Impact Cratering: Shock physics on a planetary scale

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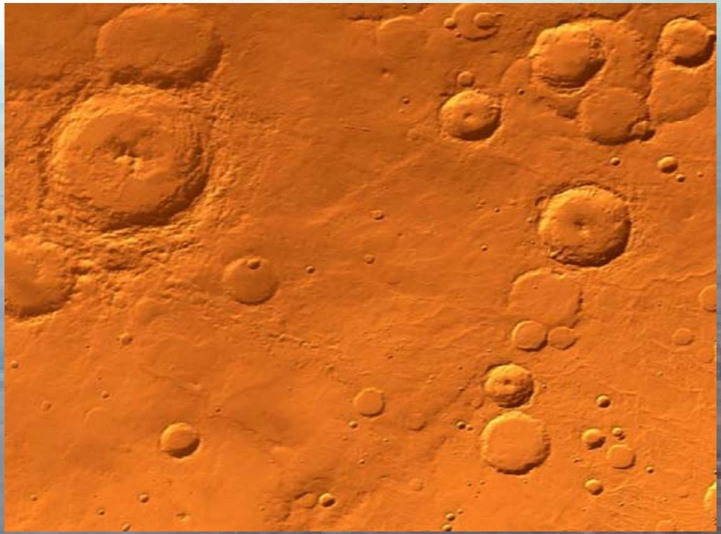
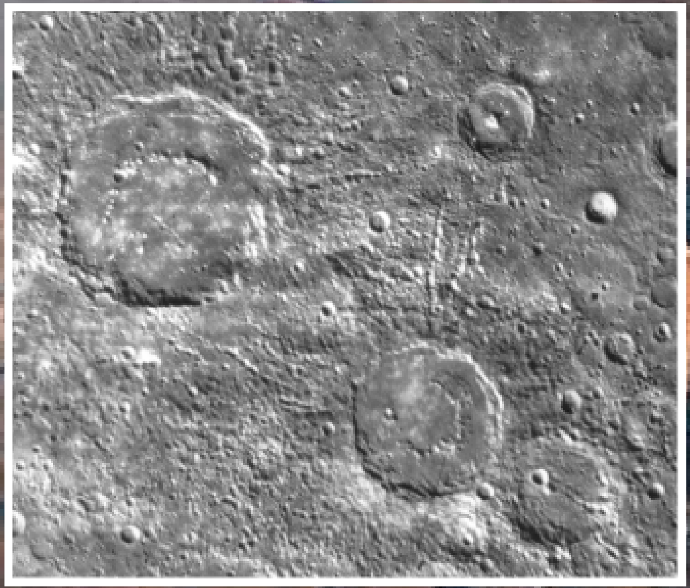
DEPARTMENT OF
EARTH SCIENCE AND ENGINEERING

Impact cratering is an important geologic process





Impacts shaped the solar system and the evolution of life

- **Mass extinction & evolution of life**
- **Formation of the moon, planetary accretion**
- **Properties / age of planetary surfaces**
- **Future hazard**
- **Ore / hydrocarbon deposits**

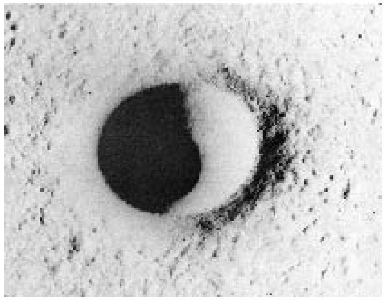


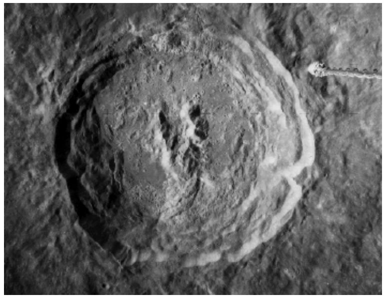
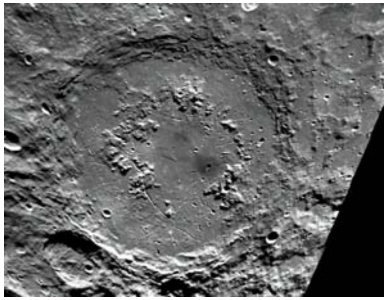
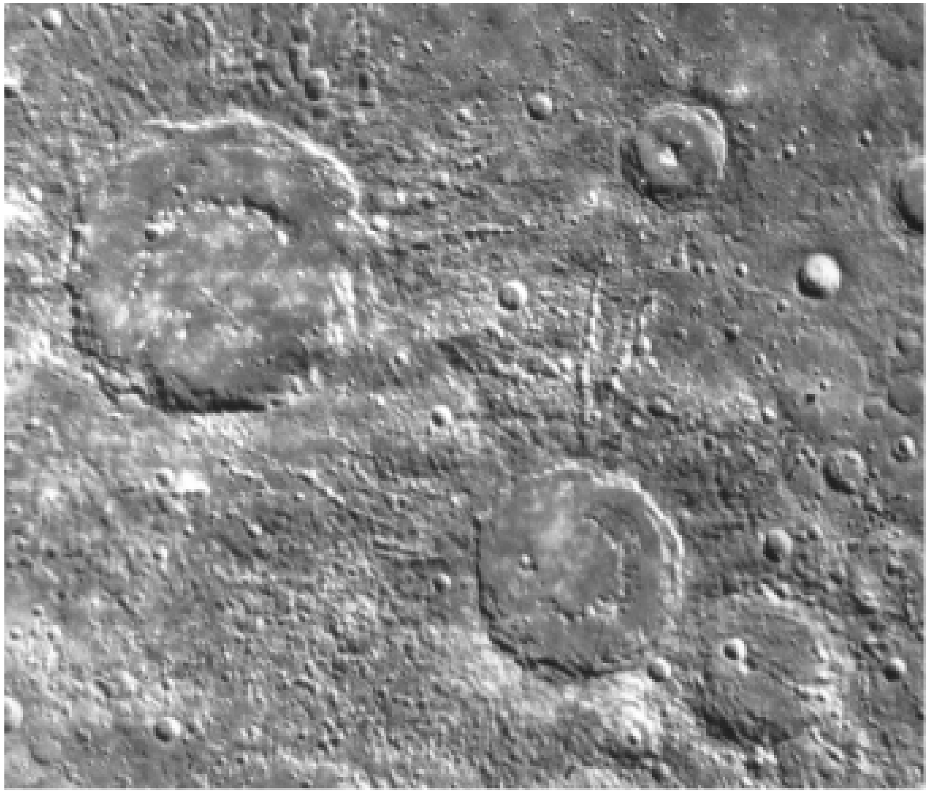


Key questions in impact cratering:

- How do impacts affect the local and global environment?
- What hazard do asteroids and comets pose to humanity?
- How might we deflect an incoming object?
- What can Earth's impact craters tell us about the surface of other planets?
- **How does crater size and shape depend on impactor and target properties?**

