Tsunamis from asteroid impacts in deep water

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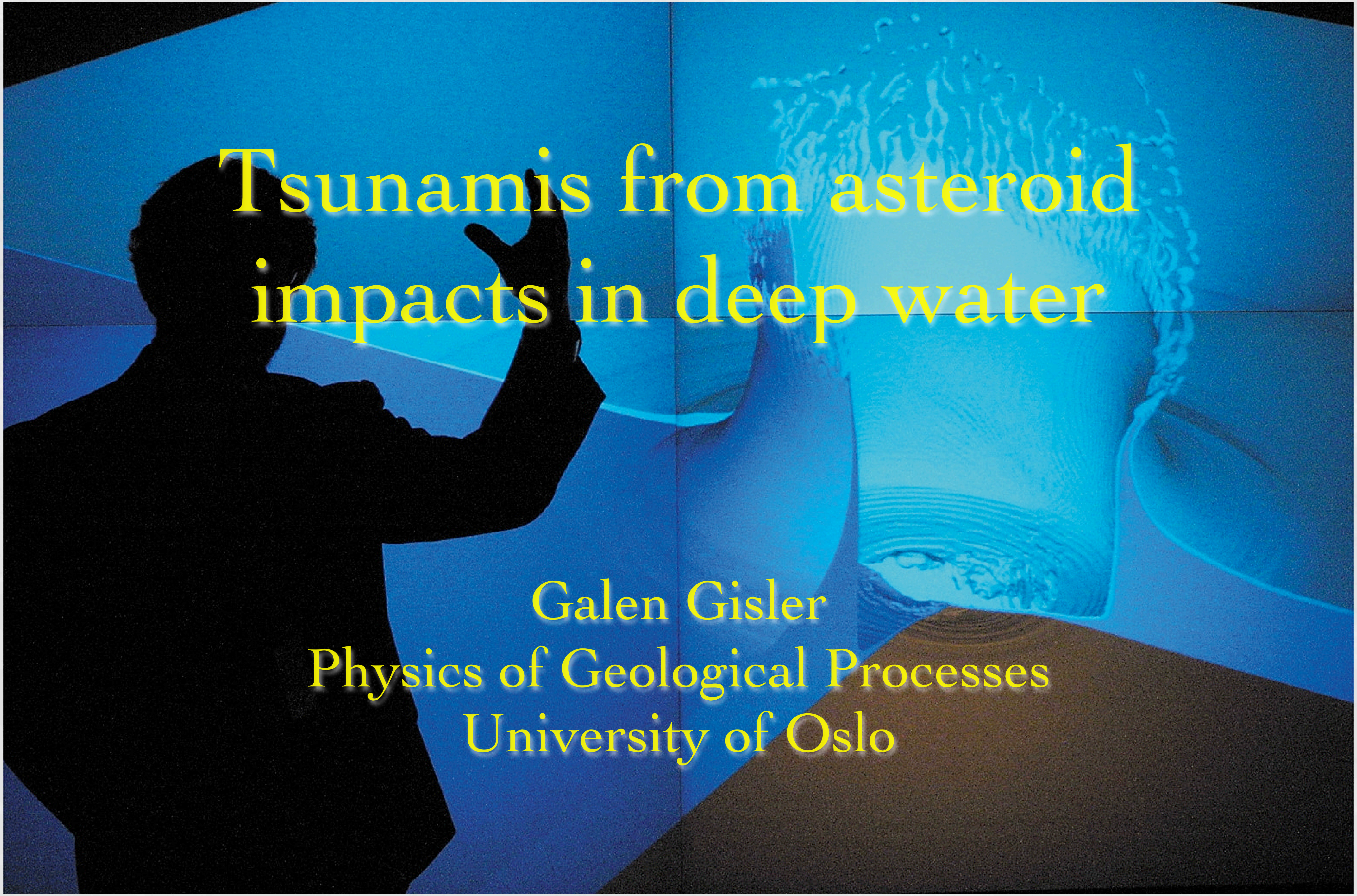

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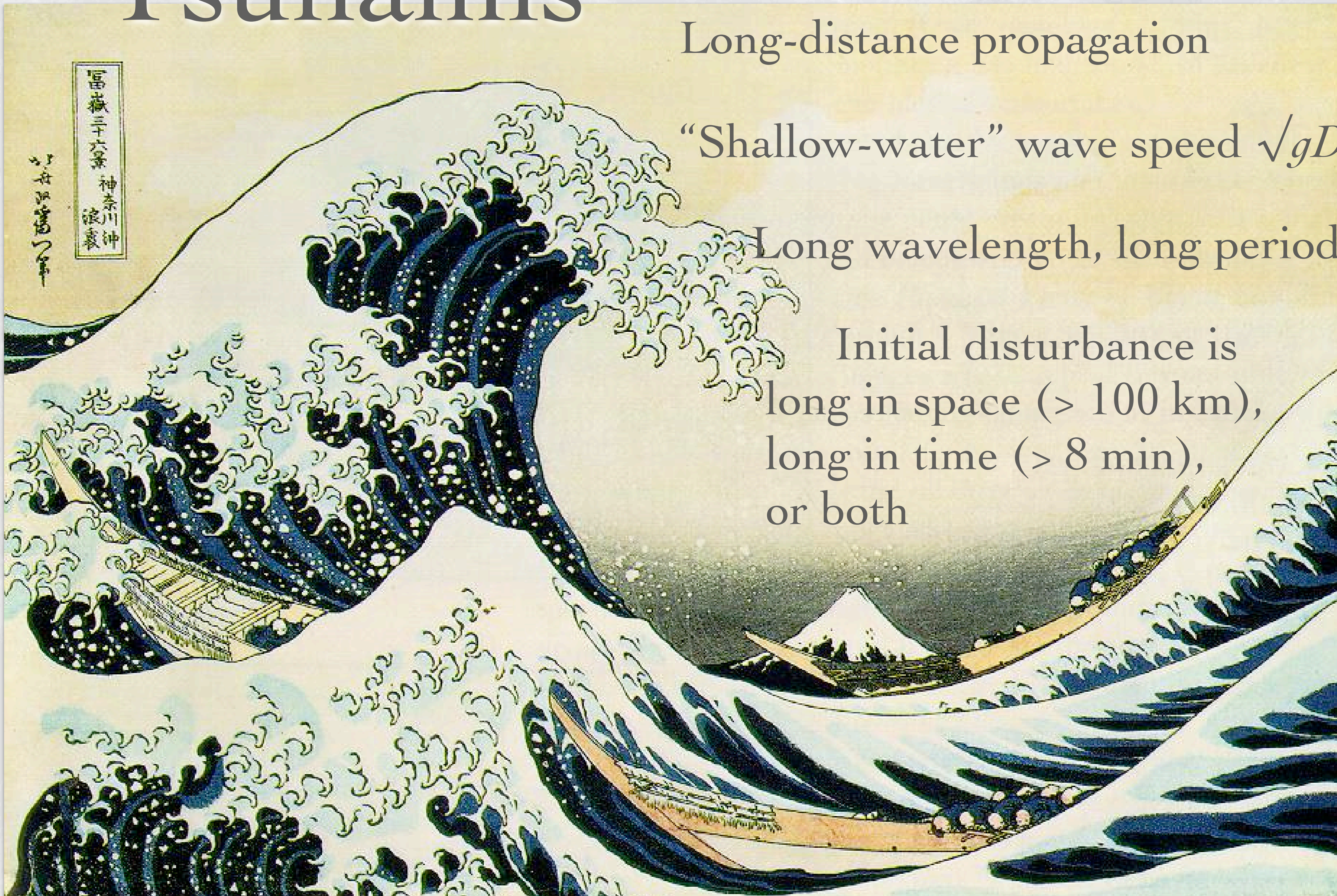
Tsunamis



