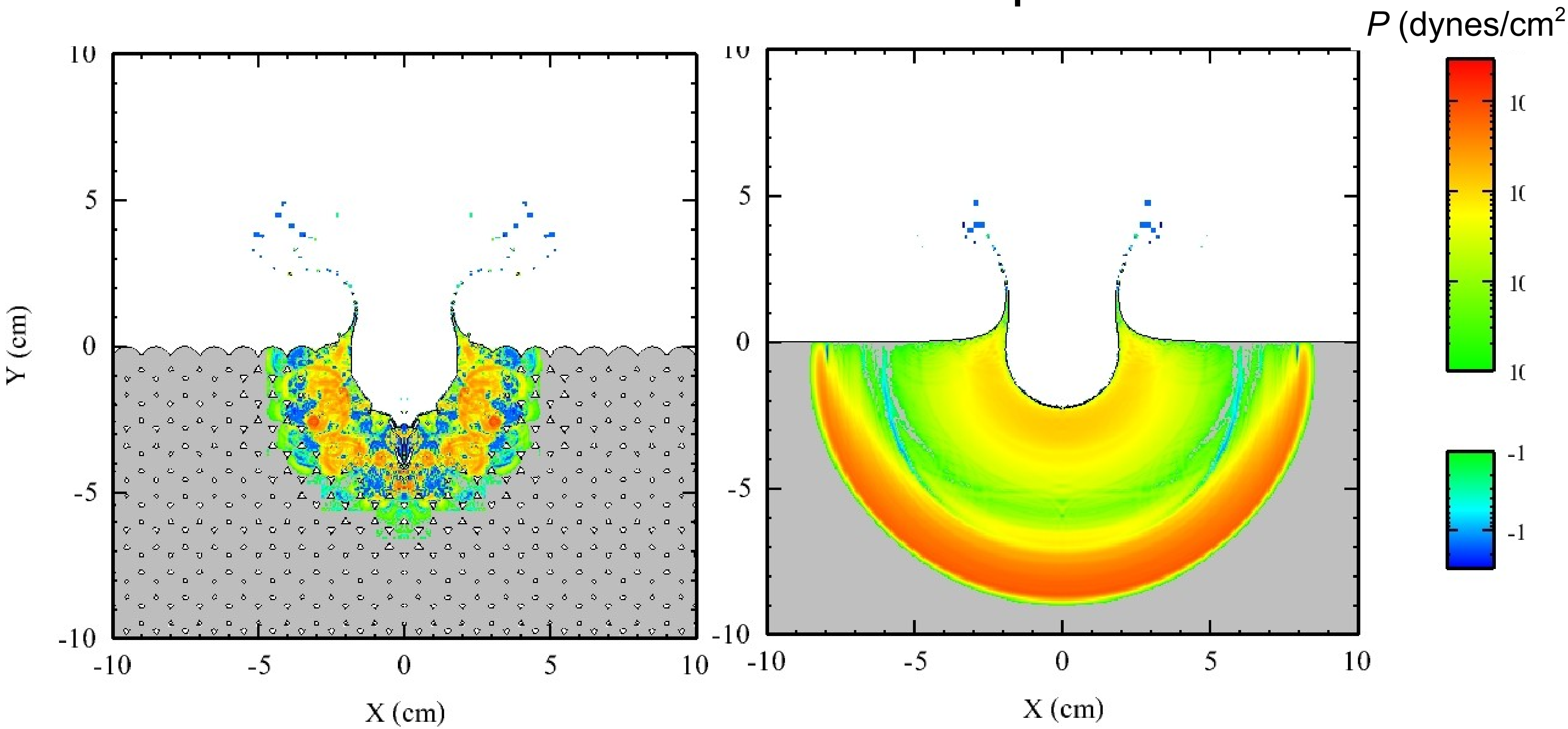


2D shock wave attenuation and crater growth for $w \sim d$

$a = d = 1$ cm
$U = 5$ km/s
No strength
$t/(a/v) \sim 10$
$X/d \sim 20$

Close-packed "spheres"