Craters show a size-morphology progression

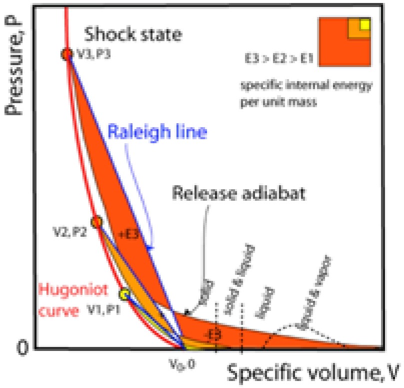



Images courtesy of NASA

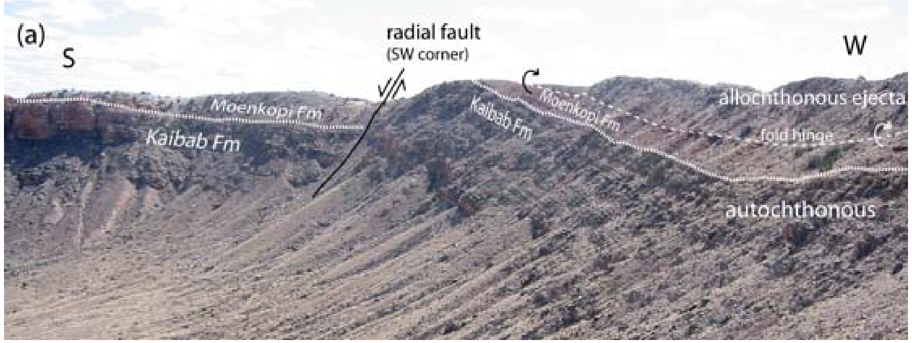
Crater formation divided into 3 stages

- **Contact and compression**
  - shock physics

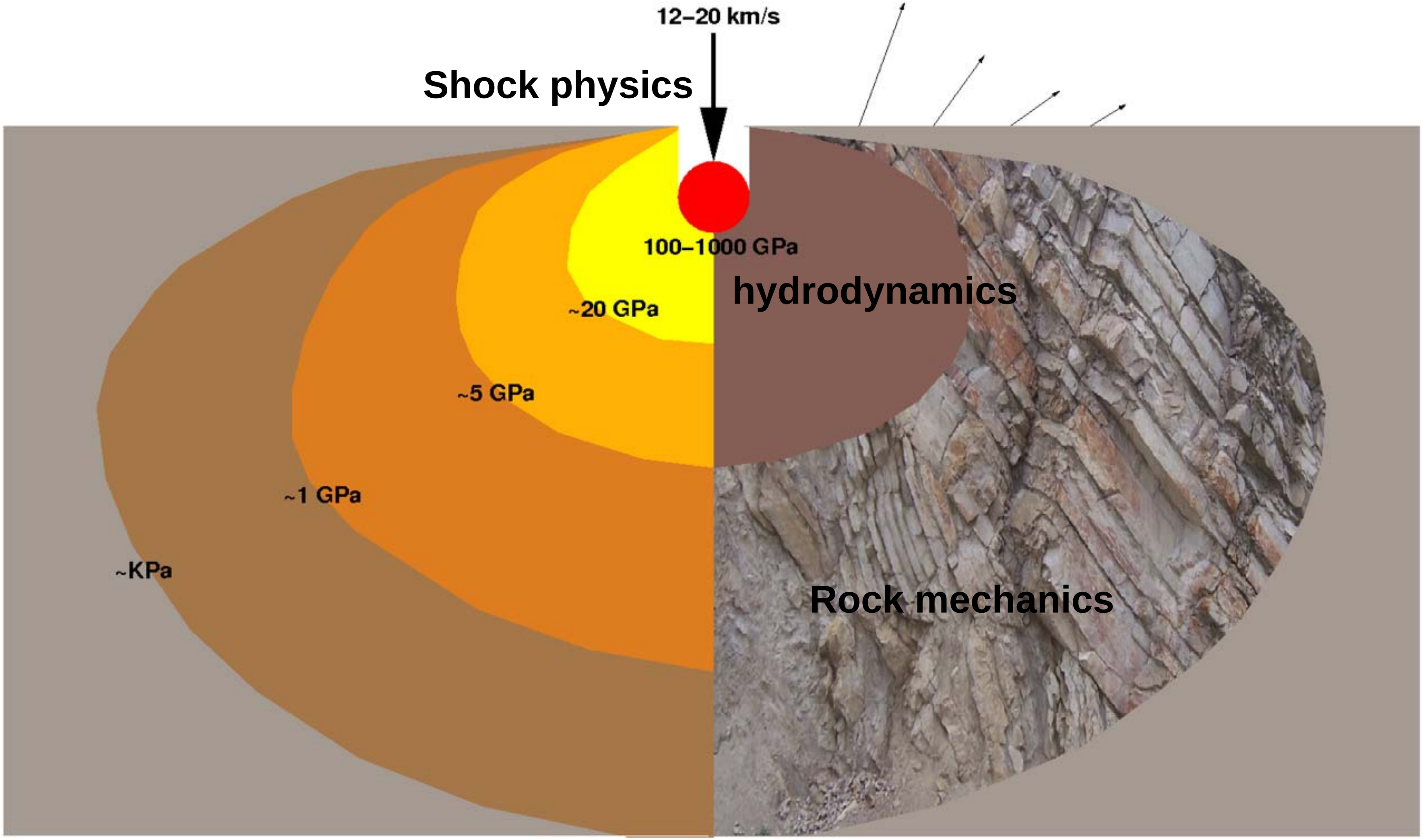


- **Excavation**
  - fluid dynamics

- **Modification**
  - rock mechanics
  - rheology, gravity

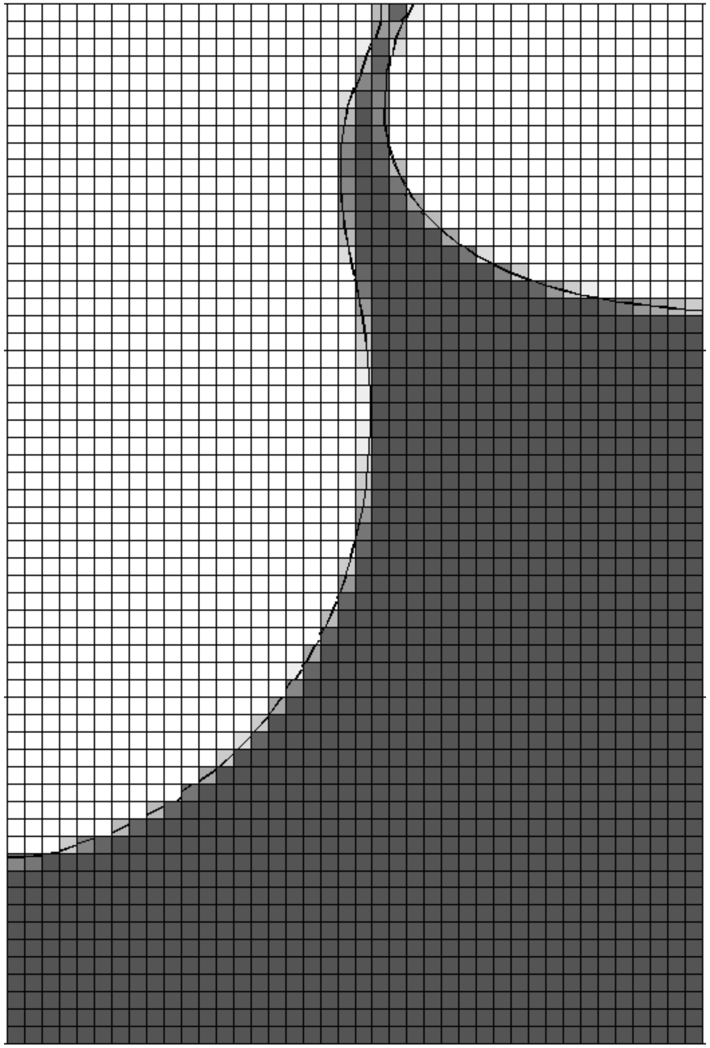


Different physics important in different zones

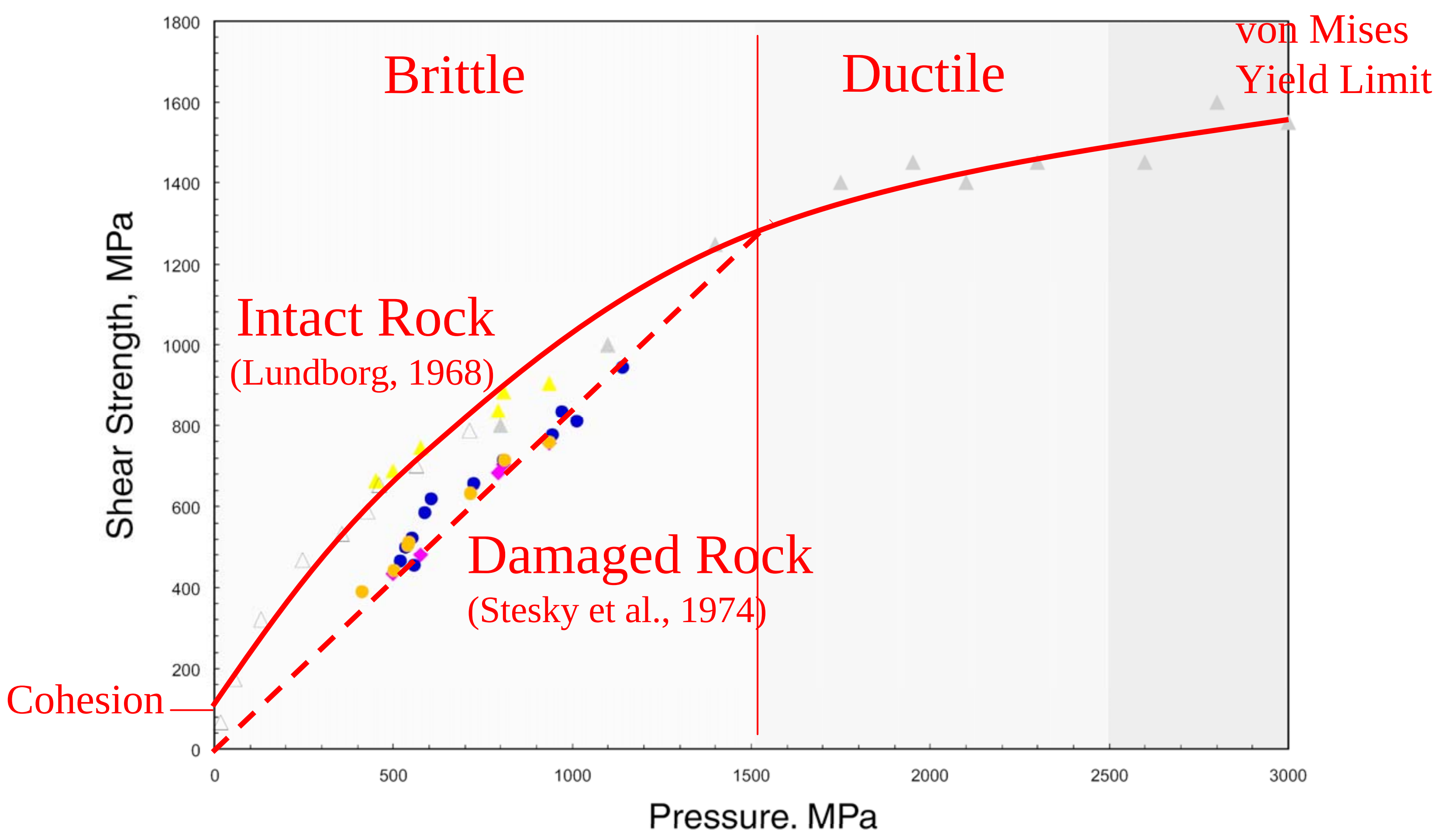


Large impacts can only be simulated by modelling

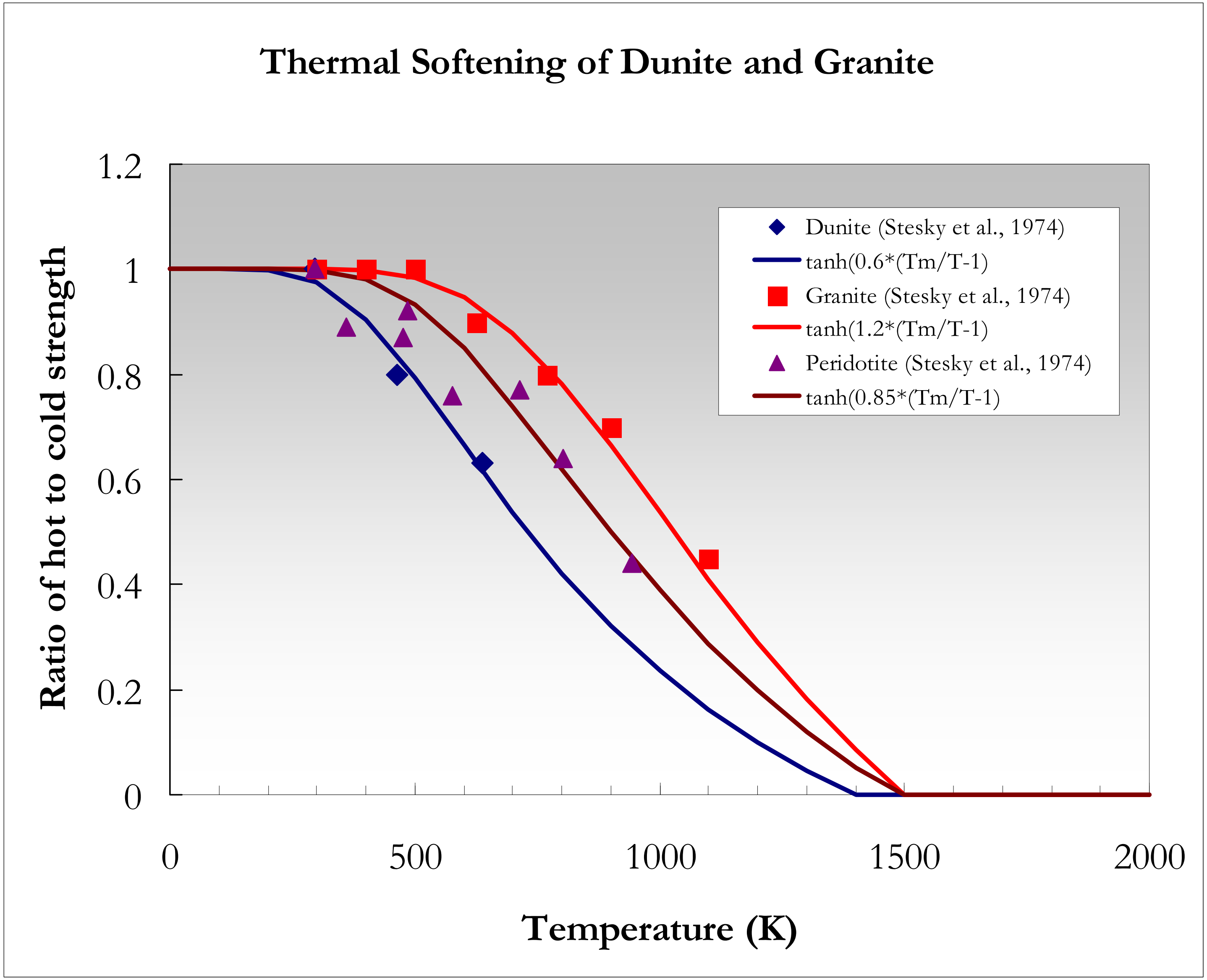
- iSALE: Eulerian finite-difference "hydrocode"
- 2D geometry (axial symmetry); vertical impacts
- Multi-material, multi-rheology, compressible flow
- Tillotson/ANEOS equations-of-state
- Custom constitutive model (relating stress to strain/strain rate) for impacts into geologic media
- Efficient porous compaction model



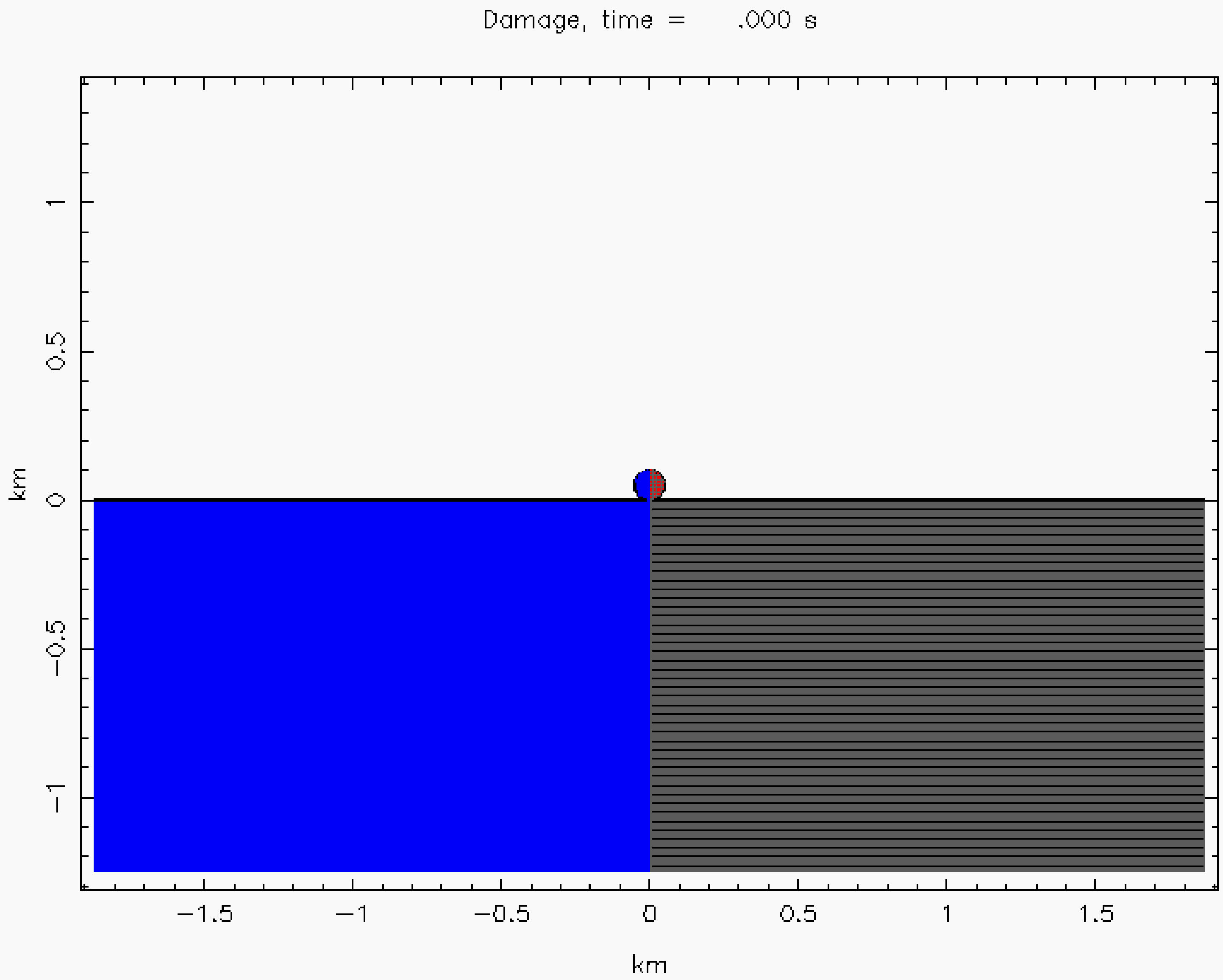
Rock Failure is Complicated!



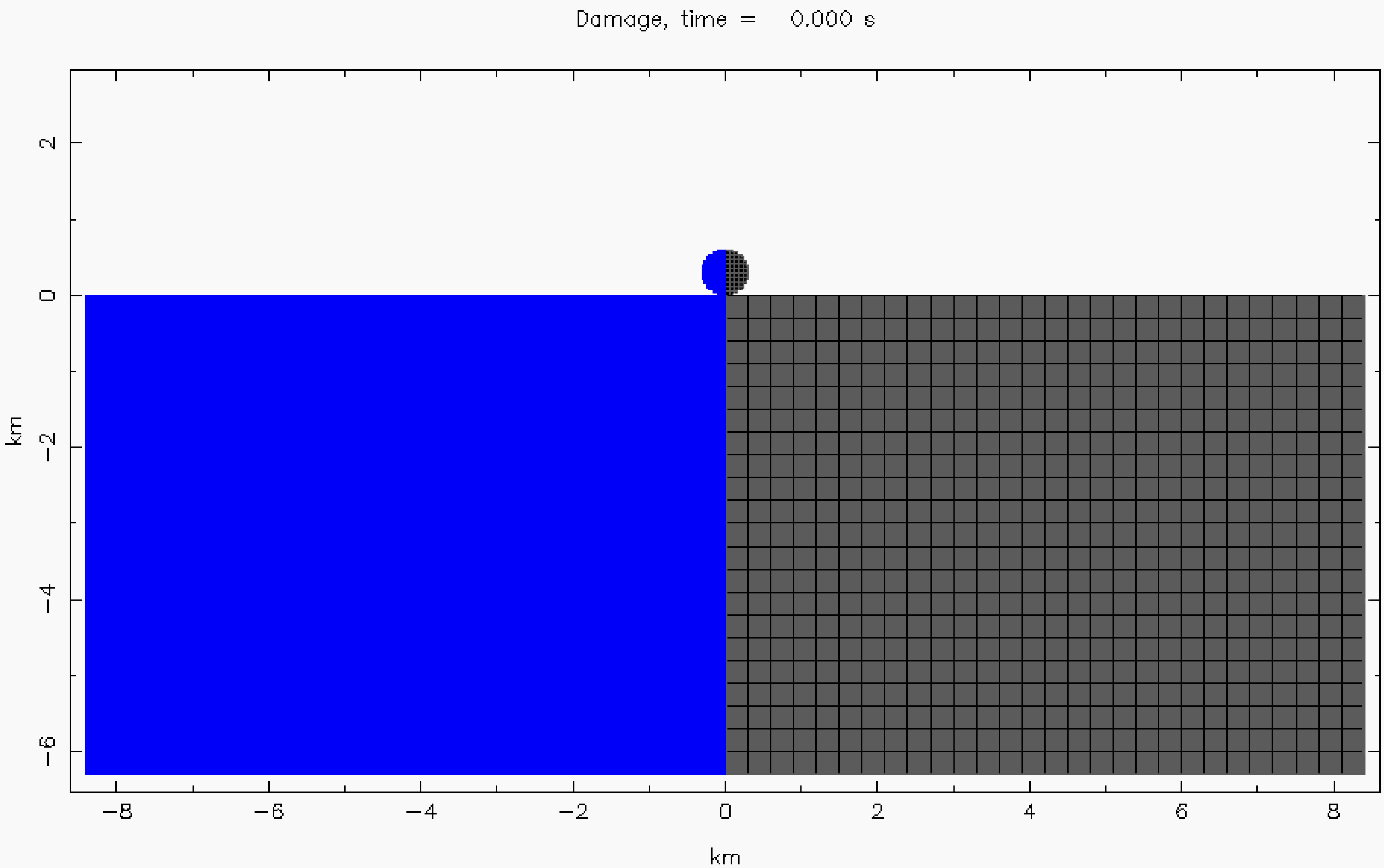
Rock strength decreases with increasing temperature