Long-distance propagation

"Shallow-water" wave speed $\sqrt{gD}$

Long wavelength, long period

Initial disturbance is
long in space (> 100 km),
long in time (> 8 min),
or both

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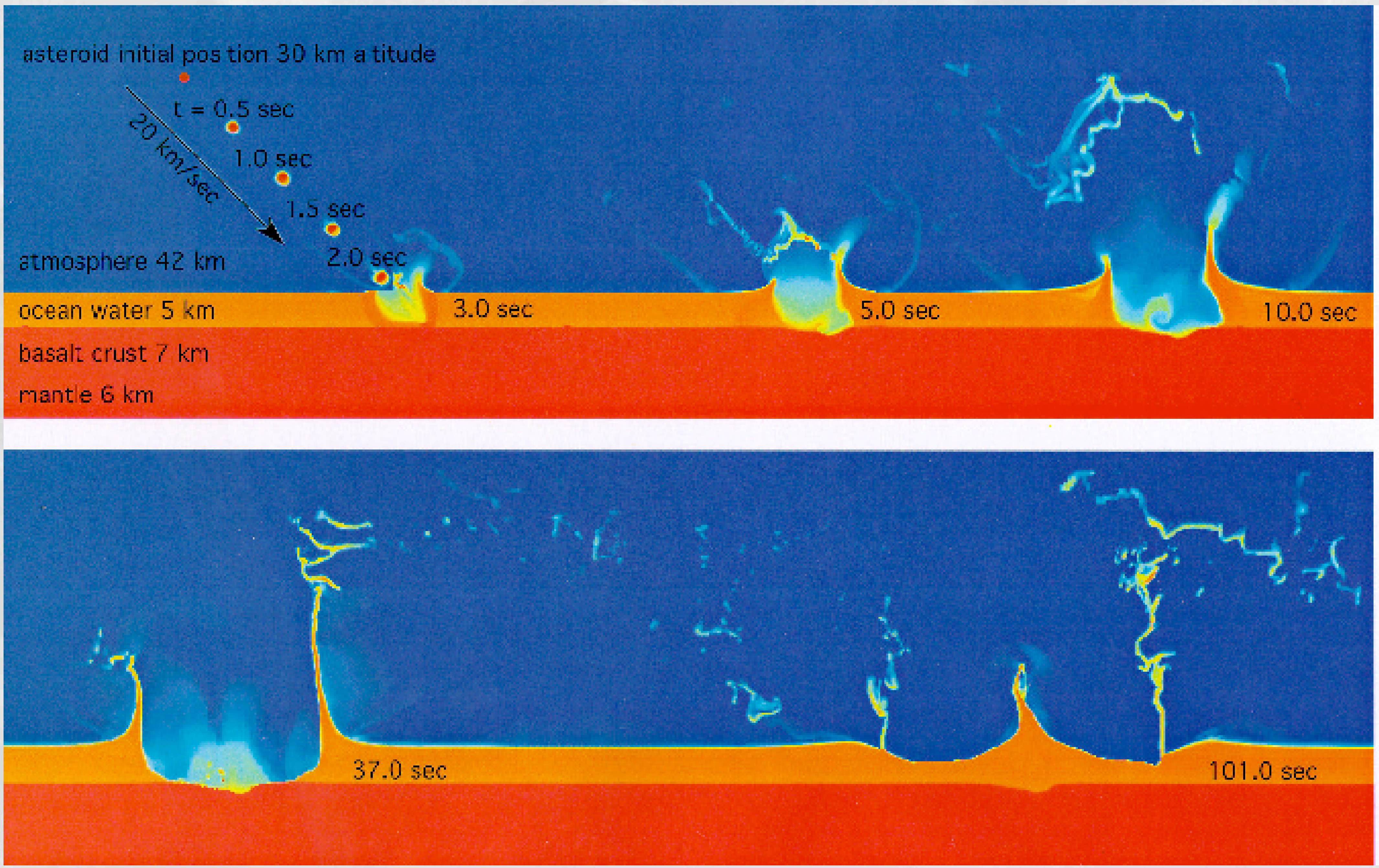
- *These conditions are not true in general for asteroid impact tsunamis*
- *Waves generated by impacts (and other explosive events) have shorter wavelengths and periods than classical tsunamis*
- *These tsunamis can nevertheless be very dangerous, especially to local populations*