Halfspace



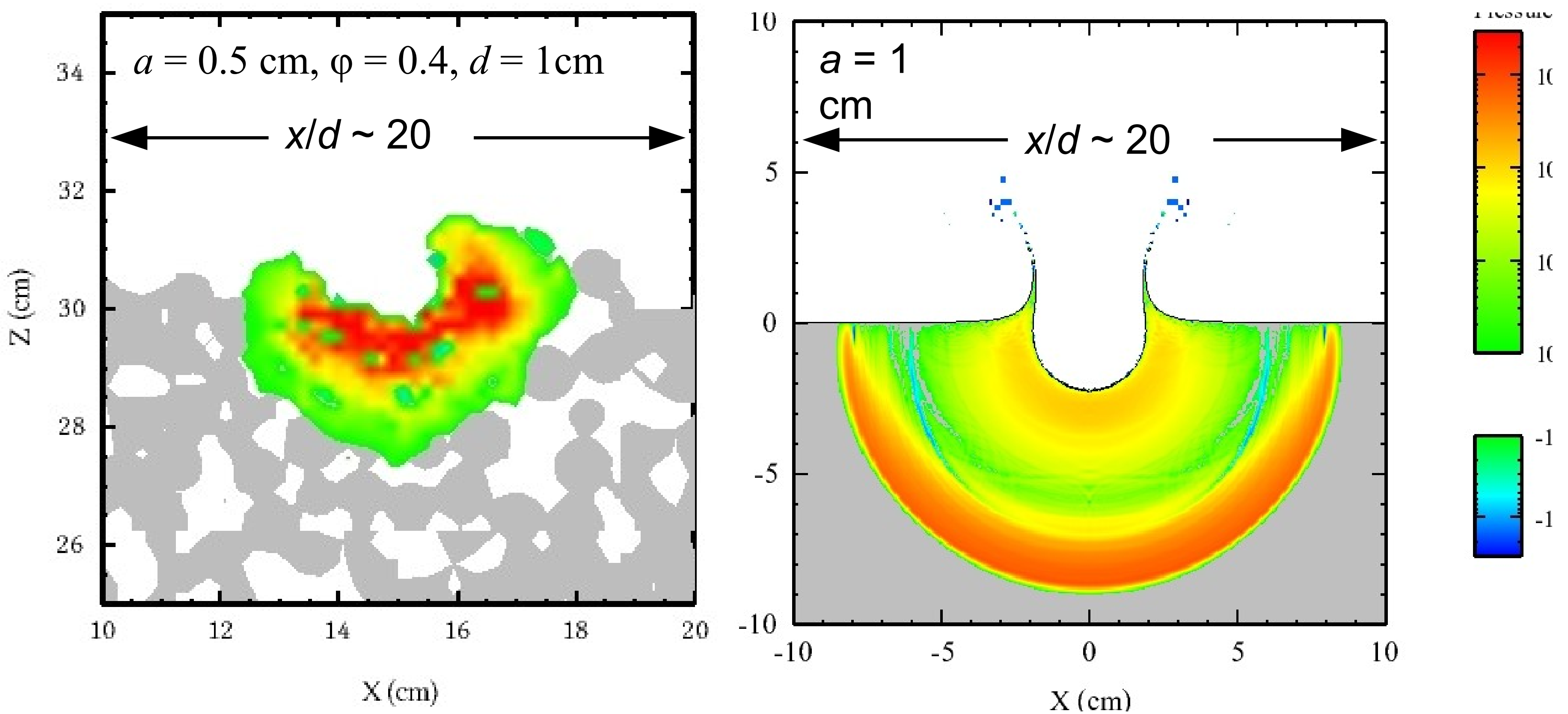
3D shock wave attenuation and crater growth for *w* ~ *d*