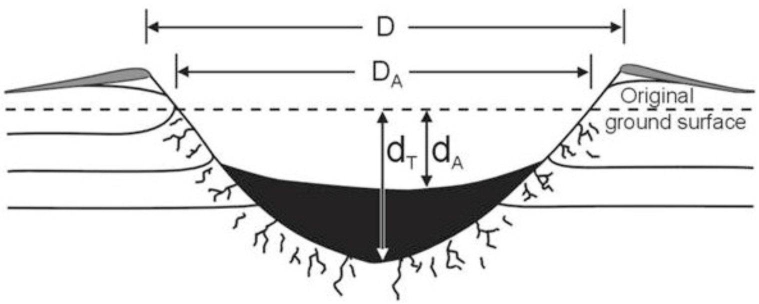
Simple crater formation

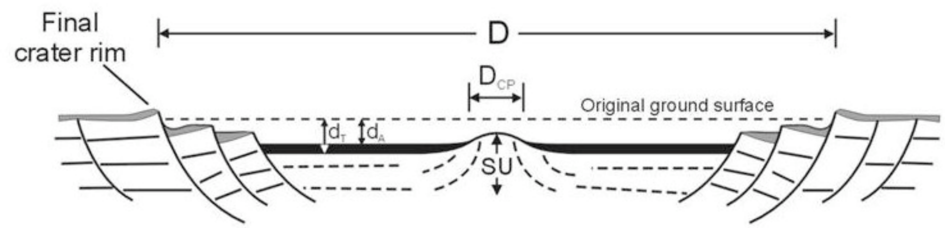


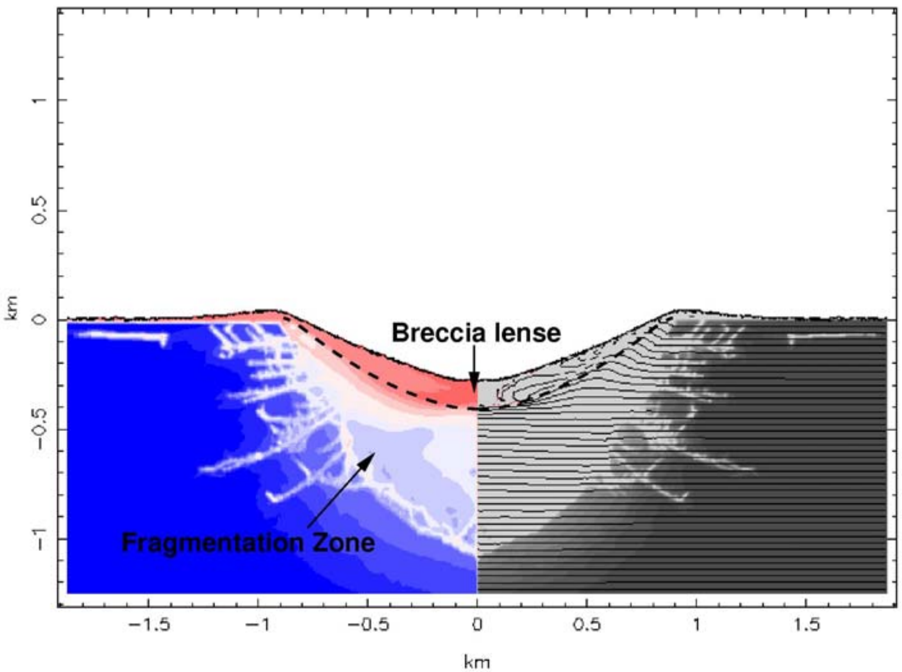
Complex crater formation

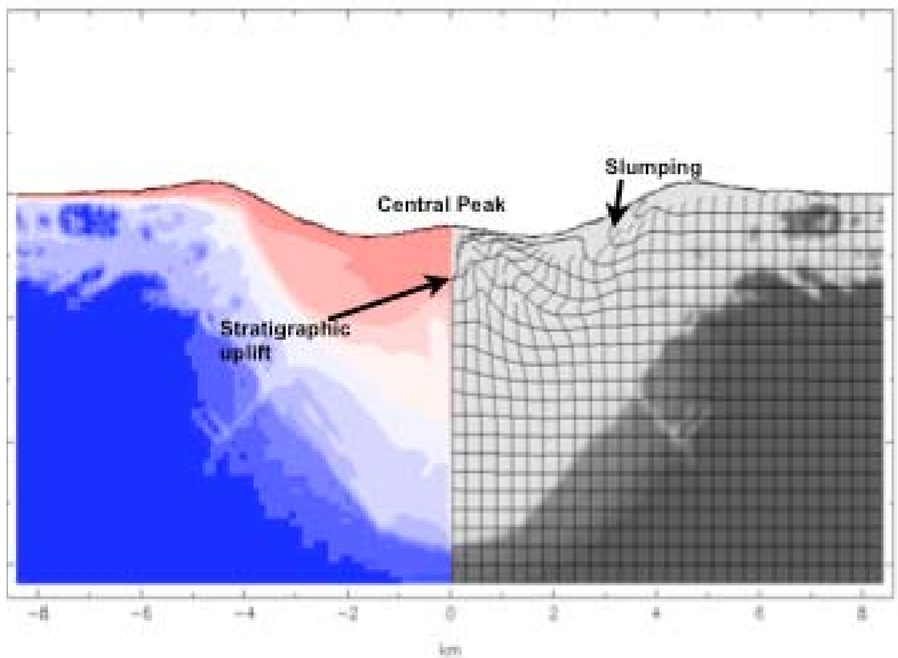


Models tested against geological and geophysical data

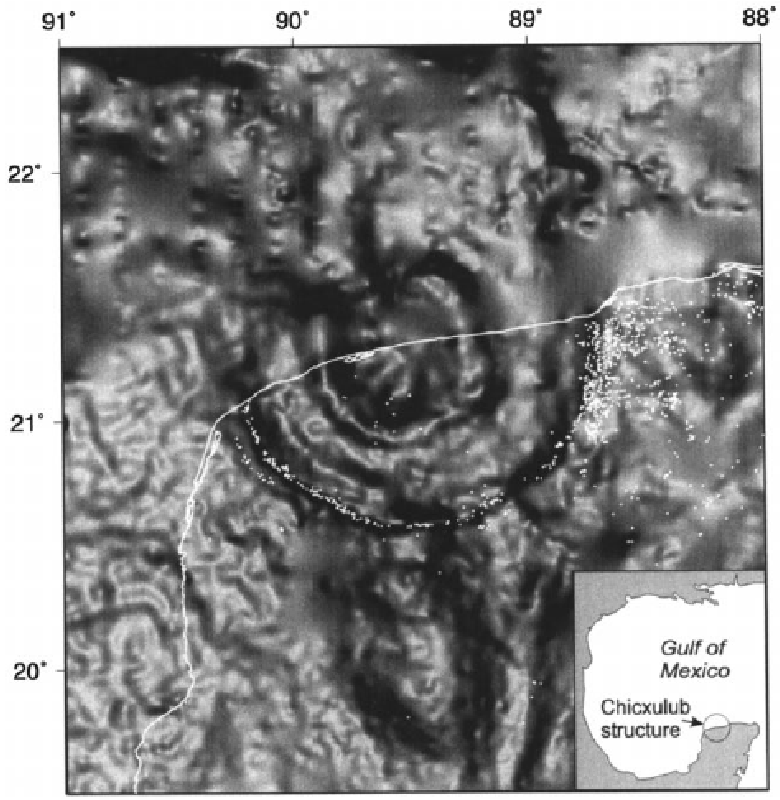


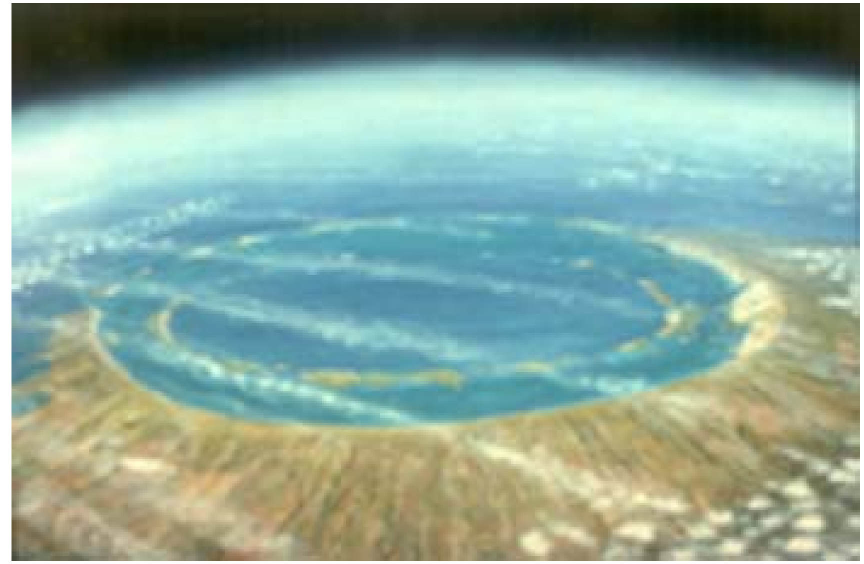


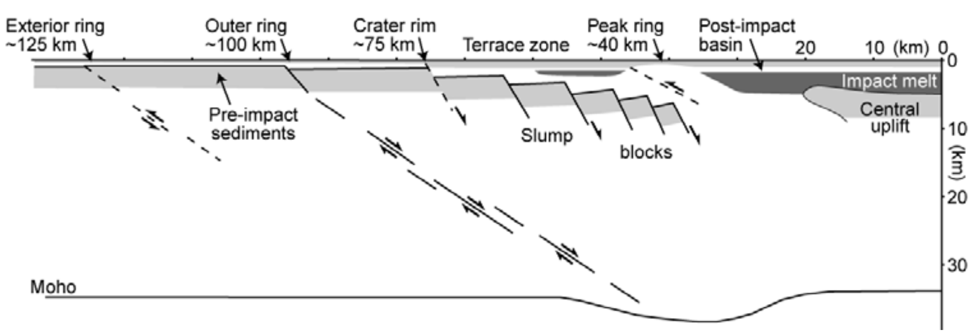




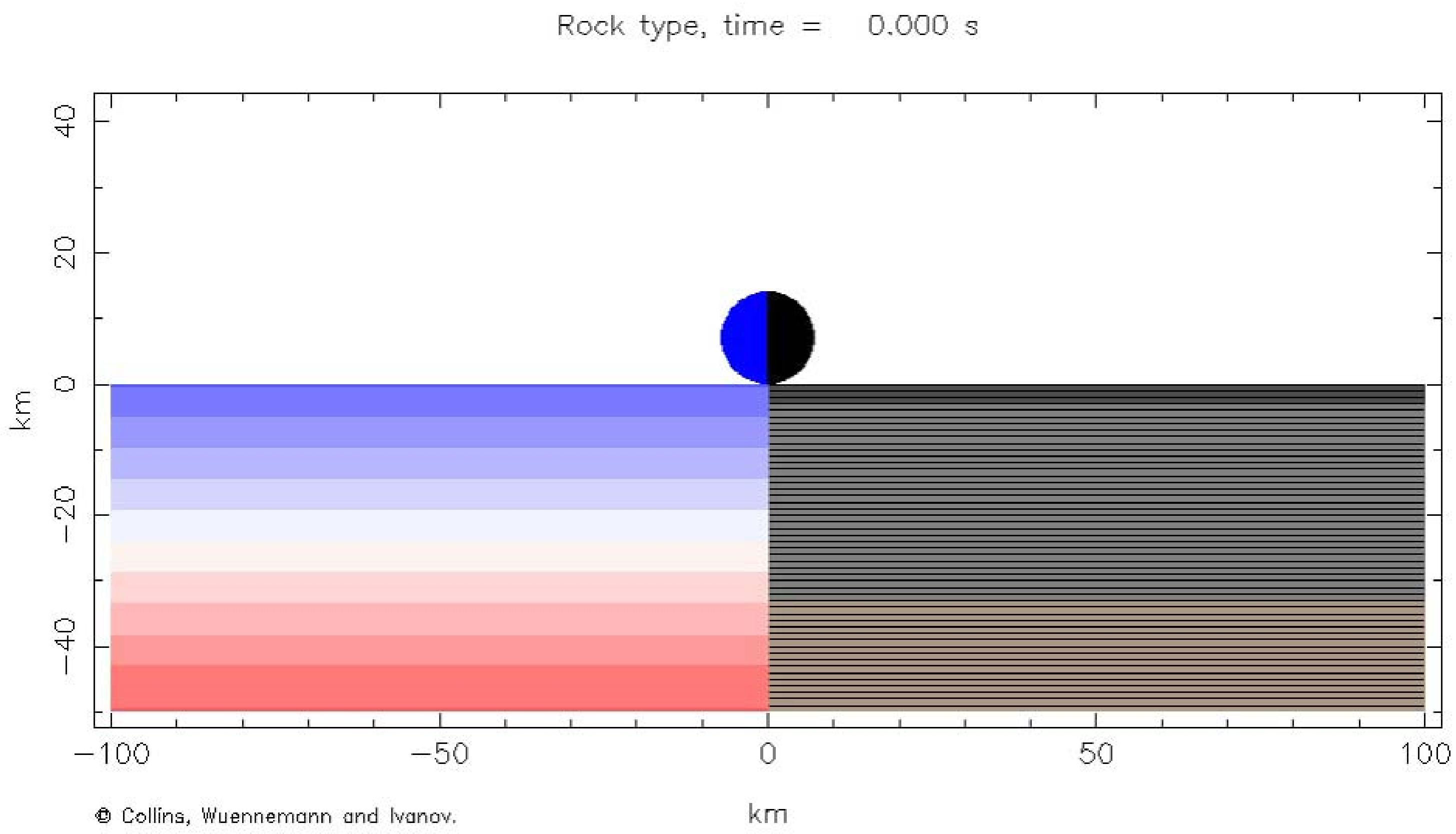
Case study: How big was the Chicxulub impact?