Cross-section of an oblique asteroid impact into water



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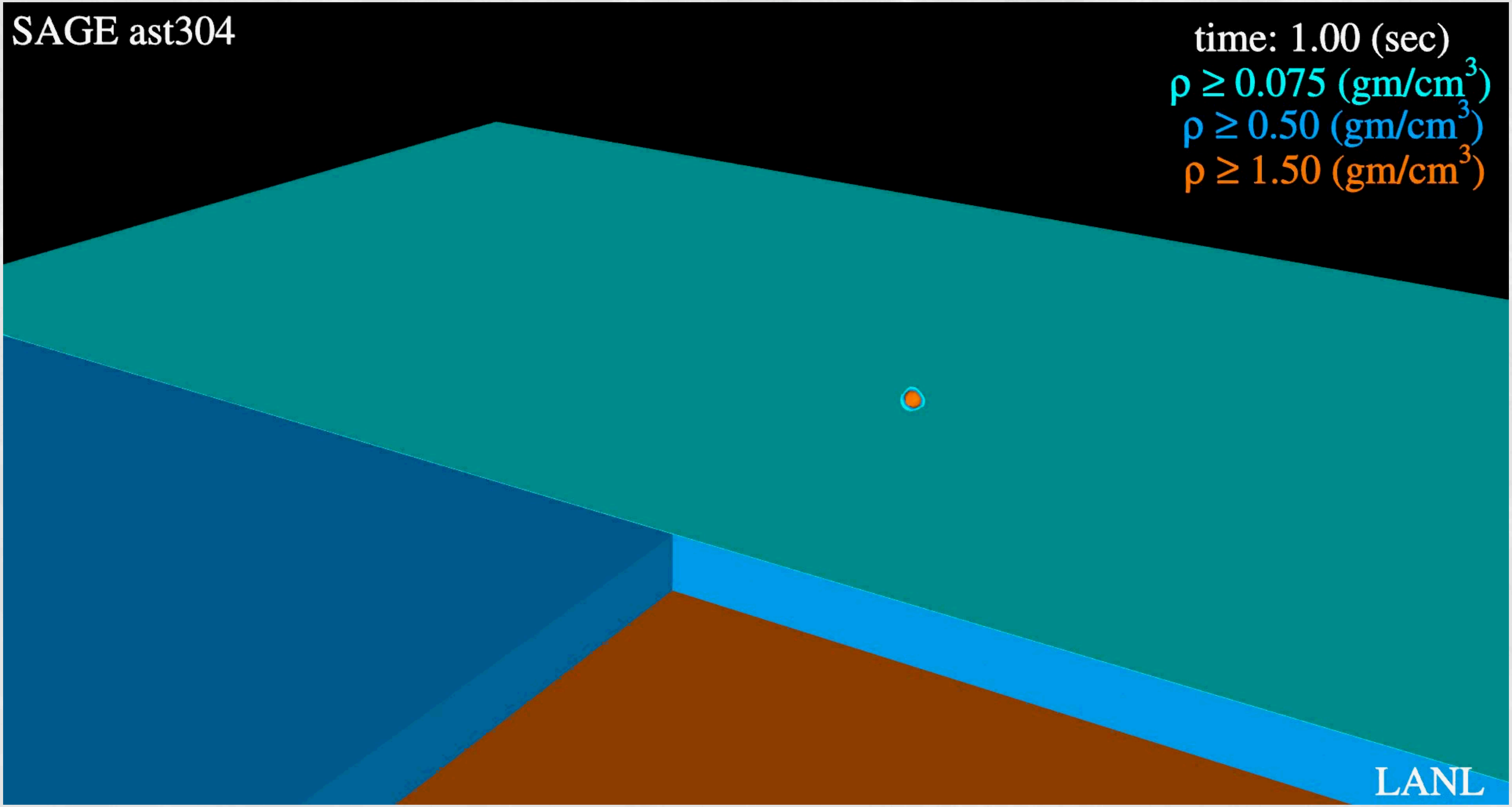
1 km iron asteroid at 20 km/s into 5 km deep water at an angle of 45°



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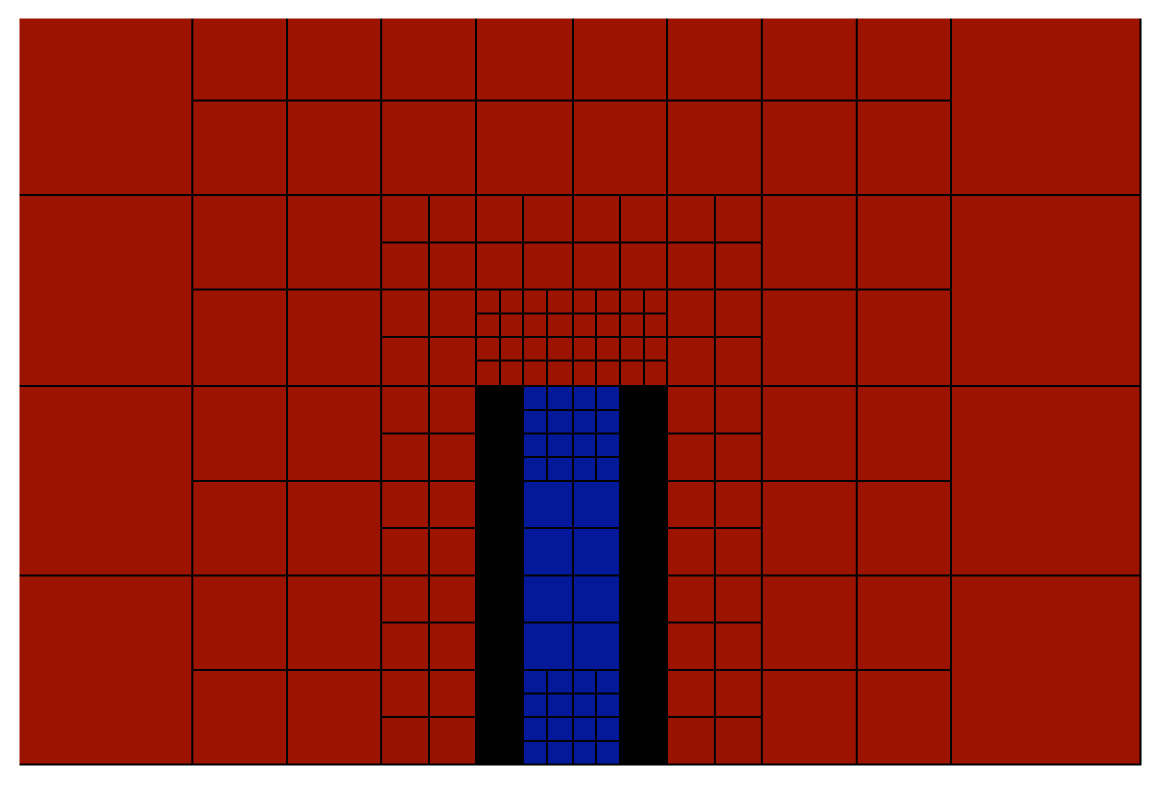
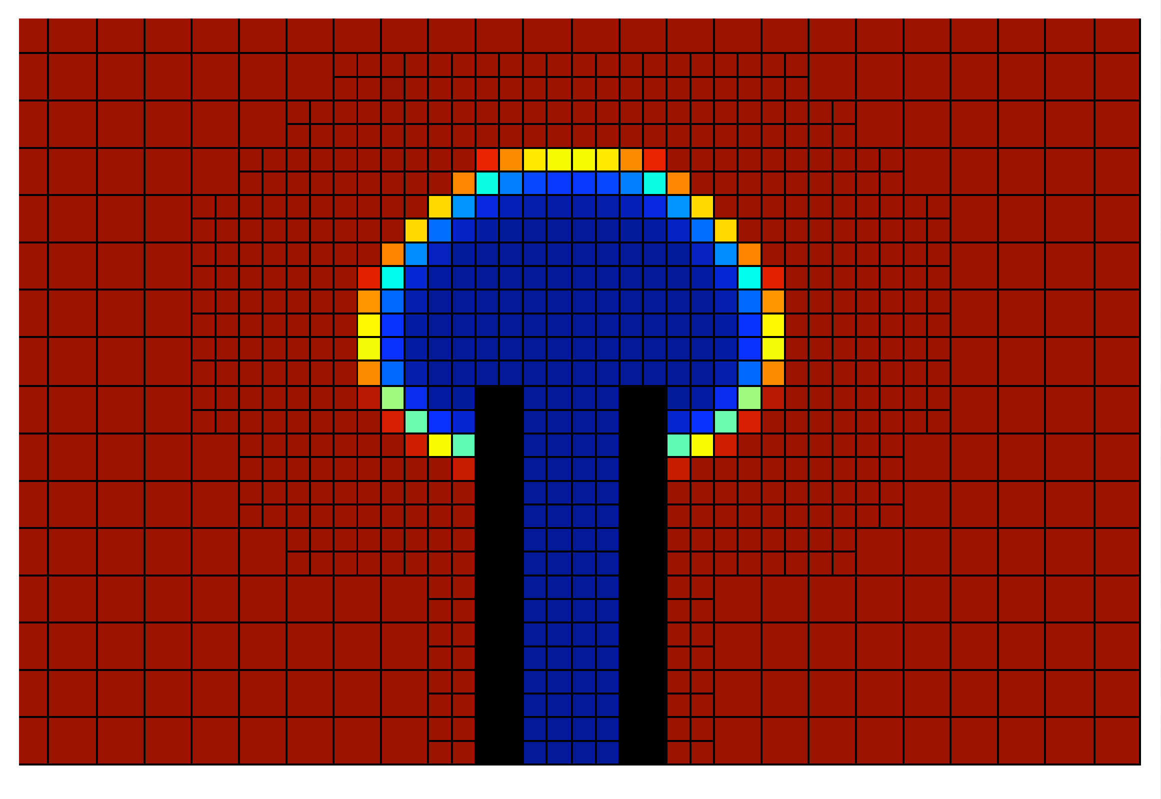
The SAGE Code