a = 1 cm
U = 5 km/s
No strength
t/(*a*/*v*) ~ 10

Natural packing of spheres

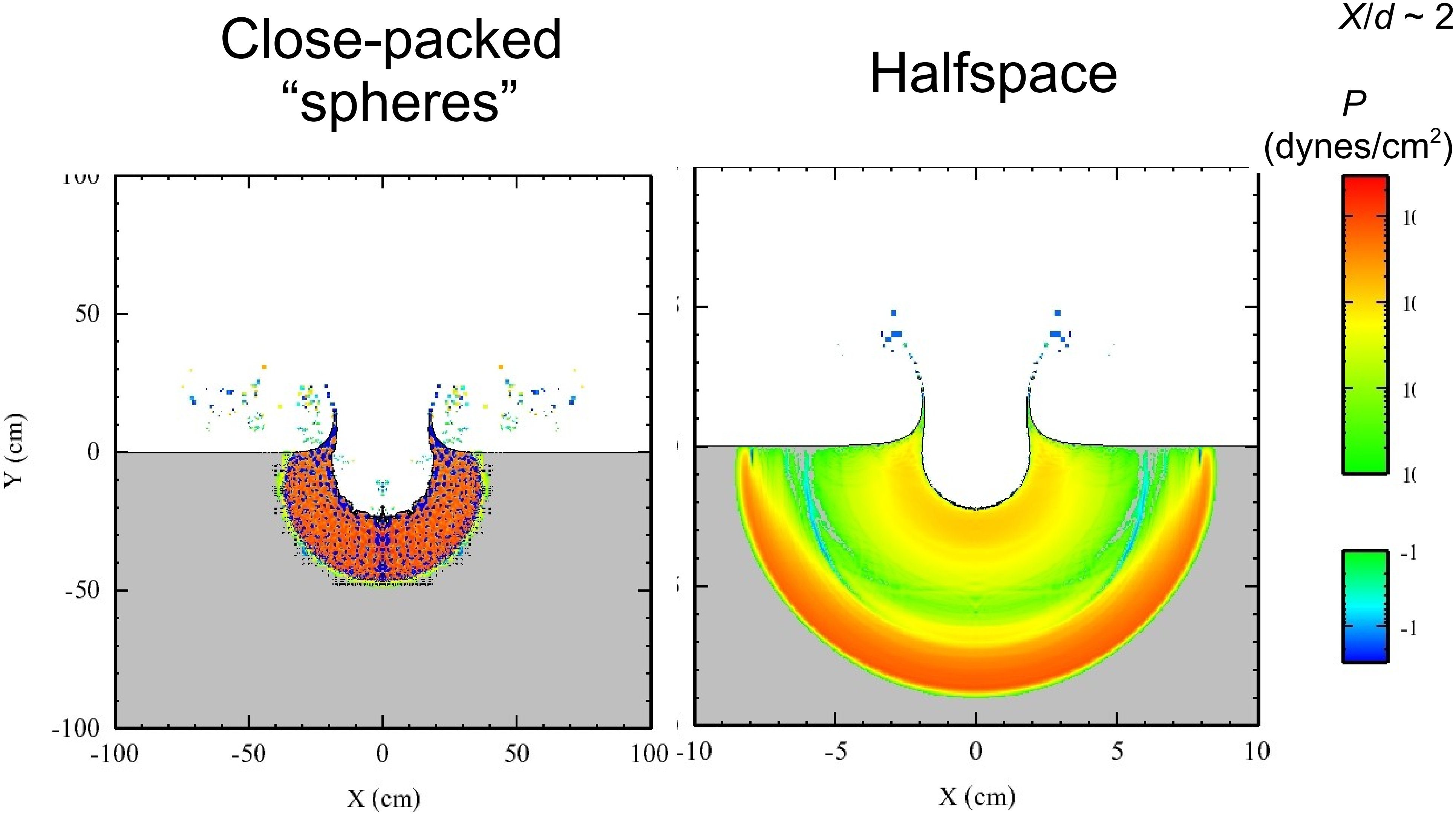
Halfspace

P (dynes/cm^2)



2D shock wave attenuation and crater growth for *w* > *d*

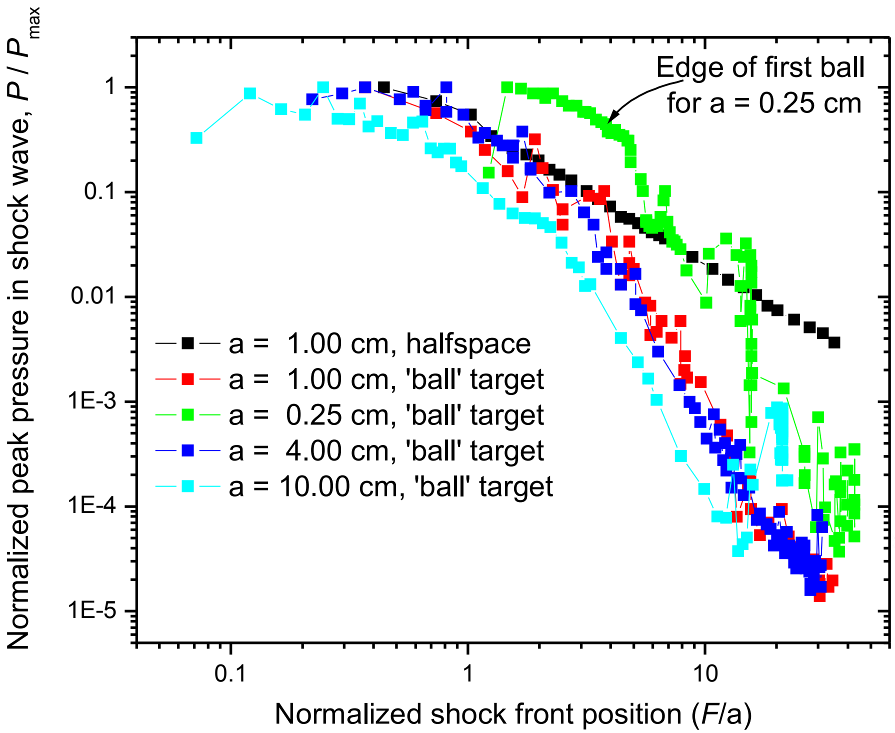
a =10 cm
U = 5 km/s
No strength
t/(*a*/*v*) ~ 10
X/*d* ~ 20