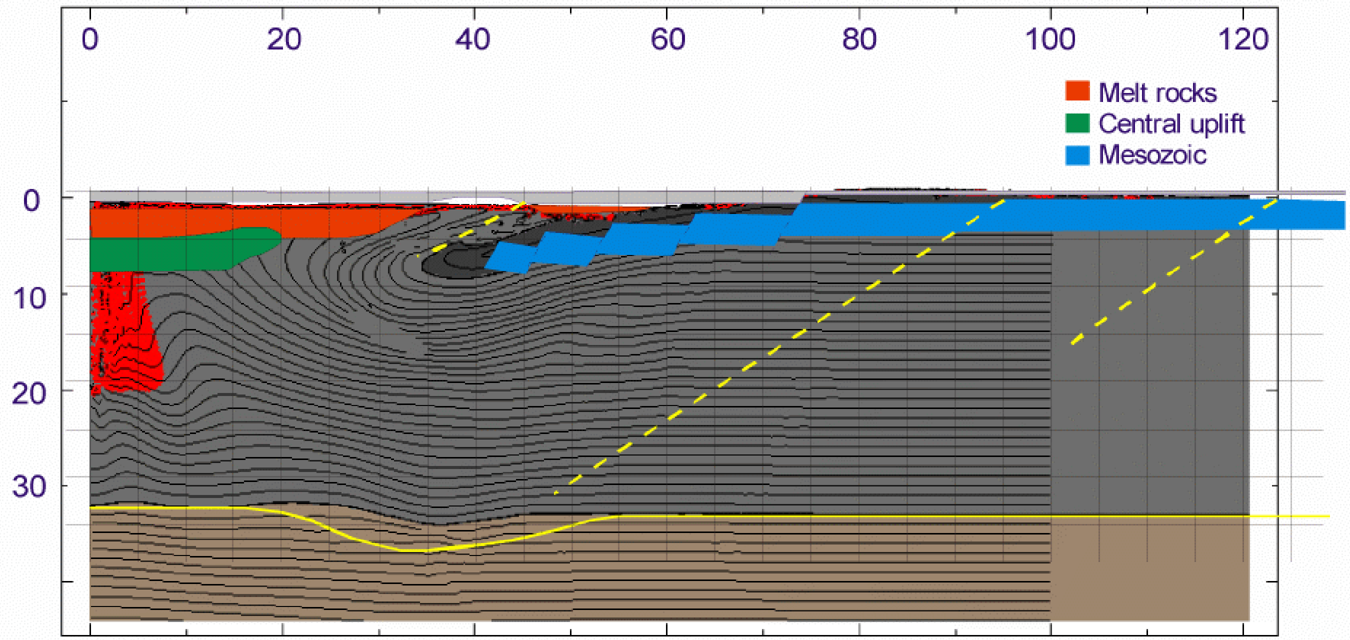




Best-fit model suggests impactor was ~10-km diam.

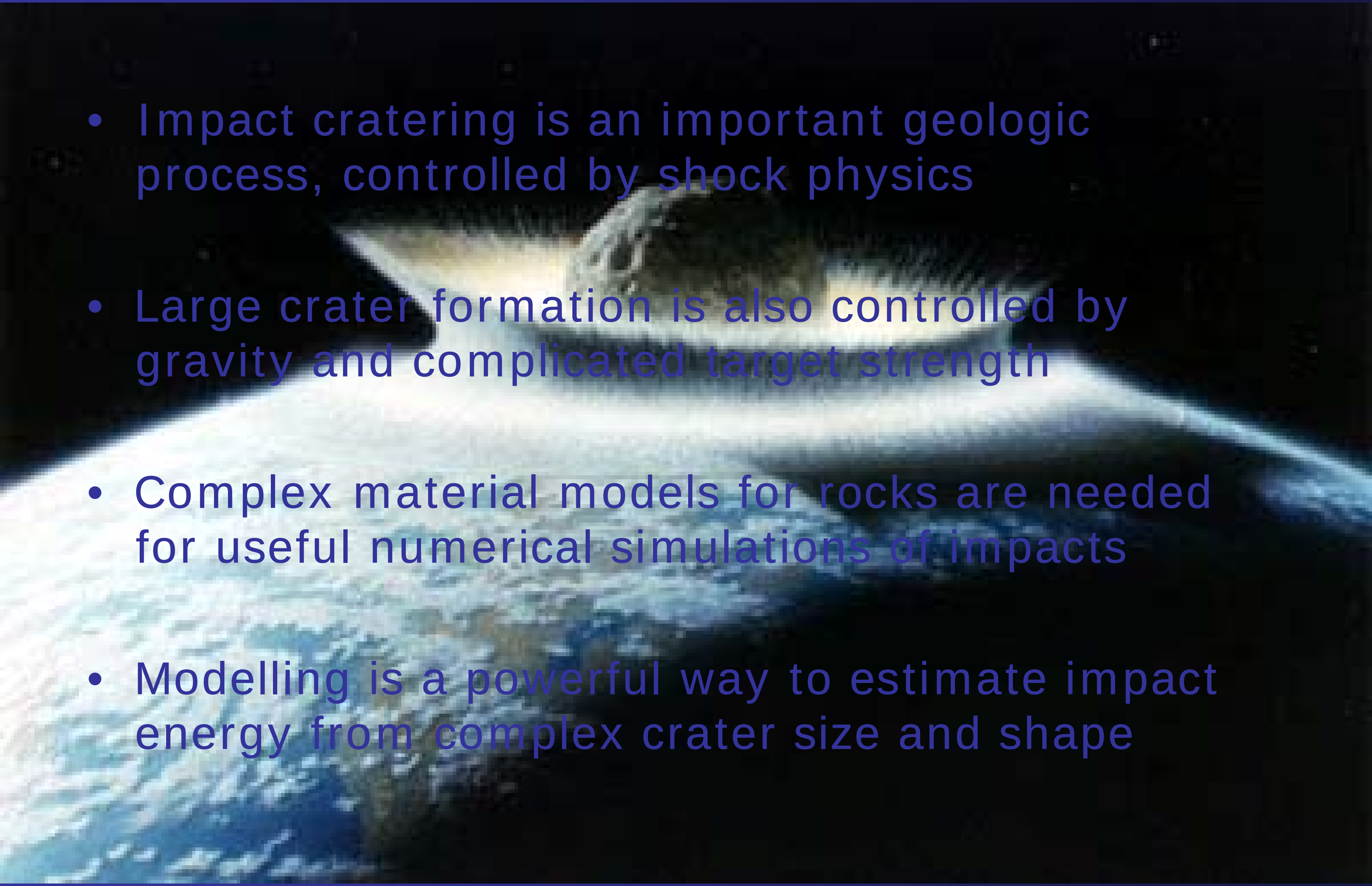


Broad agreement between numerical and geophysical models



© Collins, Wuennemann and Ivanov.

Summary so far...



- Impact cratering is an important geologic process, controlled by shock physics
- Large crater formation is also controlled by gravity and complicated target strength
- Complex material models for rocks are needed for useful numerical simulations of impacts
- Modelling is a powerful way to estimate impact energy from complex crater size and shape

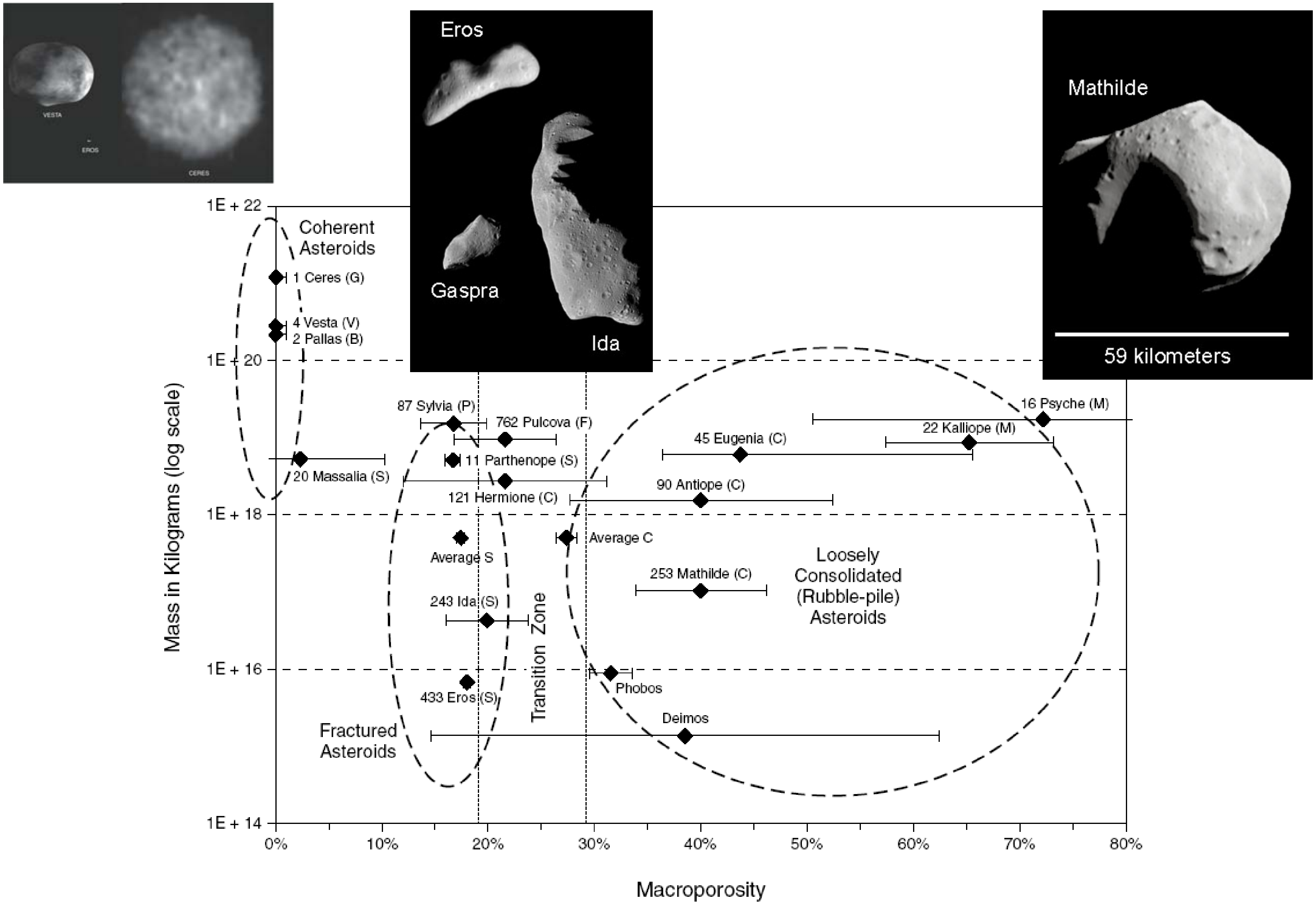
How is cratering affected by target properties?

- Cratering in nonporous, crystalline rock now quite well understood

- Porosity is important in many contexts:
  - Asteroids
  - Comets
  - Icy satellites
  - Regoliths
  - Sedimentary rocks
  - Early planetesimals

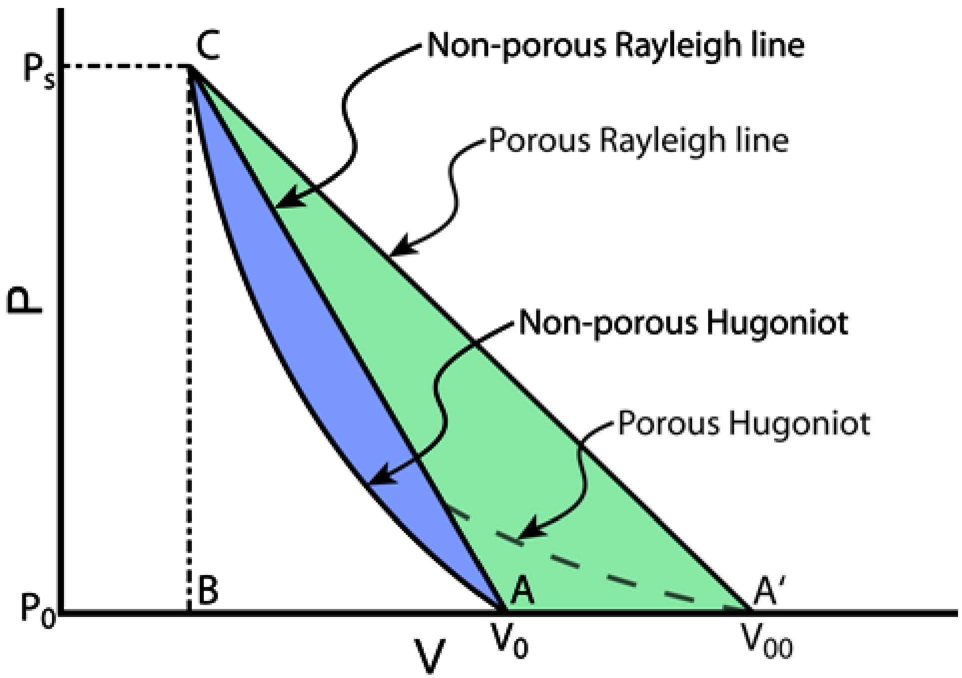
- Cratering in porous targets is poorly understood:
  - Crater size?
  - Melt and vapour production?
  - Momentum transfer?

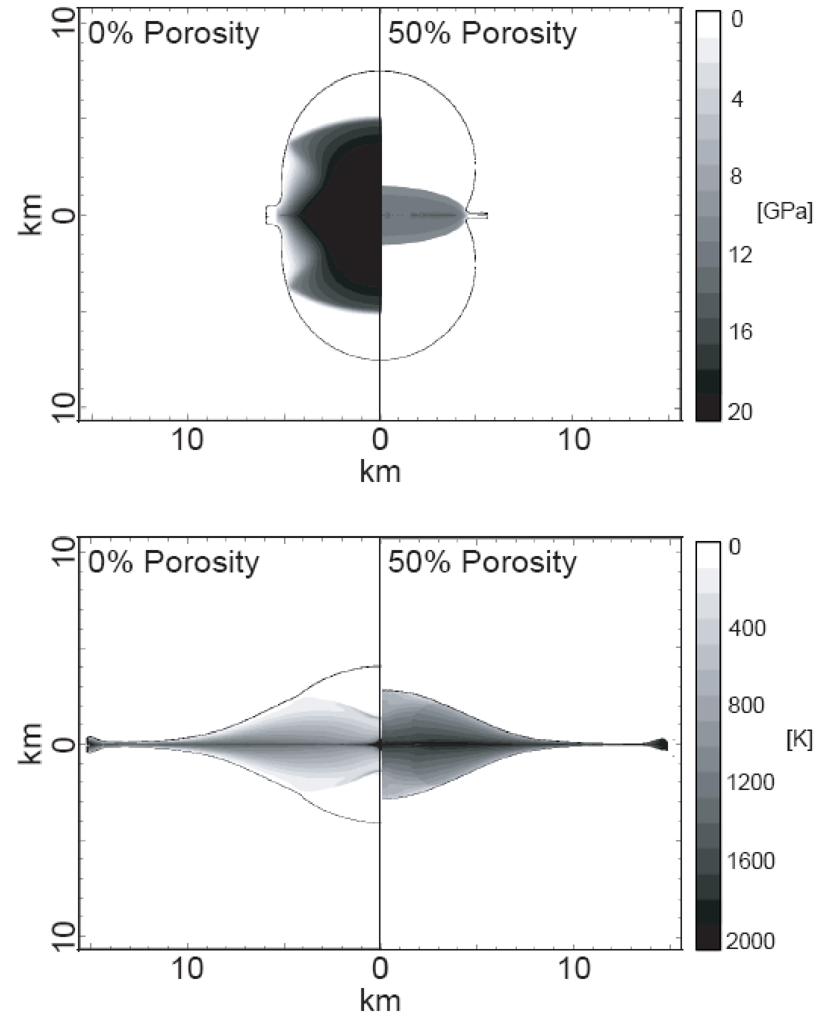
Asteroids show a large range in porosity



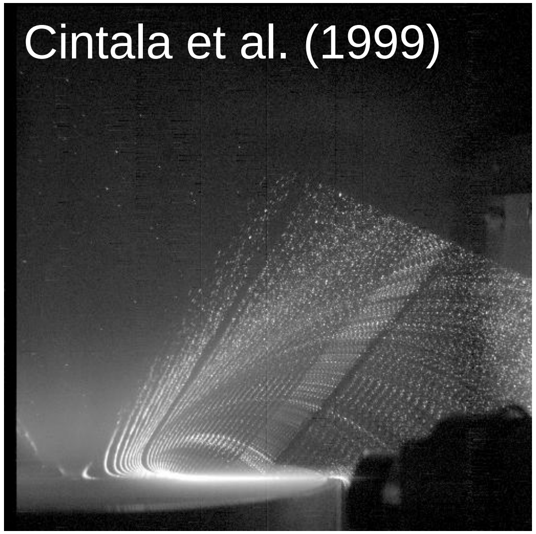
Britt et al., Asteroids III, 2004.