- Multi-material, multi-phase, fully compressible hydrocode
- Adaptive Grid Eulerian (cell-by-cell)
- Product of Science Applications International & Los Alamos National Laboratory
- License-free, but *Export-Controlled*

Crestone PROJECT

SAIC An Employee-Owned Company

Los Alamos

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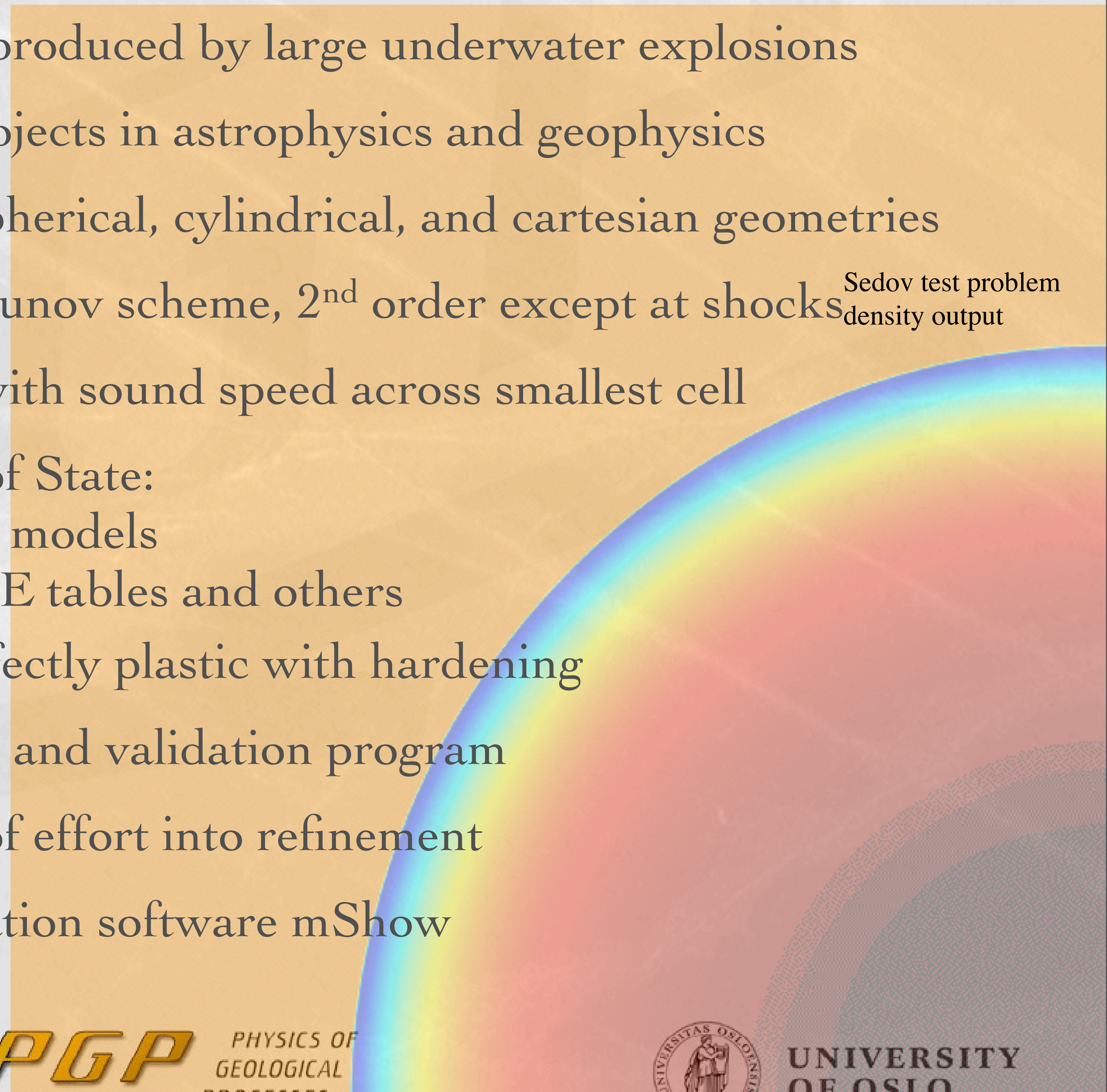
The SAGE Code