2D shock wave attenuation and crater growth for $w > d$

a =10 cm
U = 5 km/s
No strength
$t/(a/v)$ ~ 10
X/d ~ 20

‘Sphere’ target: rapid pressure decay

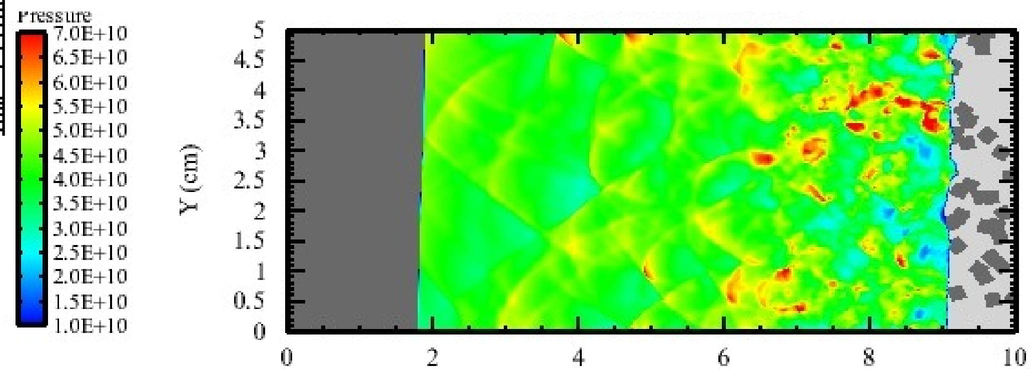


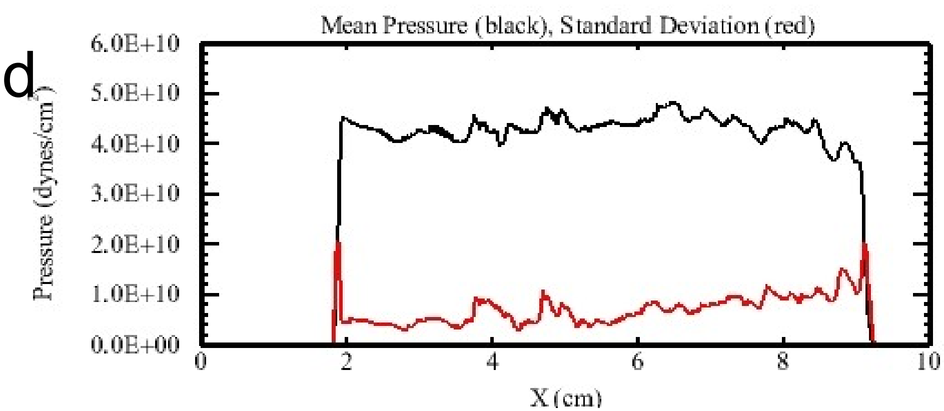
Influence of *w/d* :

- Max *P* occurs sooner for larger *w/d*
- Variation in *P* with *F/a* decreases with *w/d*

  But influence of heterogeneity not lost

Planar Impact 2 *km/s, impactor->matrix + grains*

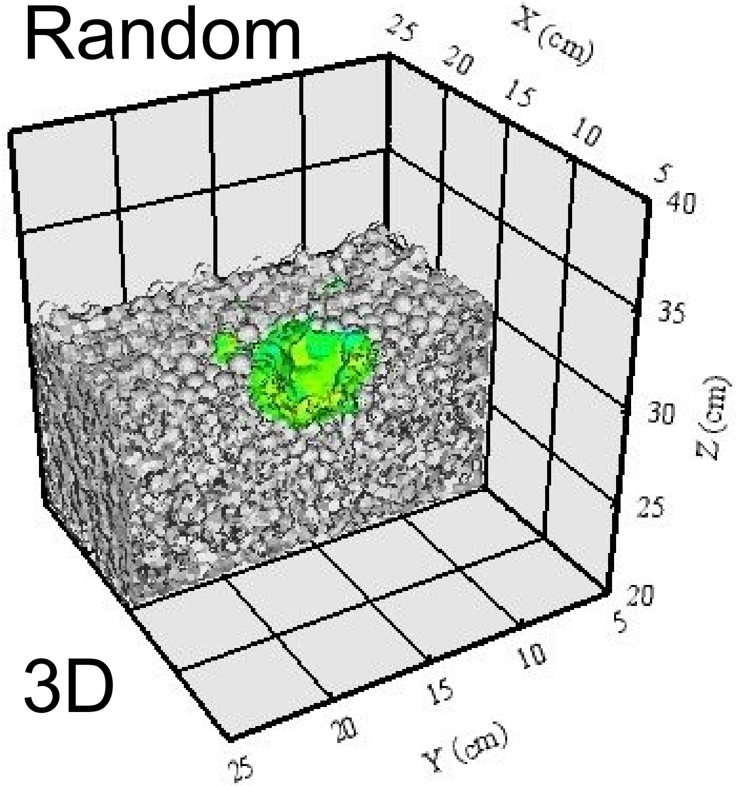




Heterogeneity leading to localized failure? *A possible target weakening process?*