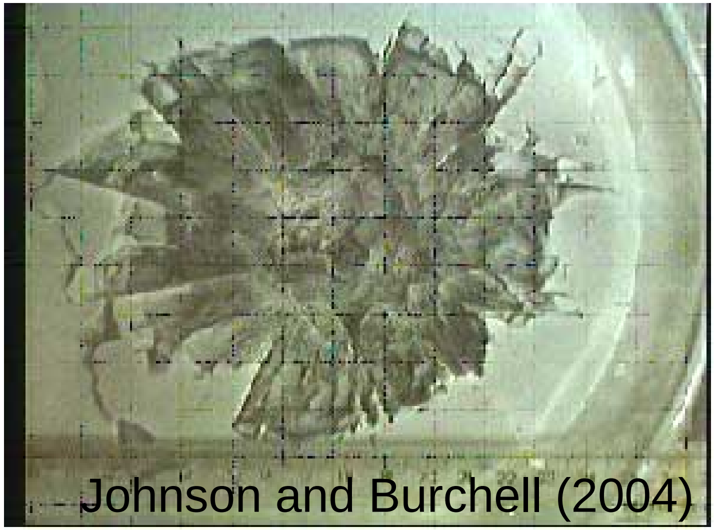
Porosity increases shock attenuation and shock heating





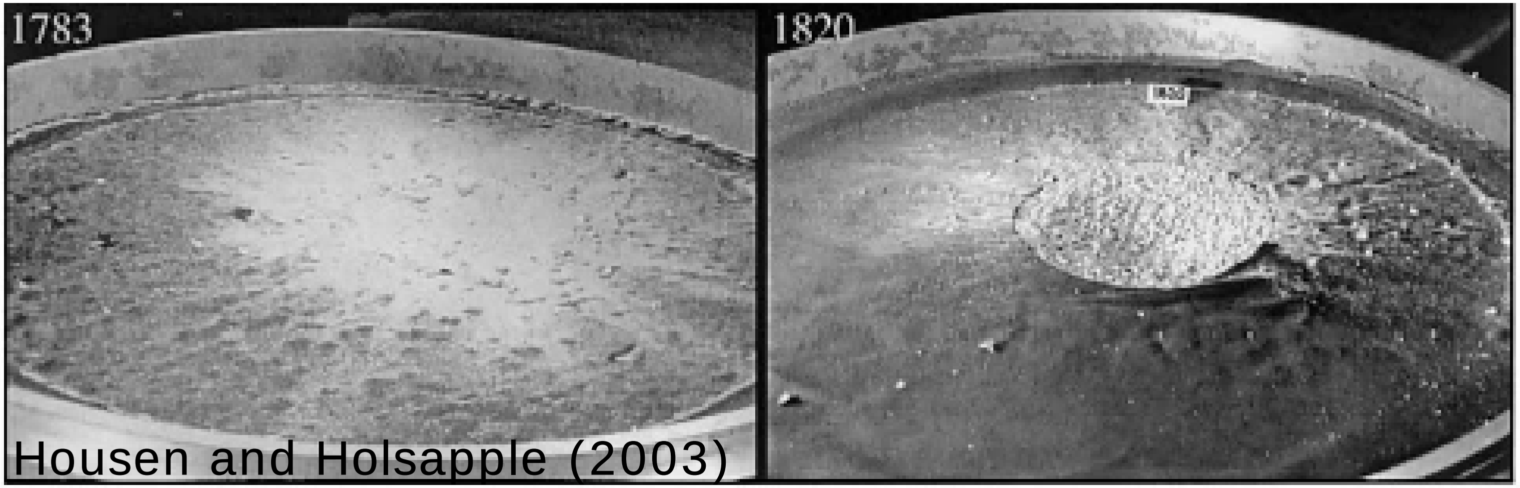
Effect of porosity difficult to study in lab-scale impacts


Cintala et al. (1999)


Johnson and Burchell (2004)

44% Porosity

70% Porosity



Housen and Holsapple (2003)

ε-alpha model for porous compaction

(Wünnemann, Collins and Melosh, 2006)

Compaction of pore space separated from compression of solid matrix:

$$P = f(E, \rho, \alpha) = \frac{1}{\alpha} P_s(\alpha\rho, E) = \frac{1}{\alpha} P_s(\rho_s, E).$$

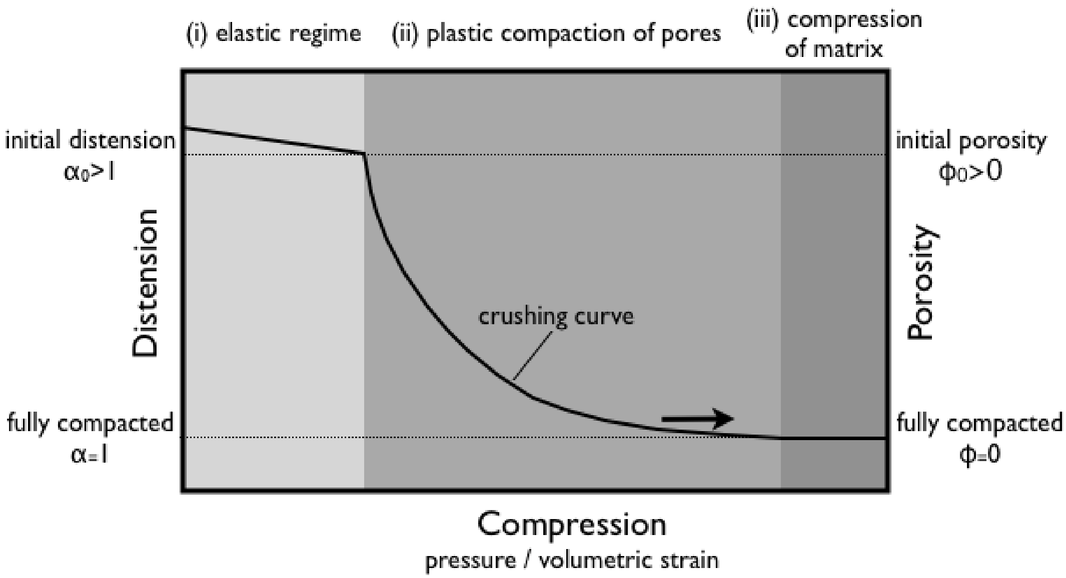
Thus, equation of state for the solid material can be used for porous material

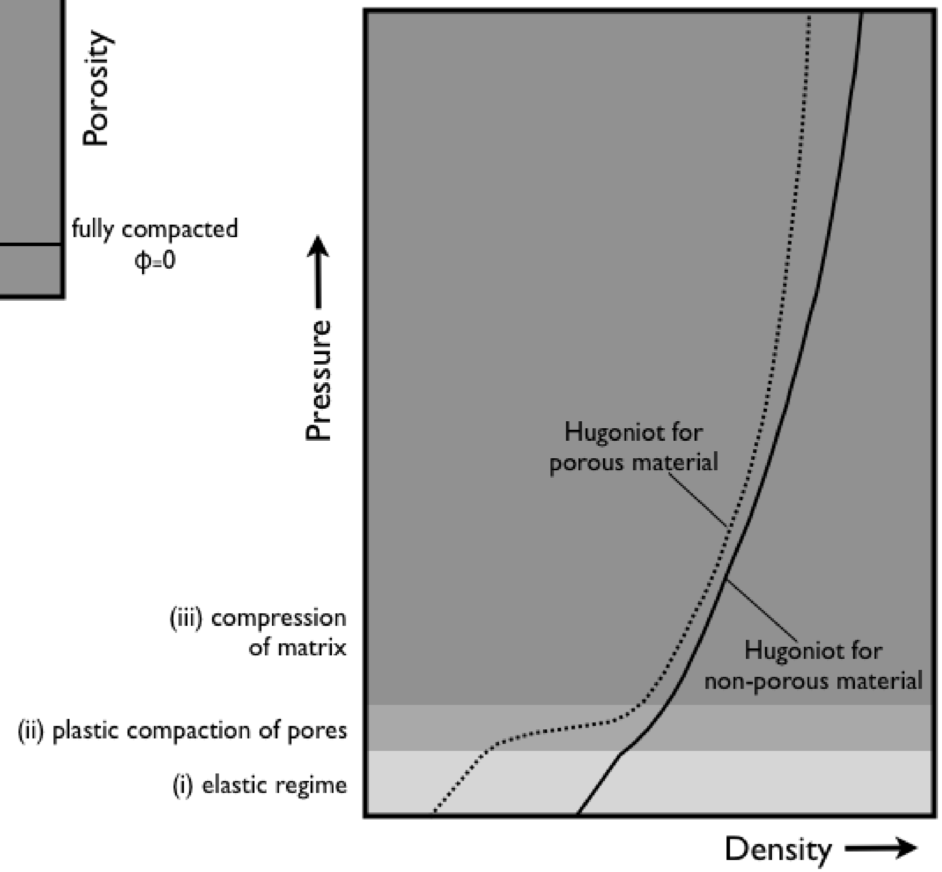
Just need to define the distension (porosity) as a function of *volume change*:

$$\alpha = f(\varepsilon_V) = \begin{cases} \alpha_0 & |\varepsilon_V > \varepsilon_e \\ \alpha_0 e^{\kappa(\varepsilon_V - \varepsilon_e)} & |\varepsilon_V < \varepsilon_e \end{cases},$$

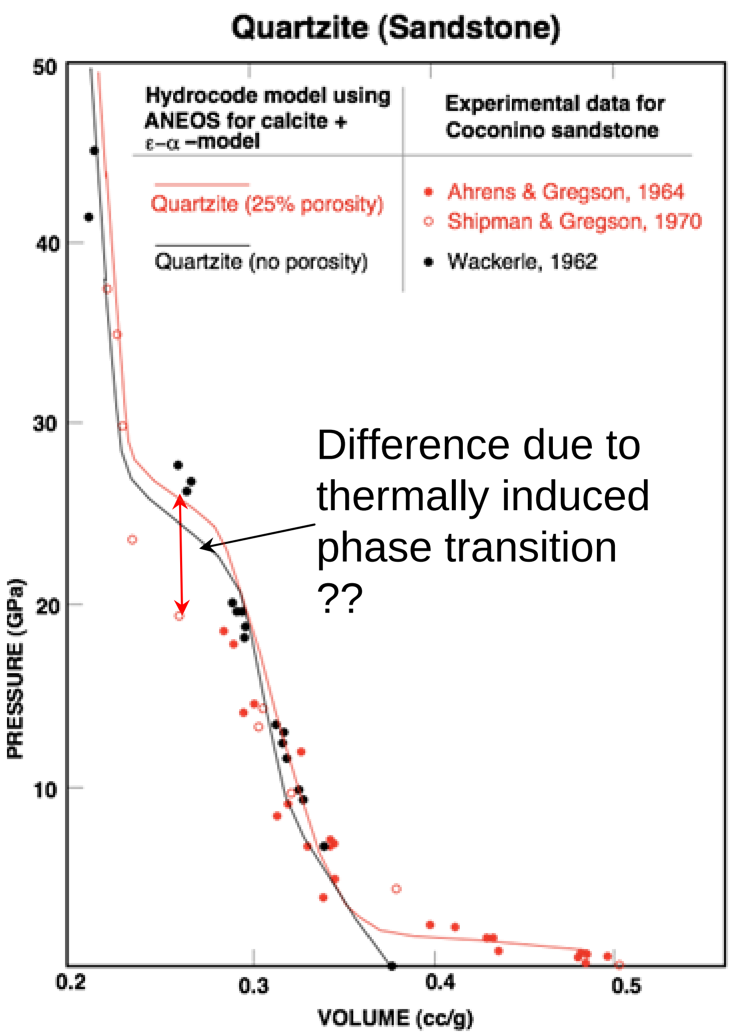
ε-alpha model for porous compaction

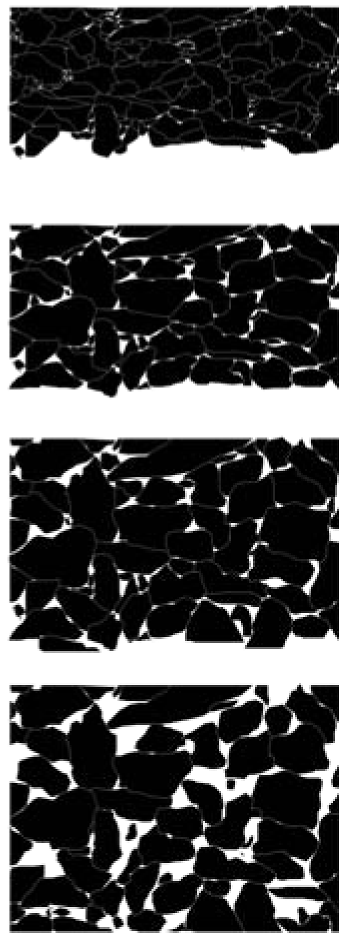
(Wünnemann, Collins and Melosh, 2006)