- Original use: waves produced by large underwater explosions
- Used for range of projects in astrophysics and geophysics
- 1, 2, 3 dimensions, spherical, cylindrical, and cartesian geometries
- High-resolution Godunov scheme, 2^{nd} order except at shocks
- Explicit: CFL limit with sound speed across smallest cell
- Multiple Equations of State:
  - Several analytic models
  - LANL SESAME tables and others
- Strength: elastic-perfectly plastic with hardening
- Rigorous verification and validation program
- Many person-years of effort into refinement
- Comes with visualization software mShow



Sedov test problem
density output

Asteroid impact tsunamis

- How different from “classical” tsunamis?
  - shorter in wavelength and period
  - less effective long-distance propagation
- How large an asteroid do we need to worry about?
  - maybe 500m iron, 1000m stony

A large parameter study of 2-D asteroid impact runs

- 3 compositions (iron, dunite, ice)
- 3 diameters (1000m, 500m, 250m)
- 3 speeds (20 km/s, 15 km/s, 10 km/s)
- impact energies from 90 Megaton to 200 Gigaton TNT equivalent
- displaced water mass from $6x10^9$ to $2x10^{12}$ metric tonnes (6 to 2000 cubic kilometers)

A large parameter study of 2-D asteroid impact runs

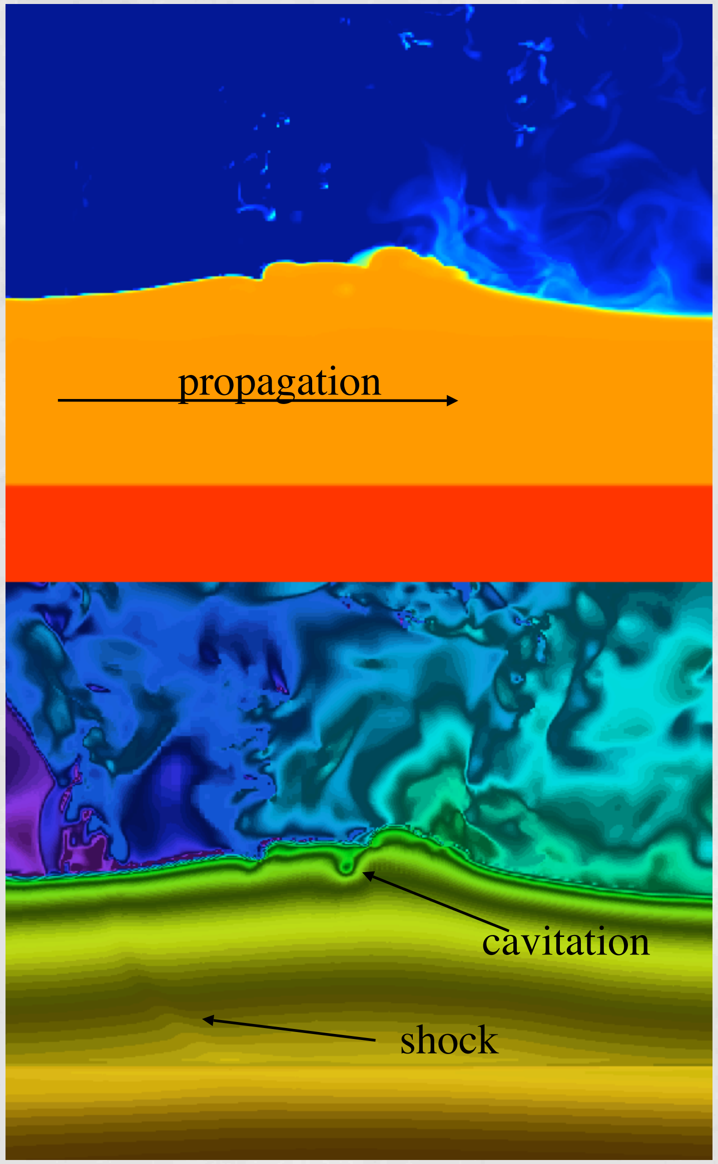
composition	diameter (m)	speed (km/s)	kinetic energy on impact (ton TNT)	wave height (m) at 10 km	wave period (s)
iron	1000	20	1.95E+11	2.10E+04	146.87
iron	1000	15	1.10E+11	1.11E+04	135.82
iron	1000	10	4.88E+10	4.92E+03	124.84
iron	500	20	2.43E+10	3.65E+03	125.33
iron	500	15	1.37E+10	2.41E+03	101.29
iron	500	10	6.08E+09	1.52E+03	105.05
iron	250	20	3.00E+09	2.44E+03	103.12
iron	250	15	1.69E+09	1.17E+03	105.90
iron	250	10	7.54E+08	4.69E+02	110.48
dunite	1000	20	8.27E+10	8.94E+03	140.15
dunite	1000	15	4.65E+10	9.95E+03	133.52
dunite	1000	10	2.07E+10	3.41E+03	127.49
dunite	500	20	1.02E+10	2.27E+03	93.89
dunite	500	15	5.74E+09	1.56E+03	96.51
dunite	500	10	2.56E+09	1.11E+03	108.19
dunite	250	20	1.24E+09	8.17E+02	107.53
dunite	250	15	7.03E+08	5.20E+02	103.68
dunite	250	10	3.15E+08	3.31E+02	88.00
ice	1000	20	2.45E+10	3.10E+03	122.01
ice	1000	15	1.39E+10	2.66E+03	102.37
ice	1000	10	6.22E+09	1.54E+03	98.65
ice	500	20	2.89E+09	1.09E+03	101.77
ice	500	15	1.69E+09	9.29E+02	107.29
ice	500	10	7.66E+08	5.33E+02	117.11
ice	250	20	2.66E+08	2.07E+02	76.75
ice	250	15	1.69E+08	1.97E+02	73.77
ice	250	10	8.72E+07	1.77E+02	86.60

Focus on wave train

- iron, 1000m, 20 km/s
- movie follows speed of leading wave
- train is complex, turbulent