Impact geometry

Random

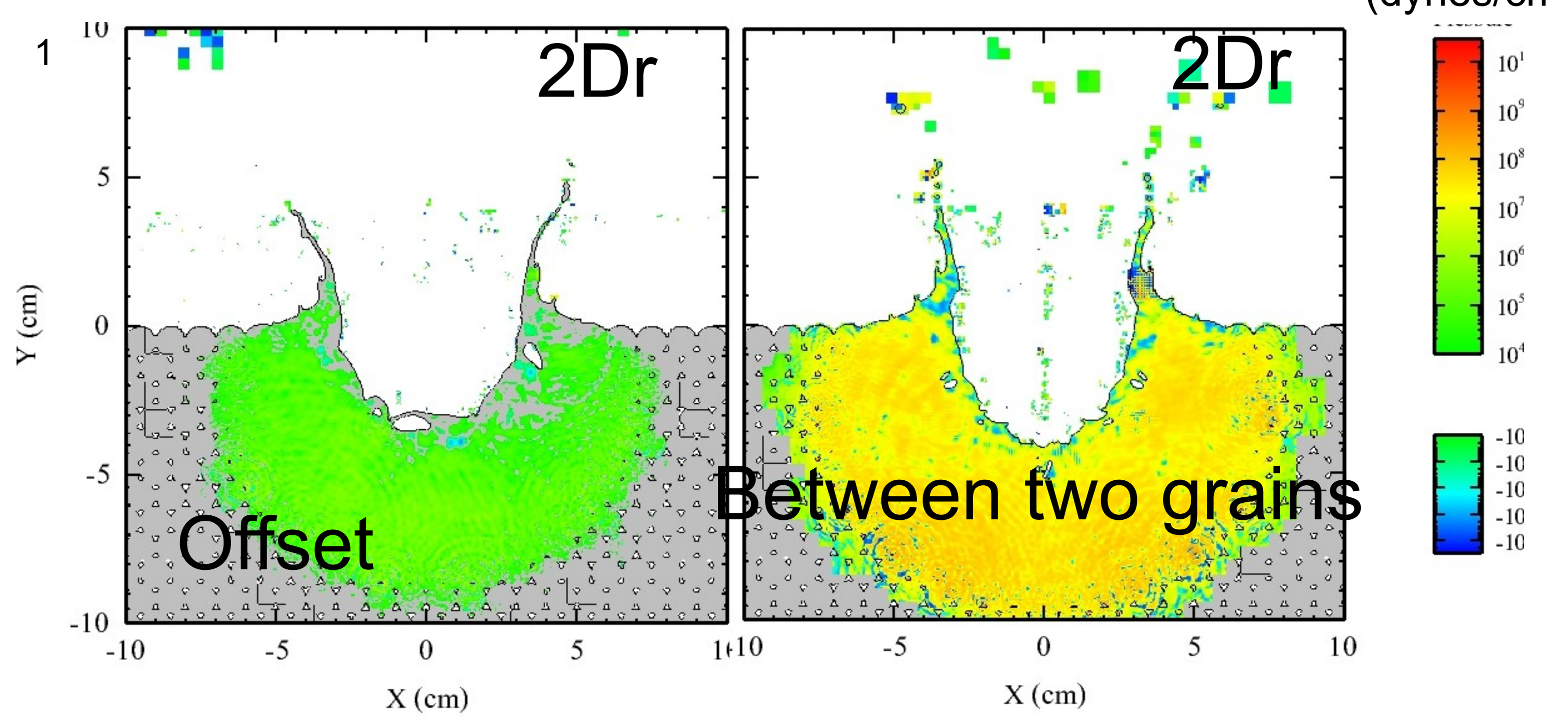


3D

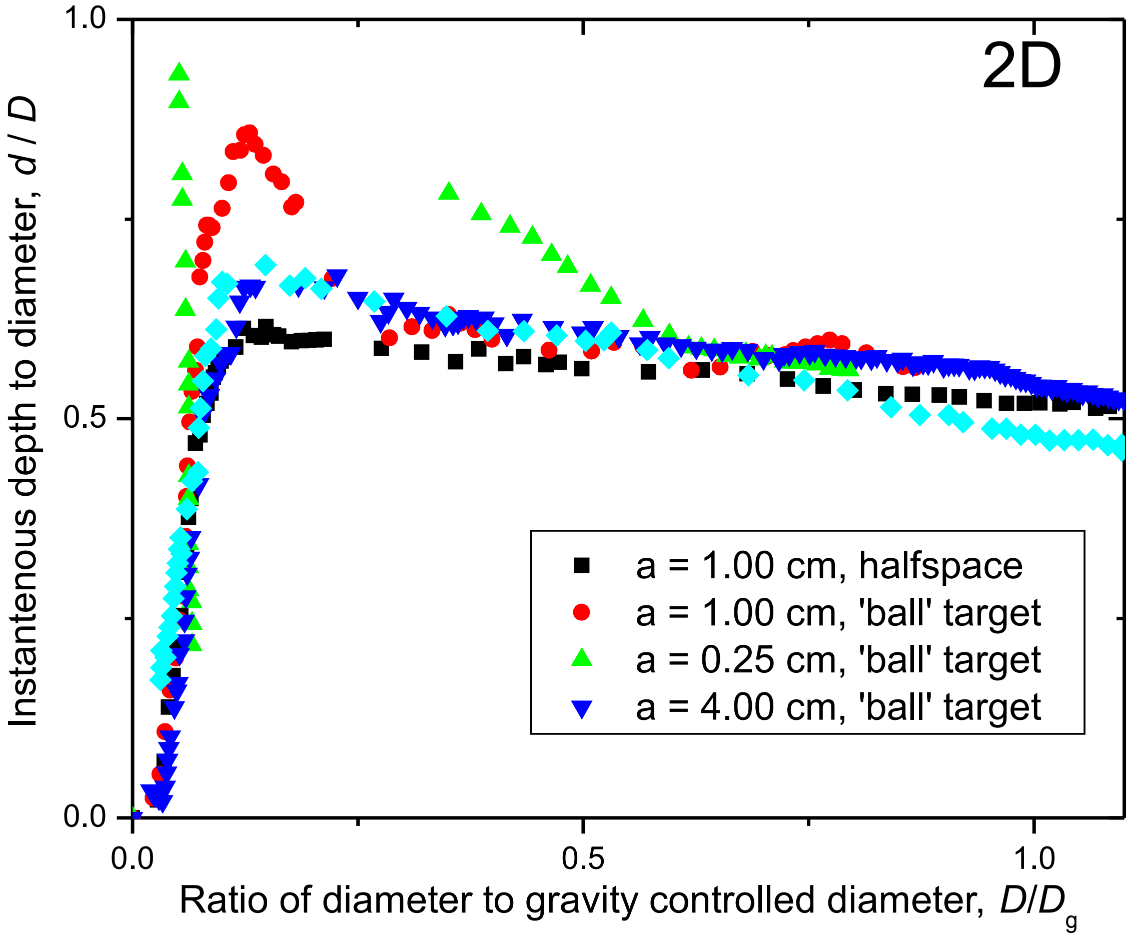
- Strong coupling influence even at late time leads to
  - Asymmetric crater shapes
    - Variable *d/D*
  - Random ejection angles
  - Asymmetric and variable pressure attenuation
- 3D - rapid pressure attenuation

a =0.25 cm
U = 5 km/s
No strength
t/(*a*/*v*) ~ 10
X/*d* ~ 20

P (dynes/cm^2)