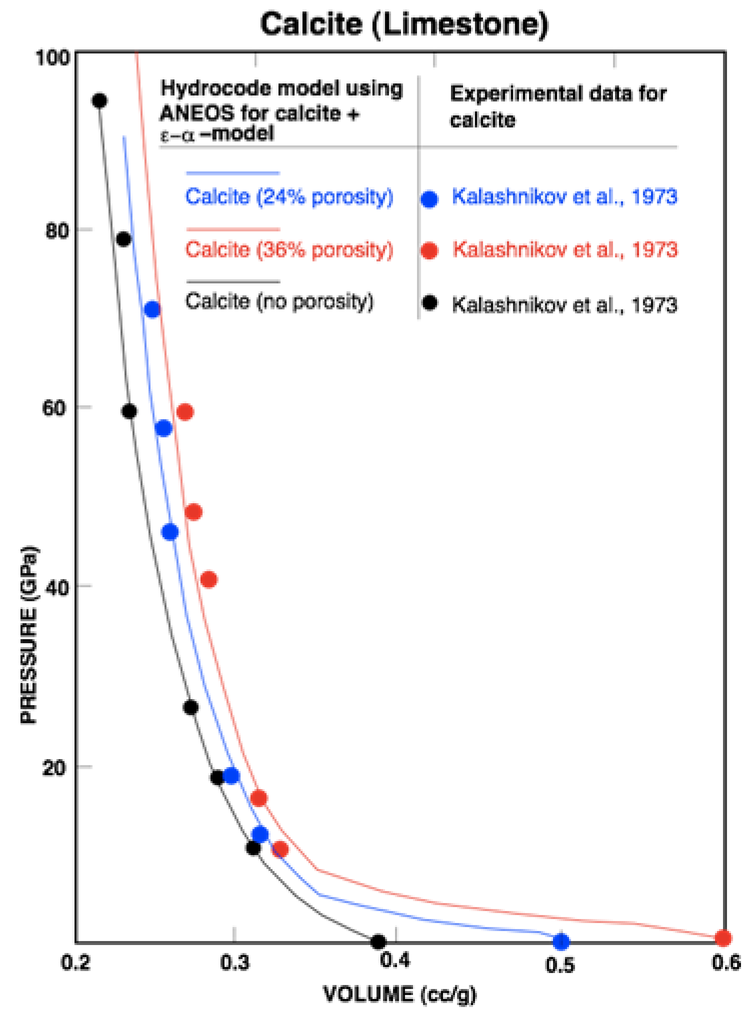




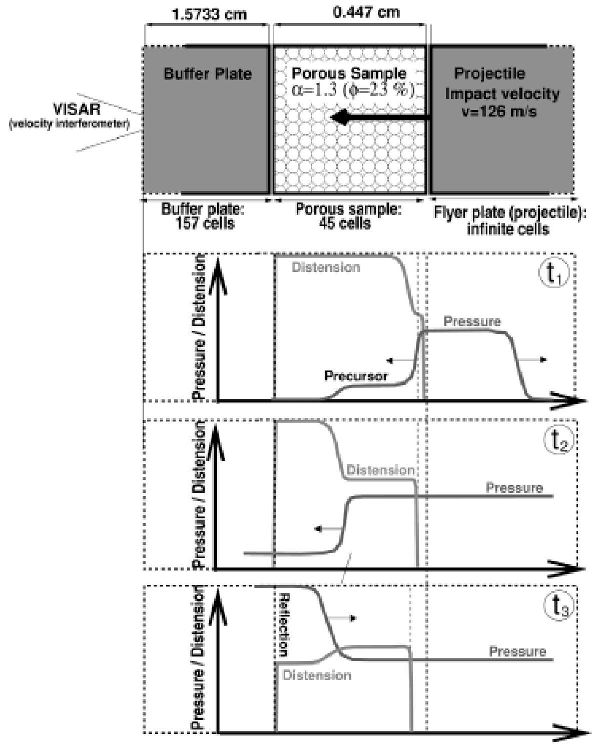
Model validated against Hugoniot data from experiments



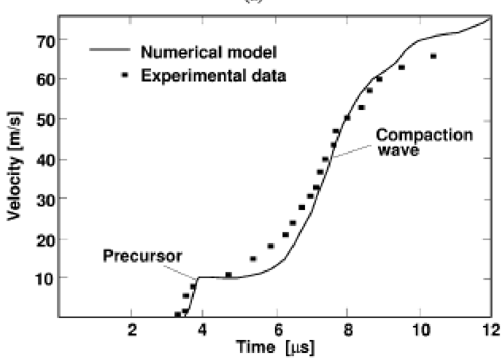




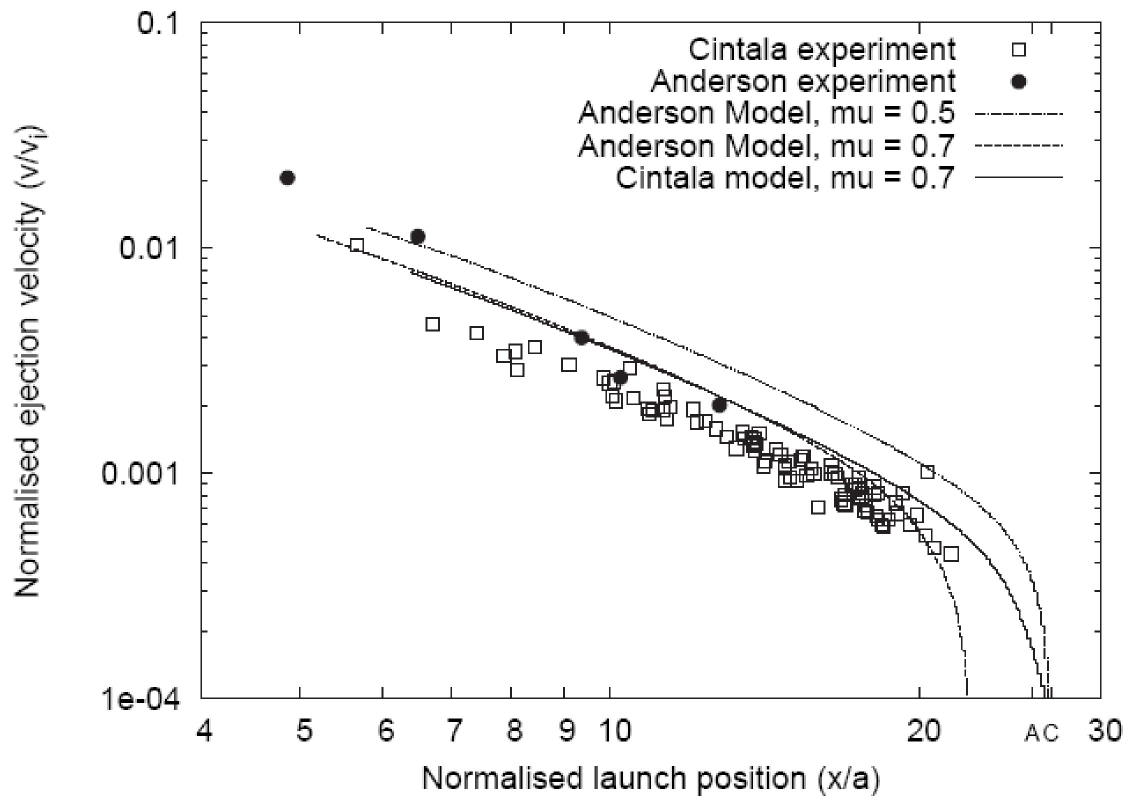
Model validated against experiments

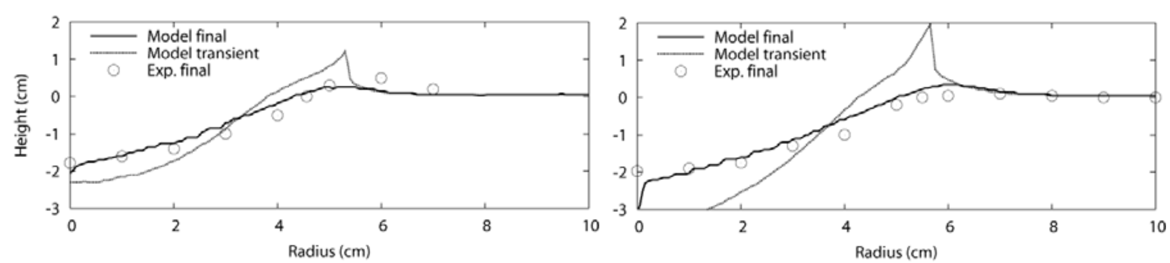


(a)

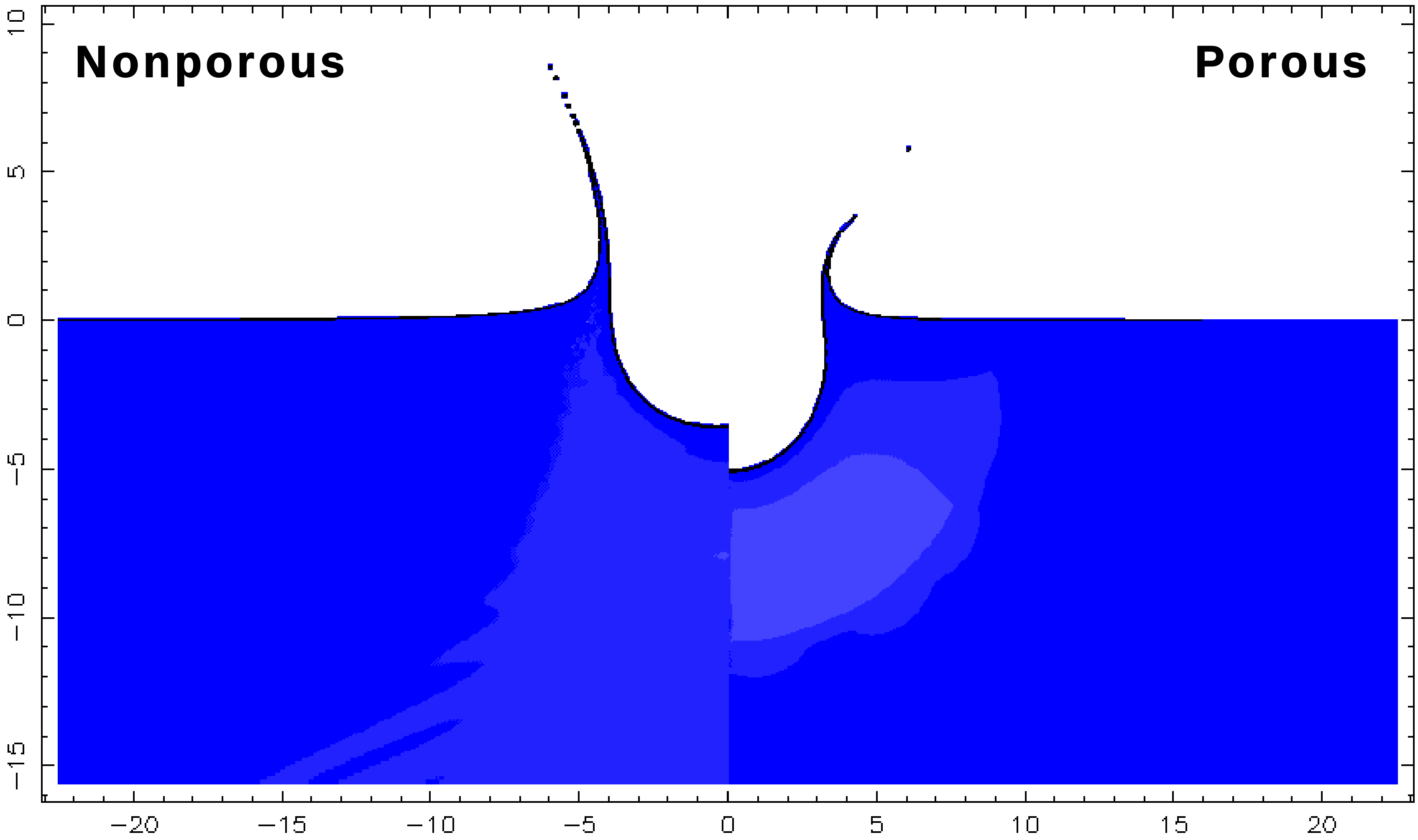


(b)