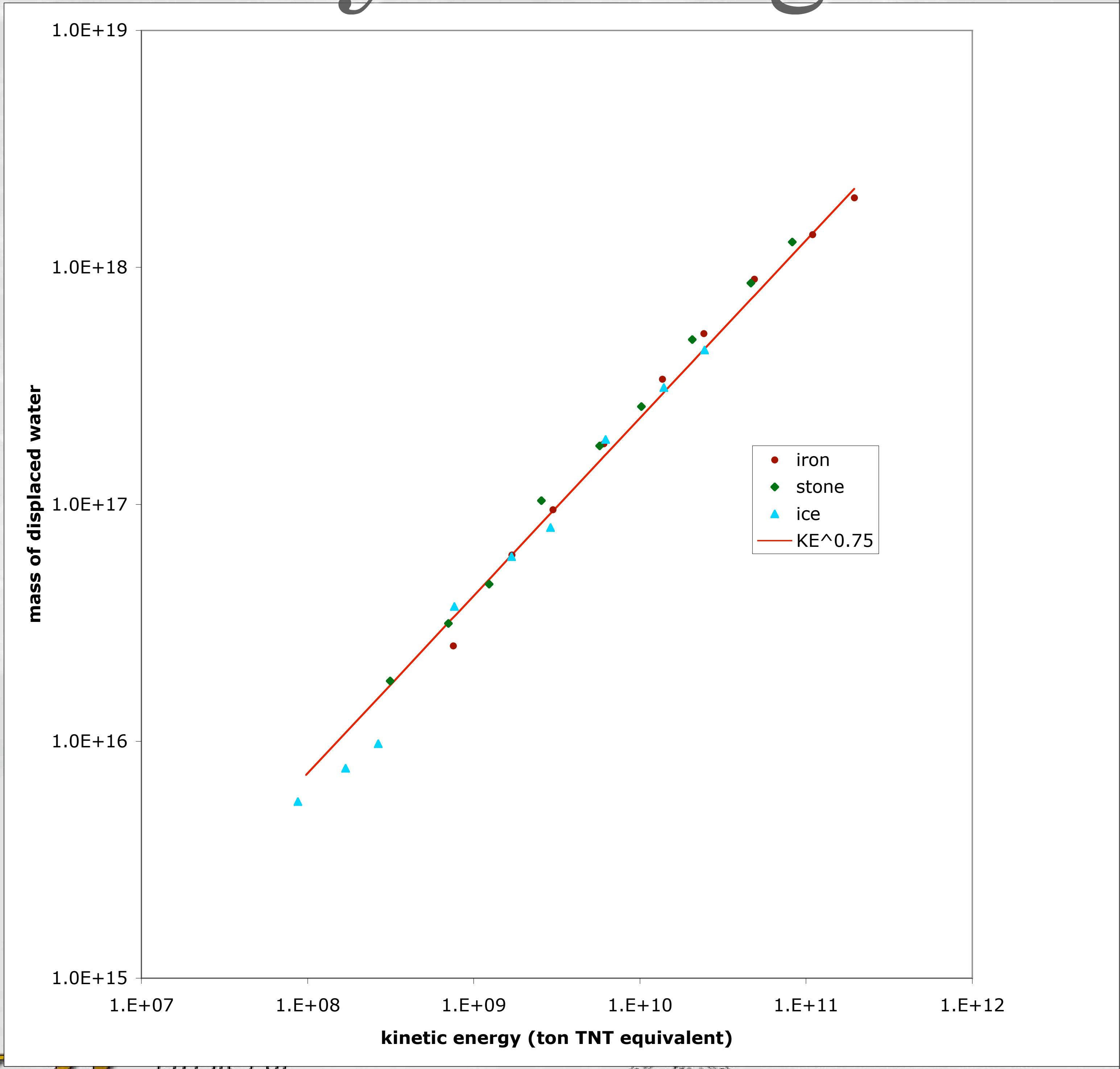
Why we need compressible hydrodynamics

- At right: top is density, bottom is pressure with a banded palette.
- Interactions between water & air, water & bottom are important
- The development of the wave train is affected by shocks reflecting between the sea floor and the surface.
- Note the decaying cavitation event and the backward propagating shock it produced.
- Turbulence and cavitation steal energy from the wave.
- In deep water, $\sqrt{gD}$ is > 15% c_s



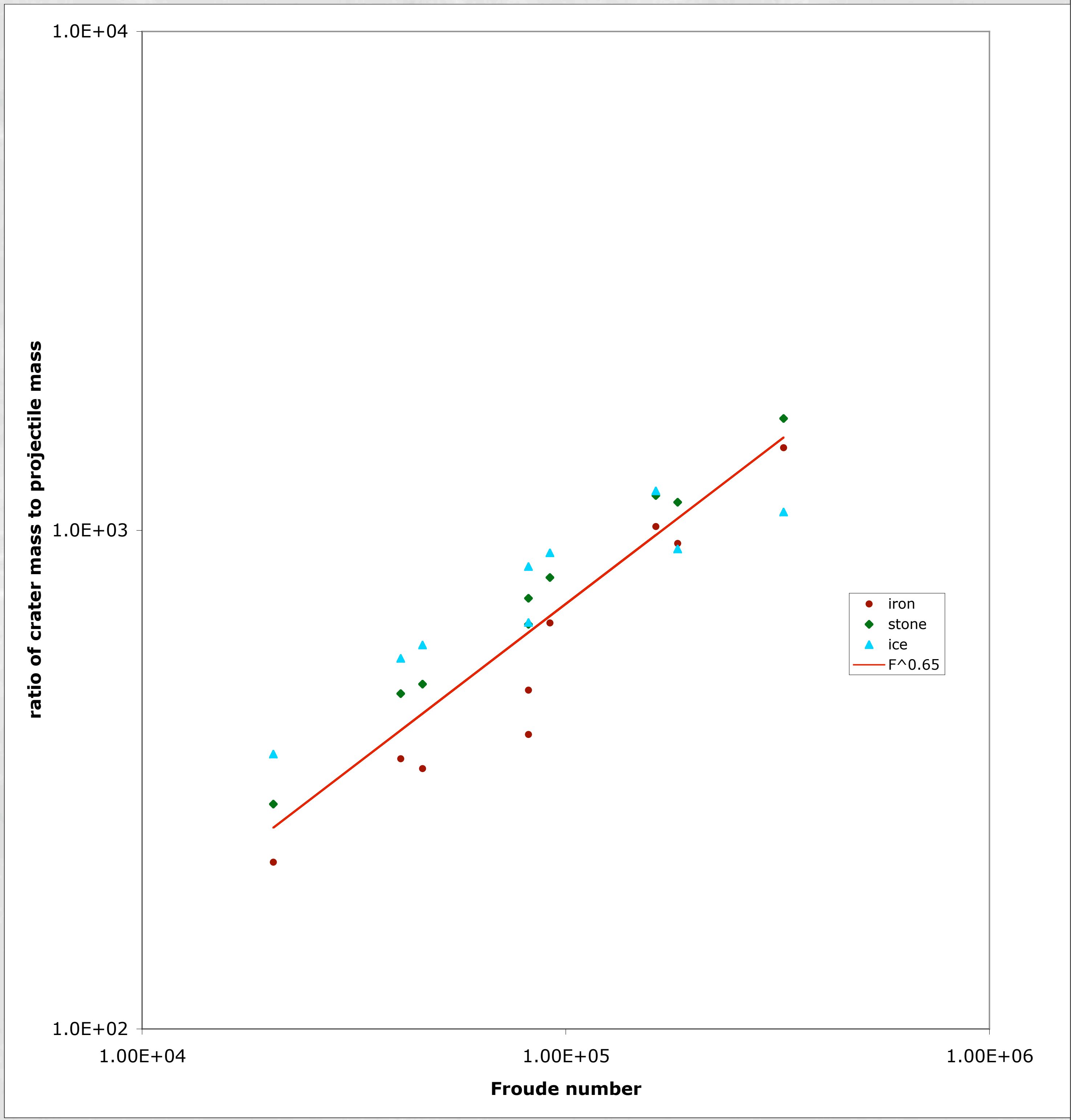
Results from parameter study: I(a). Water Cavity Scaling