Heterogeneity leads to variable transient crater diameter



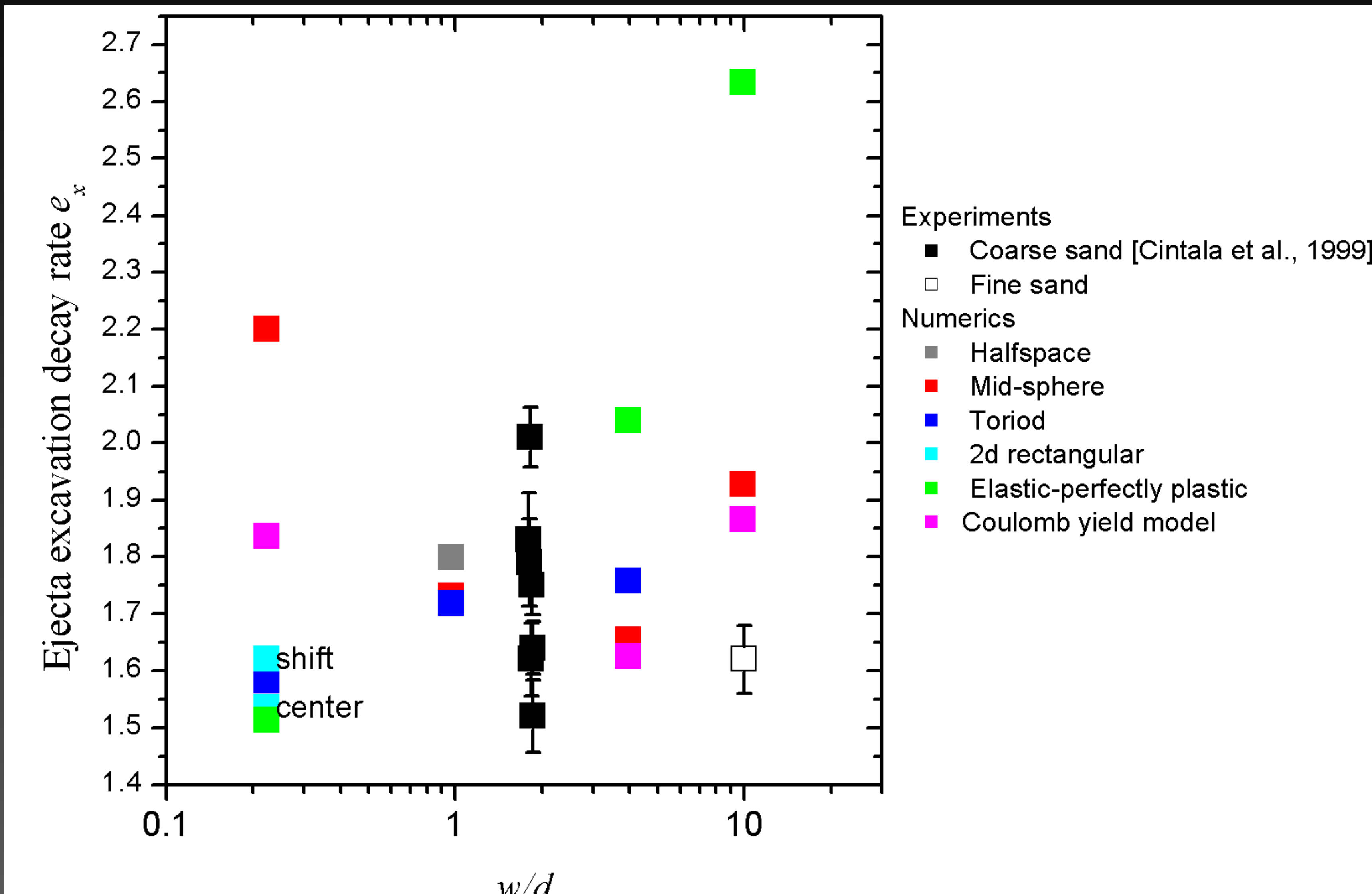
Starting conditions for crater modification could vary with heterogeneity:

D/D_g <0.5 => deeper

D/D_g <0.5 => variable

D_g is the final crater diameter after some modification

Ejection parameter $e_x = 1/\mu$: strong dependence on coupling



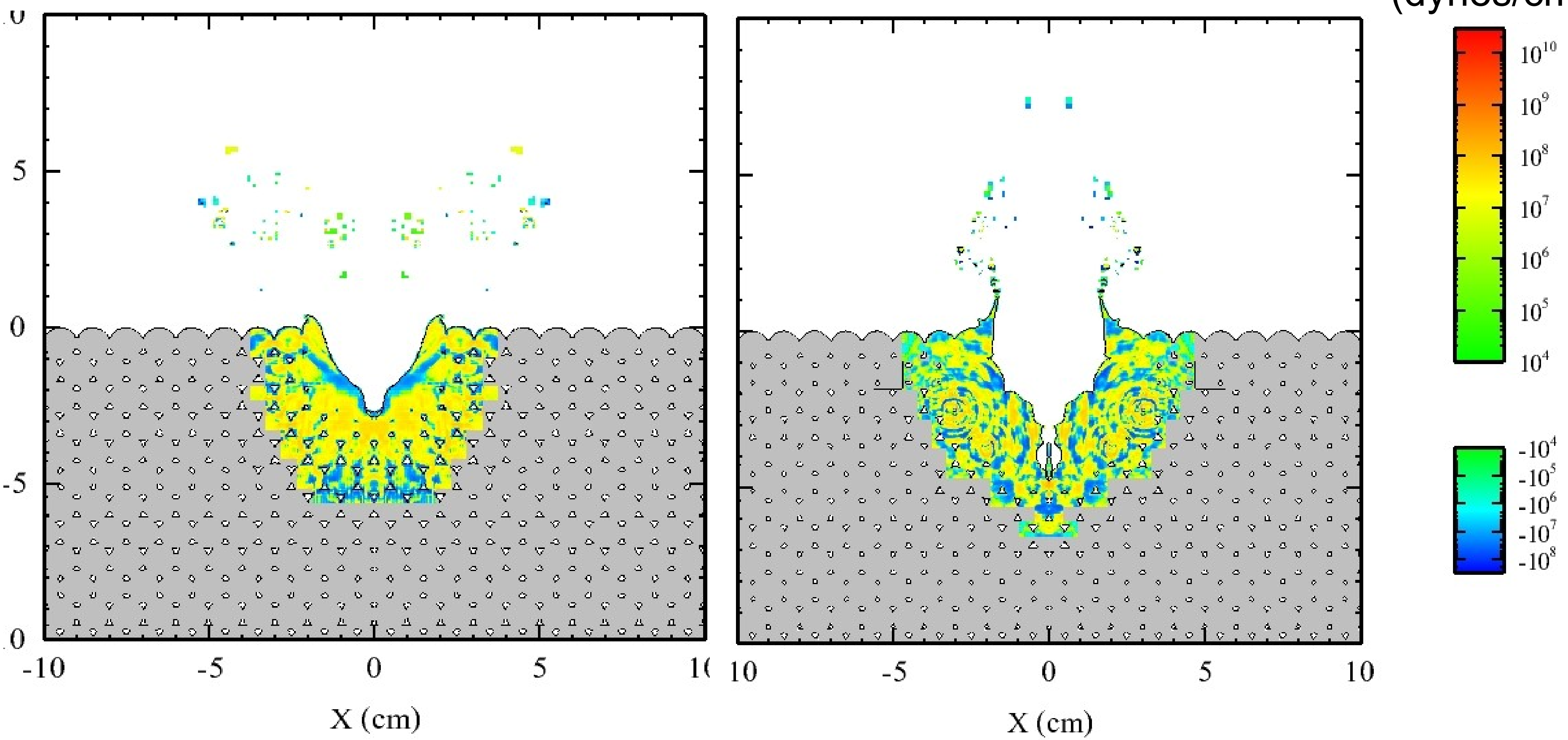
Target strength: prevents pore space collapse

a =0.25 cm
d =1 cm
U = 5 km/s
Axisymmetric

Coulomb yield model

No strength

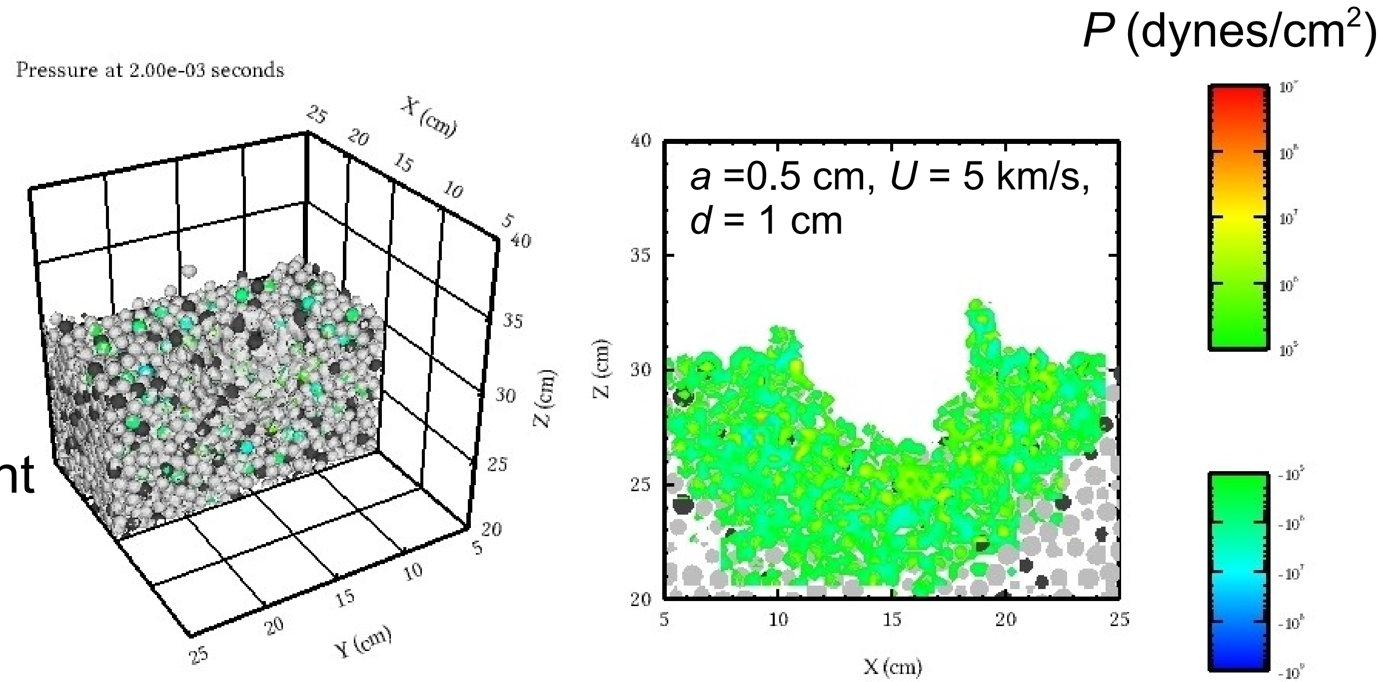
P (dynes/cm^2)