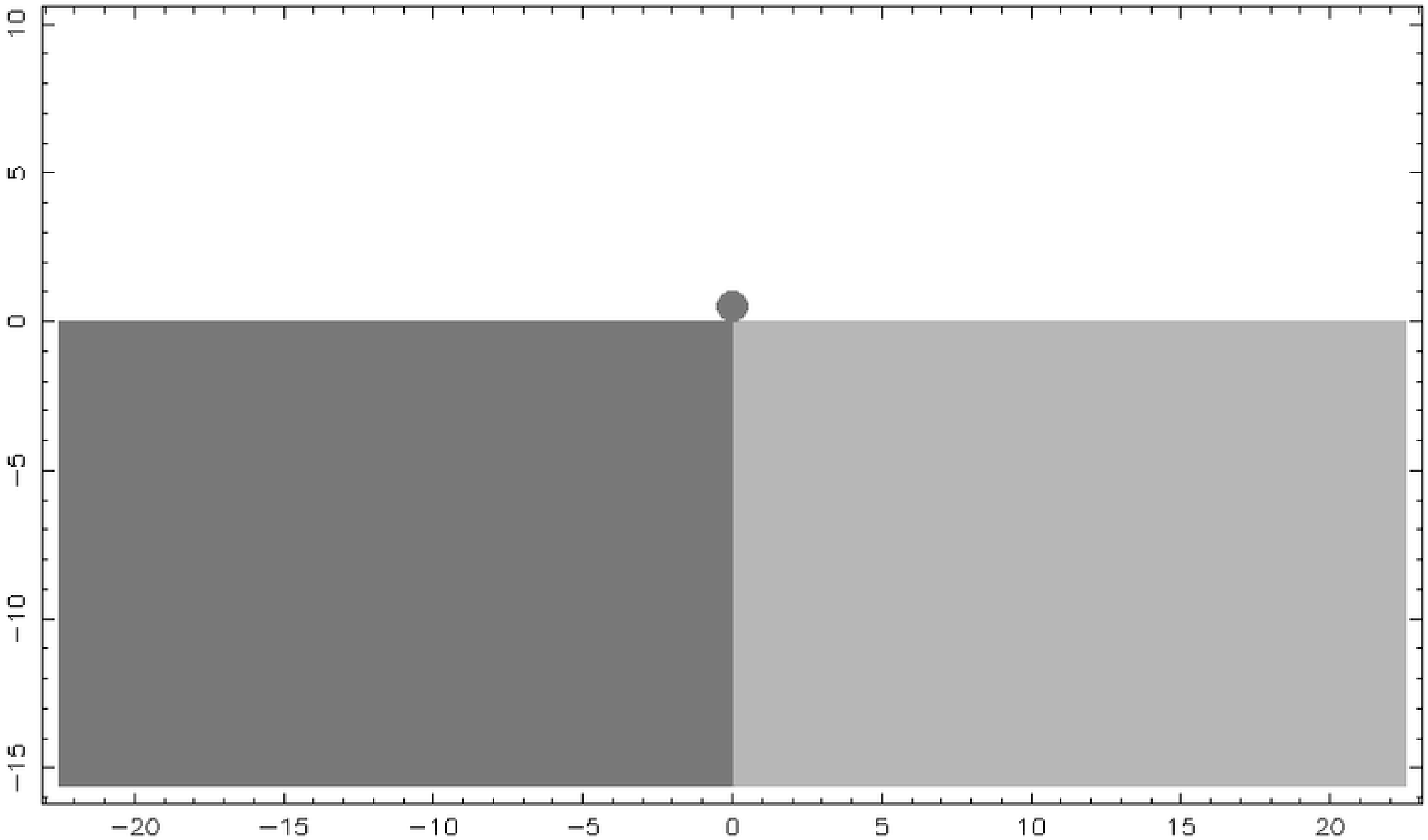


Porous material absorbs shock wave more efficiently

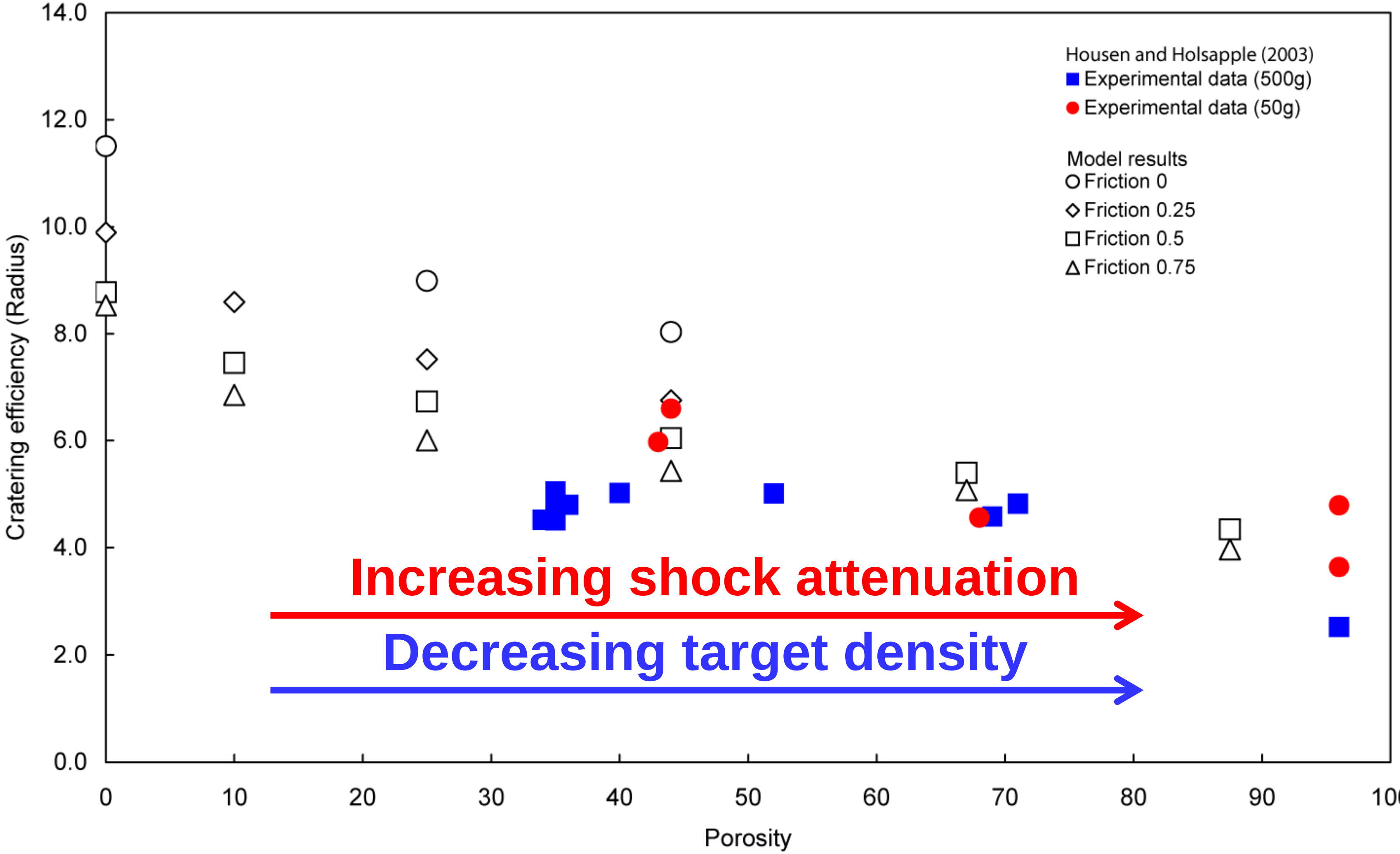


Porosity reduces crater diameter and cratered mass

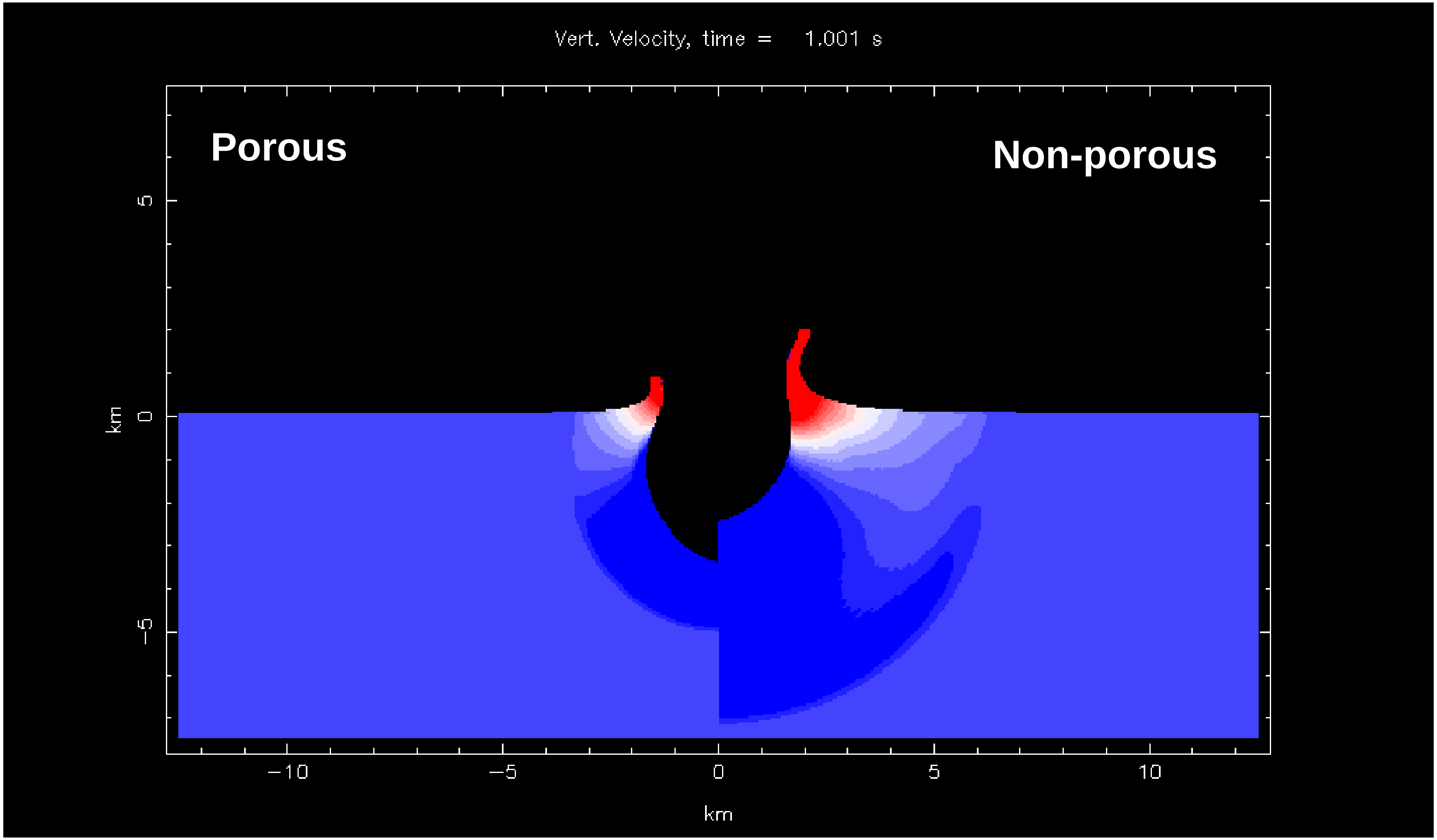
Nonporous **Porous**



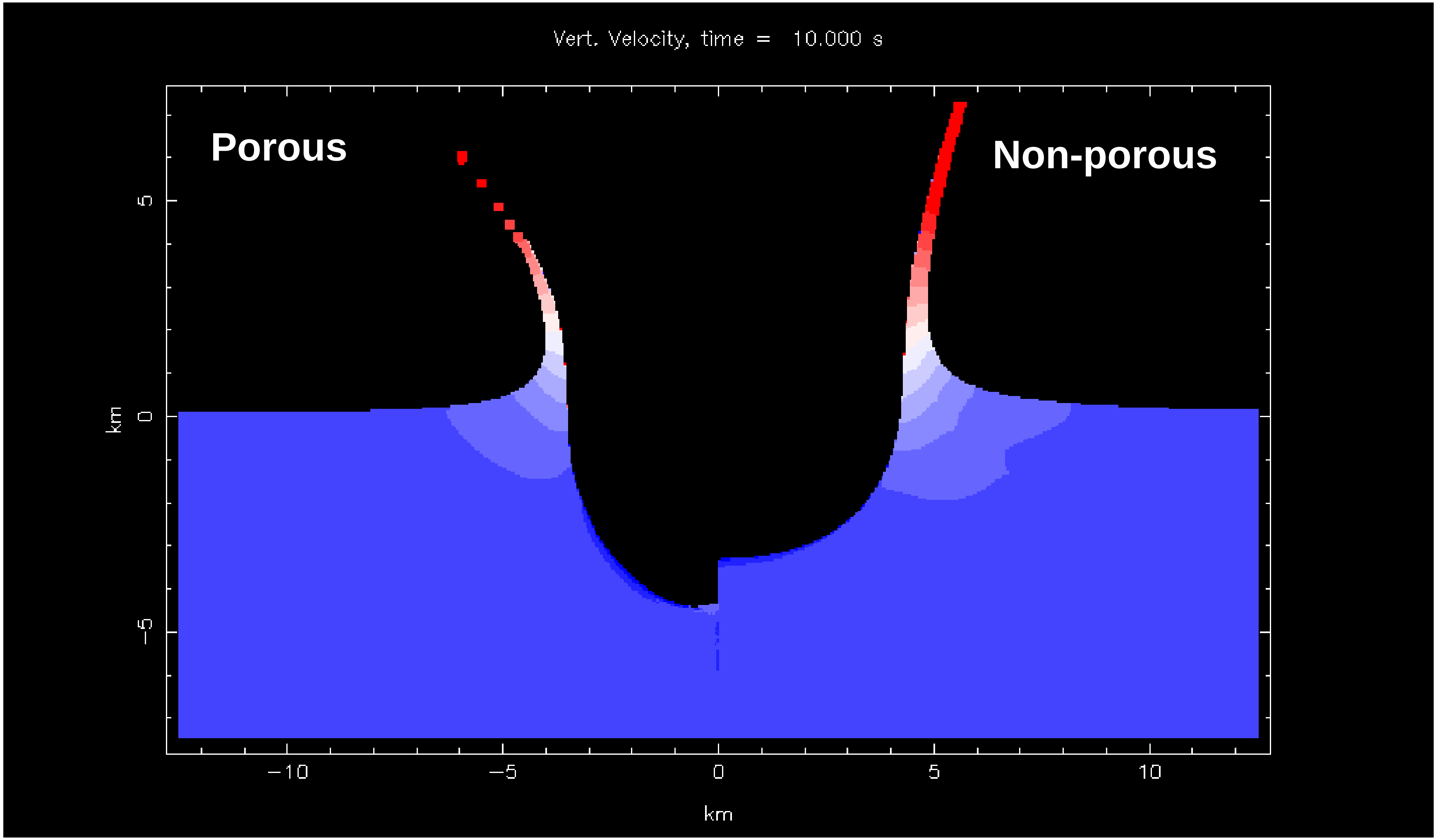
Porosity and friction decrease cratering efficiency