- Mass of displaced water scales as 3/4 power of projectile kinetic energy



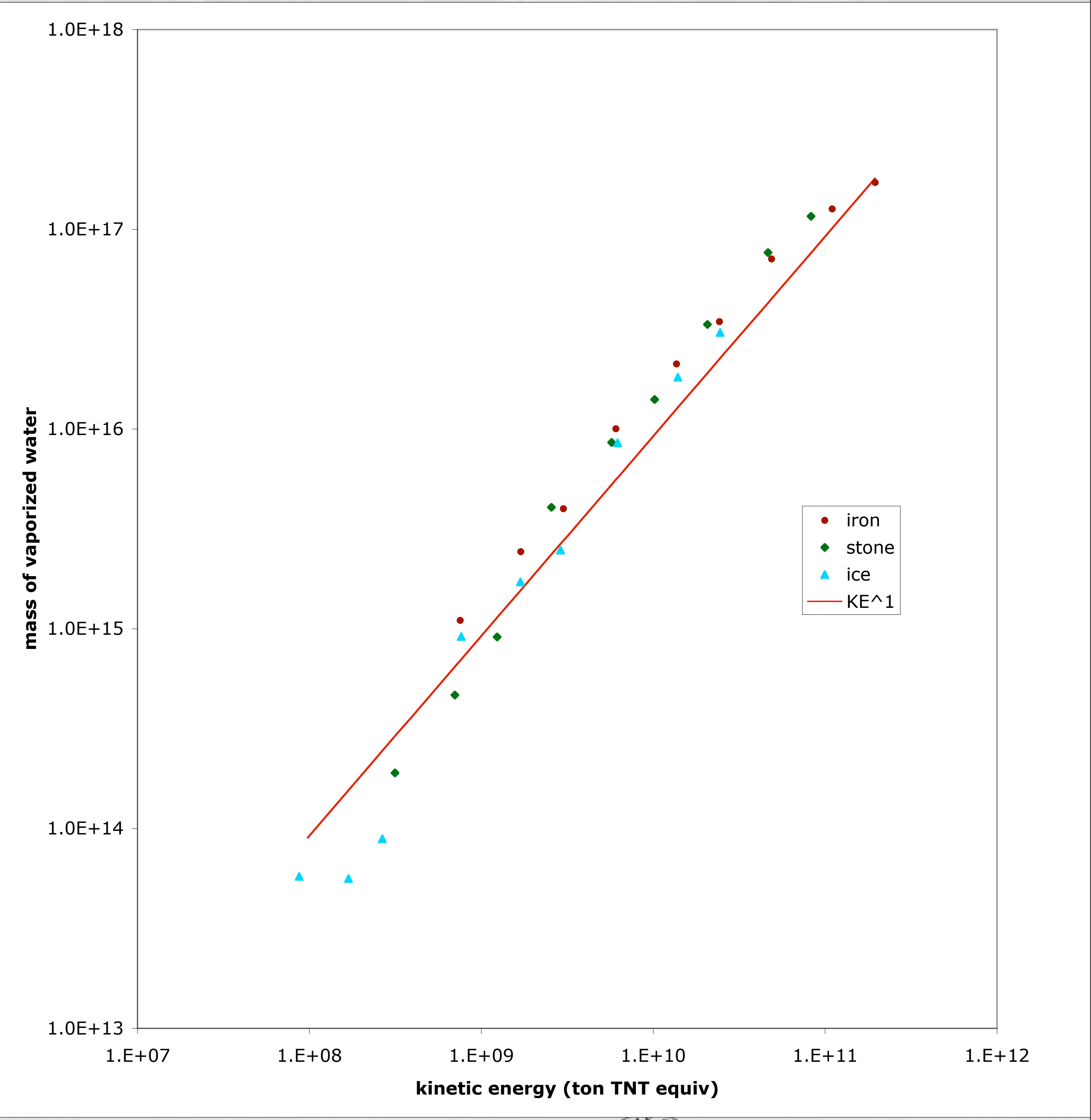
I(b). Not "Pi" Scaling

- Mass ratio to Froude number (v^2/gr) scaling doesn't work as well
- separation by composition
- vaporization of water not included in usual dimensional analysis