Target strength: reduces shock attenuation

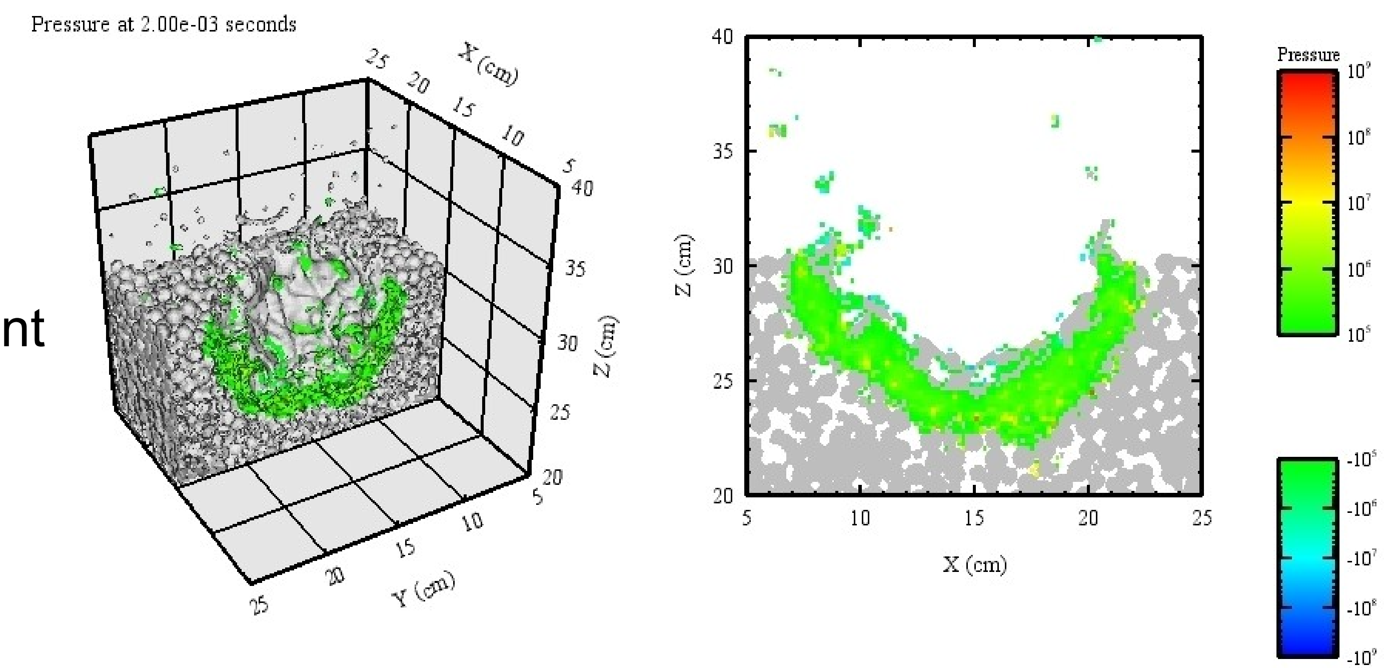
Strong spheres (but no cohesion)

- Broad shock
- Ringing in spheres
- Weaker crater asymmetry
- Smaller craters at equivalent time



Weak sphere

- Greater peak pressures
- Narrow shock
- Strong crater asymmetry
- Large craters at equivalent time



Conclusion and implications

- Heterogeneity important at any scale of *w/d*
  - Enhances attenuation of shock wave
  - Introduces large local deviations in pressure field

    => localized failure => possible weakening mechanism?

    => localized variations in melting and shock history
  - Introduces asymmetries in crater shape and ejection
  - Wide range of efficiencies as derived from ejection flow
  - Strengthens initial projectile/target coupling effects
    - Variability in transient crater shape => crater modification
- Target strength
  - Reduces heterogeneity effects by preventing pore collapse (also seen by Collins and Wunnemann, 2007)
  - Localizes ringing

    => does mechanical granular-flow dominate excavation?
  - Explains why lab craters in coarse target are efficiently cratered
- 3D – More efficient pressure attenuation