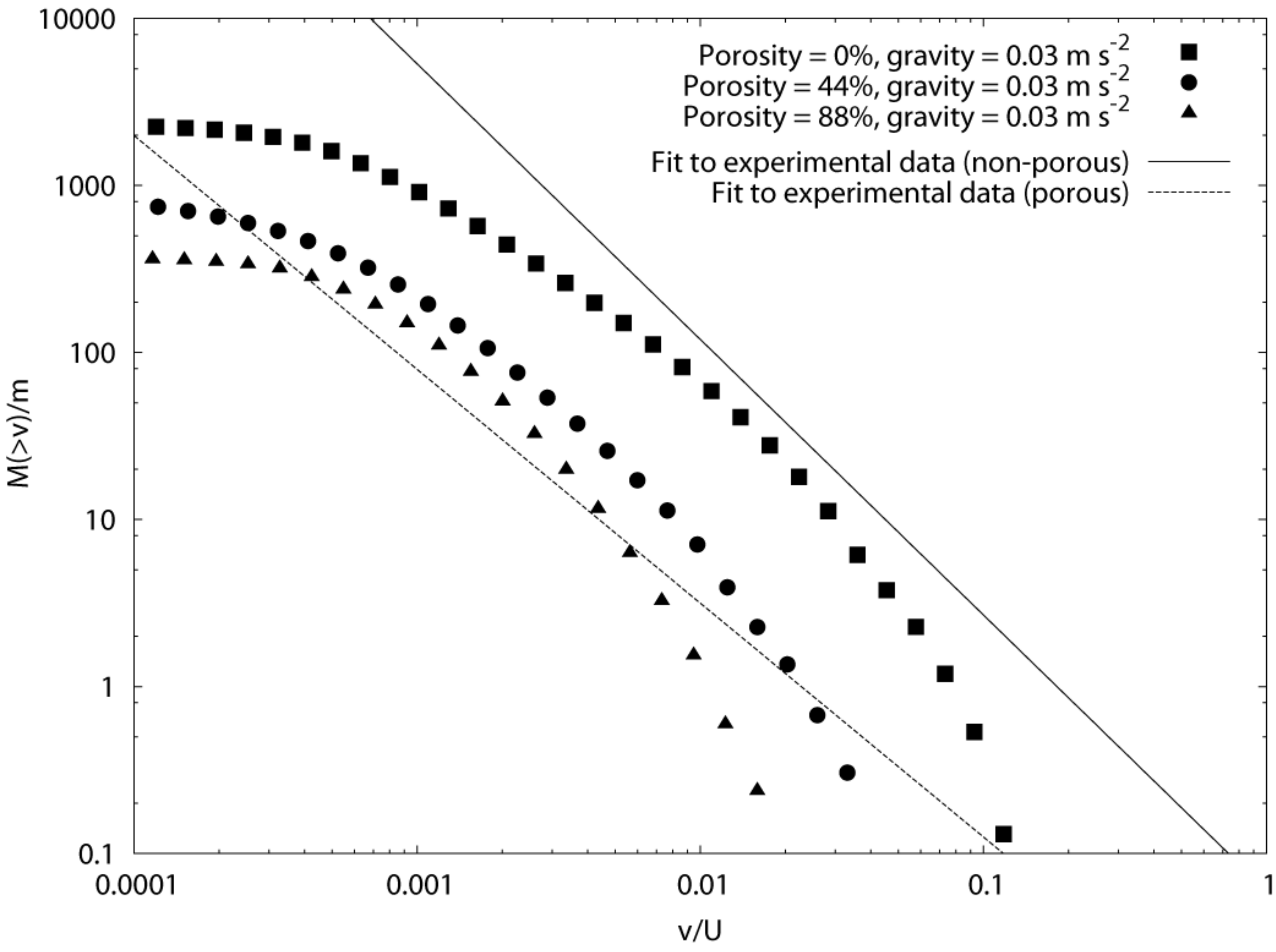
Porous targets absorb shock energy



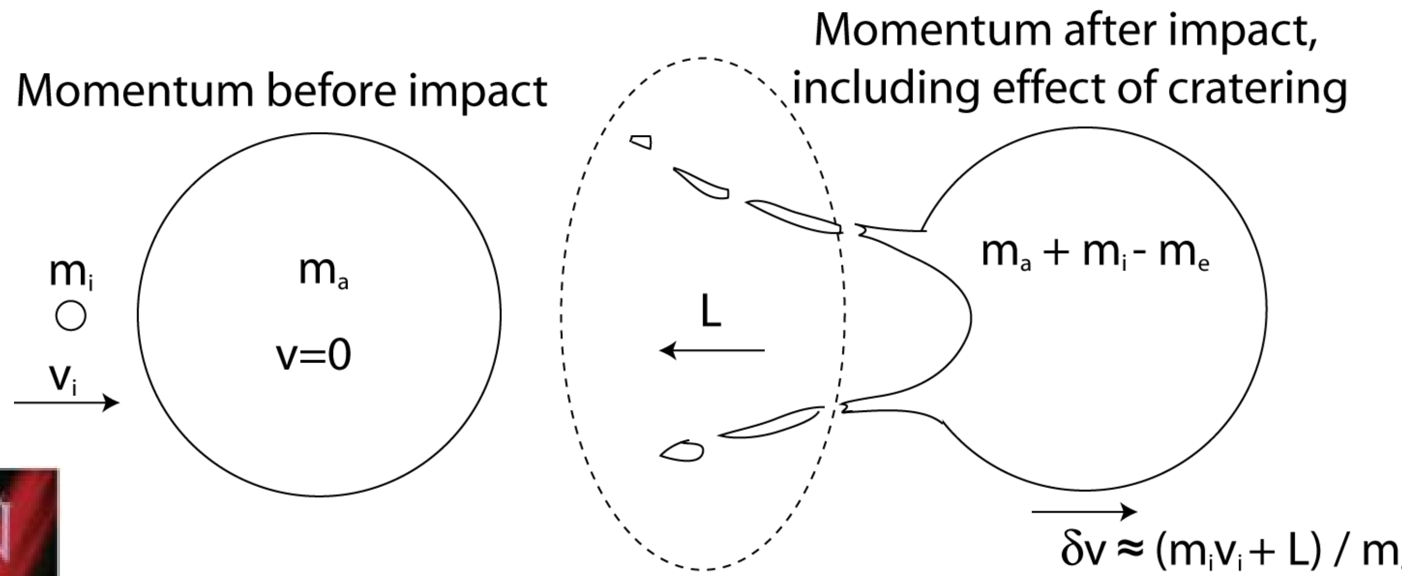
This means lower ejection velocity and smaller craters

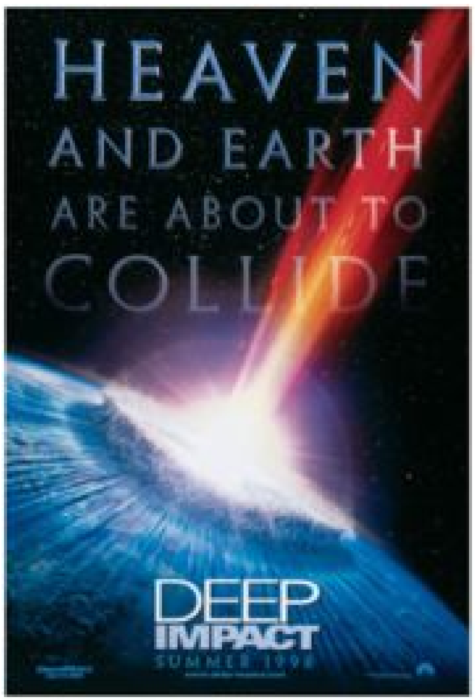


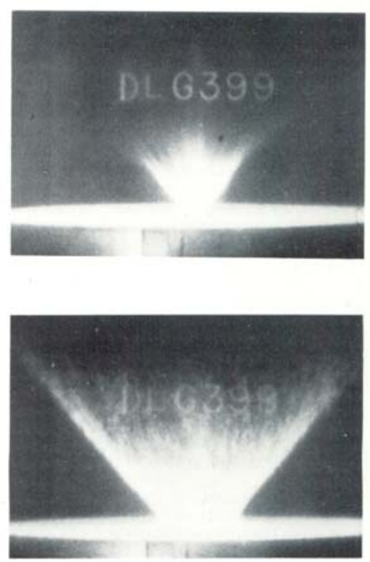
Porosity greatly reduces velocity and total mass of ejecta

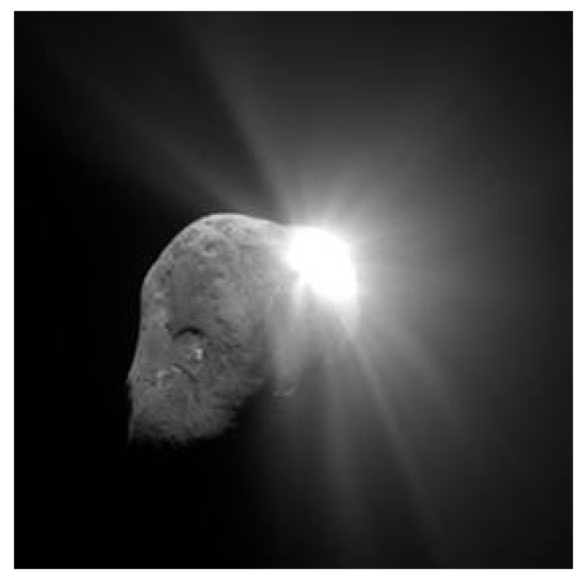


Application: Asteroid deflection by direct impact

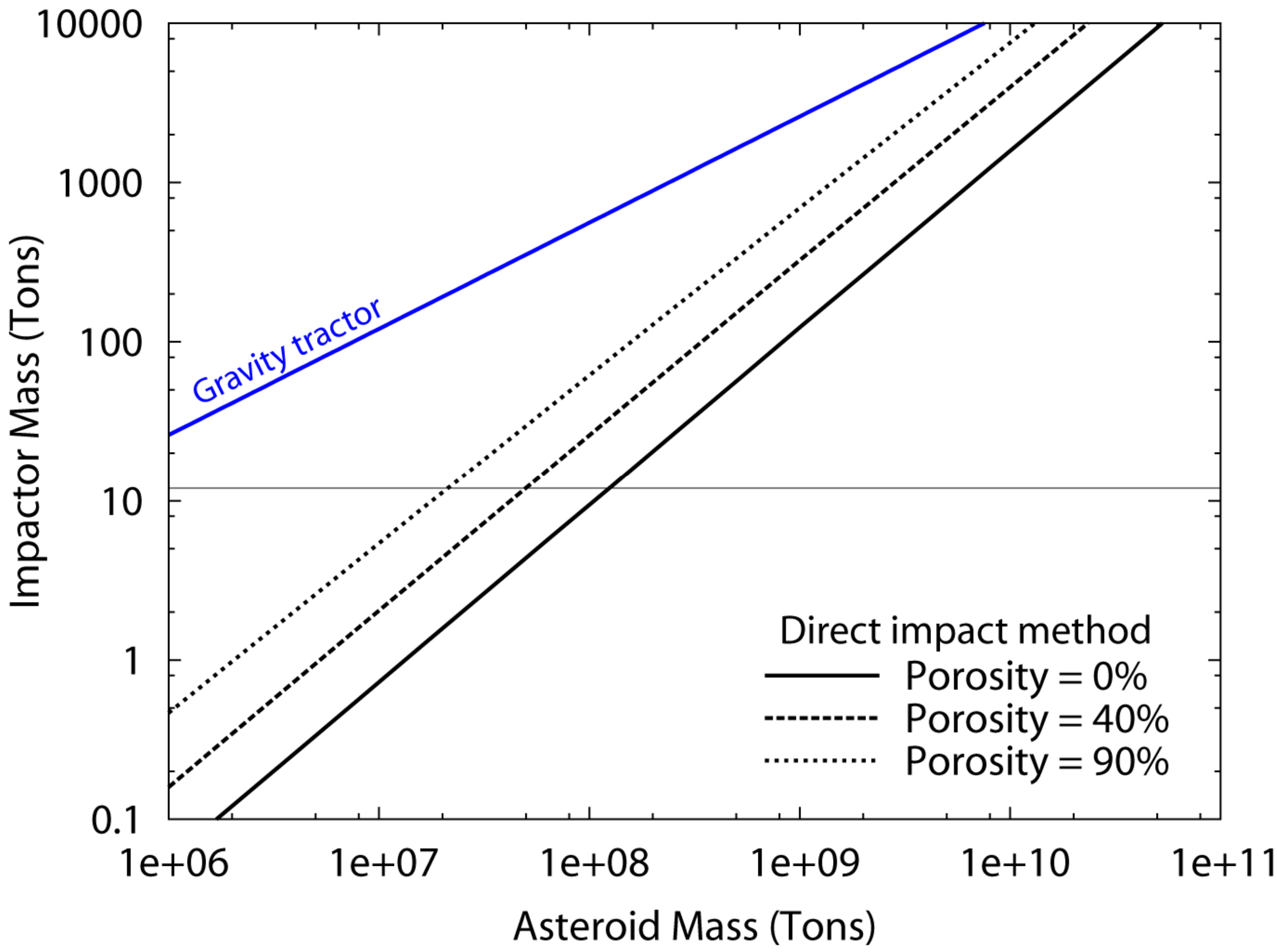




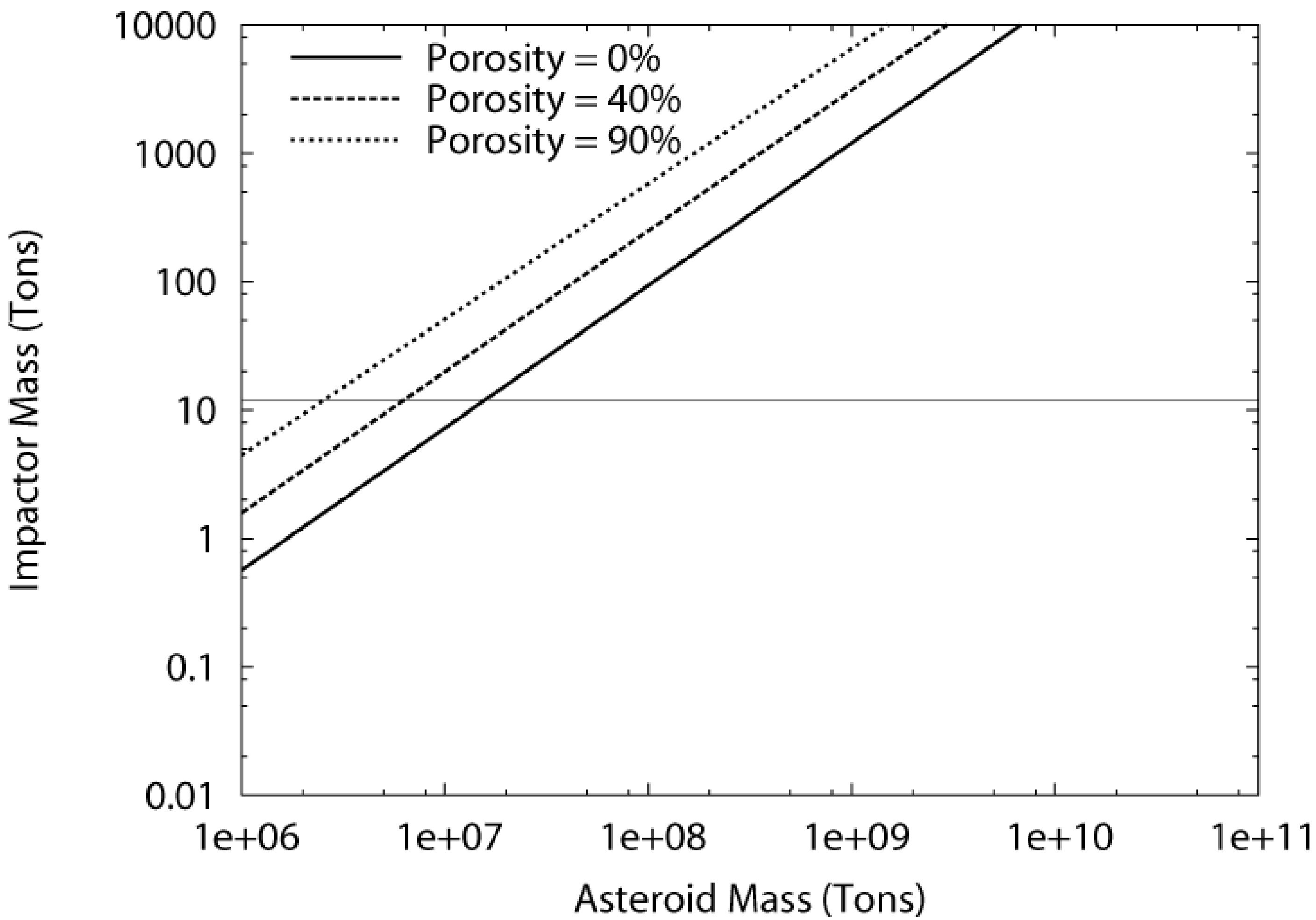




10 yr lead: <~400-m wide asteroids could be deflected



With 1 yr lead, this drops to <~150-m asteroids



Conclusions

- Porosity has an important effect on impact cratering
- Porous materials absorb shock wave energy, leading to lower cratering efficiency
  - Less mass excavated and displaced
  - Lower ejection velocities and shock pressures
  - Less efficient momentum transfer
  - Efficacy of deflection by impact reduced if asteroid porous
- The absorbed energy leads to greater melting of porous materials
  - More melt expected in sedimentary target craters
  - Impact melt production in early, low velocity collisions of planetesimals?