I(c). Vapor Mass Scaling

- Mass of vaporized water scales directly with projectile kinetic energy



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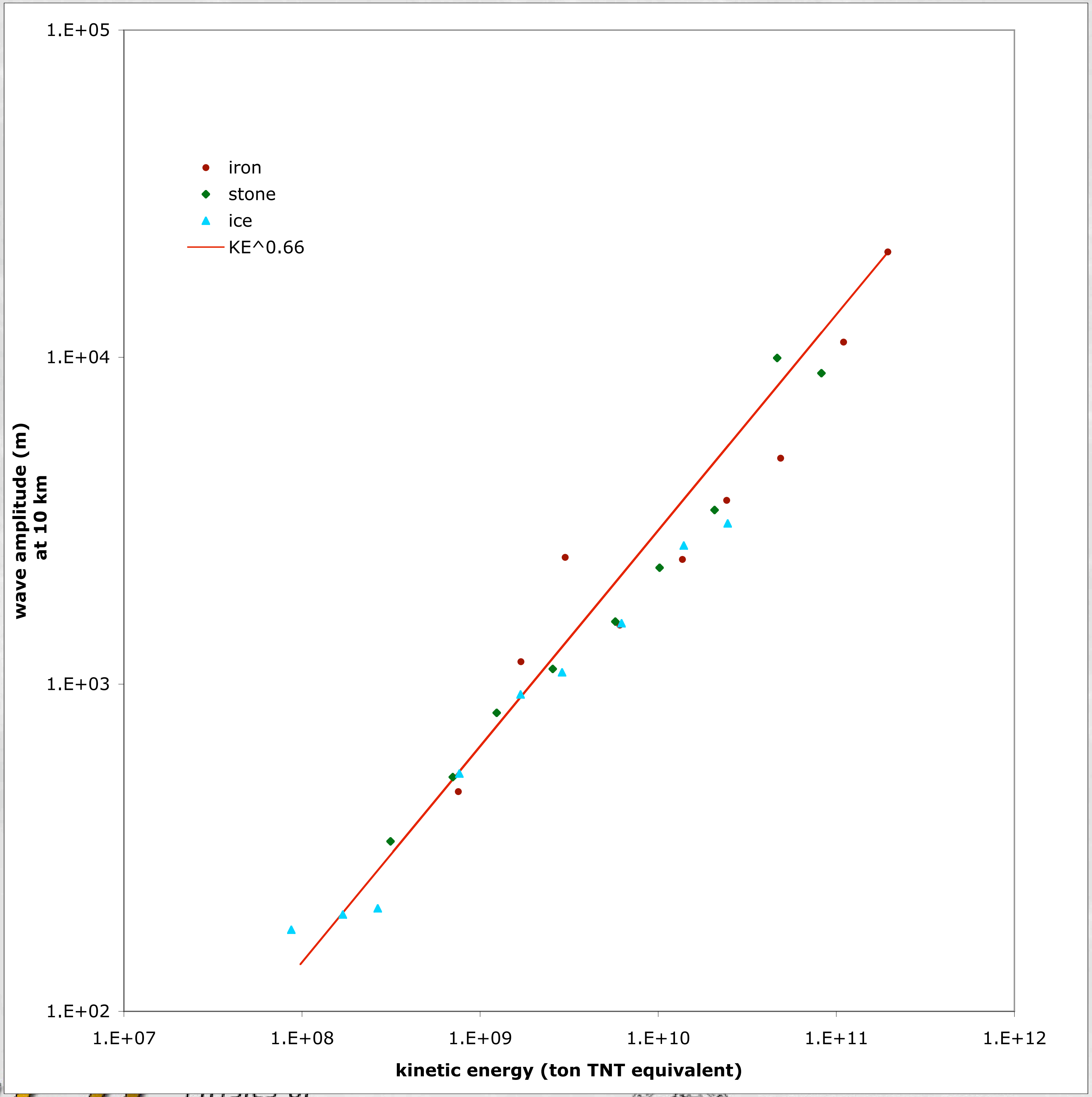
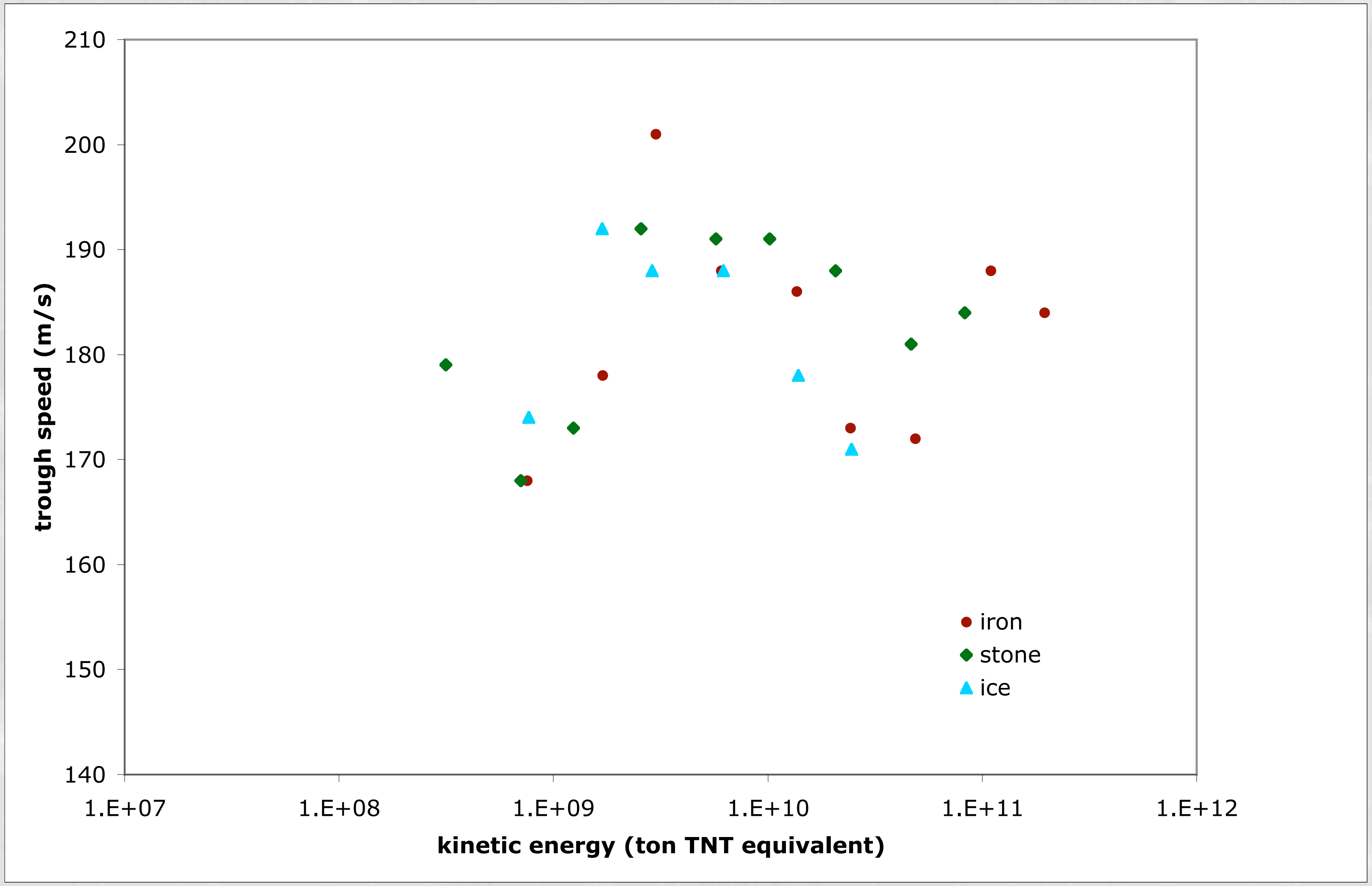
II. Wave Amplitude

- Initial wave amplitude scales as 2/3 power of projectile kinetic energy

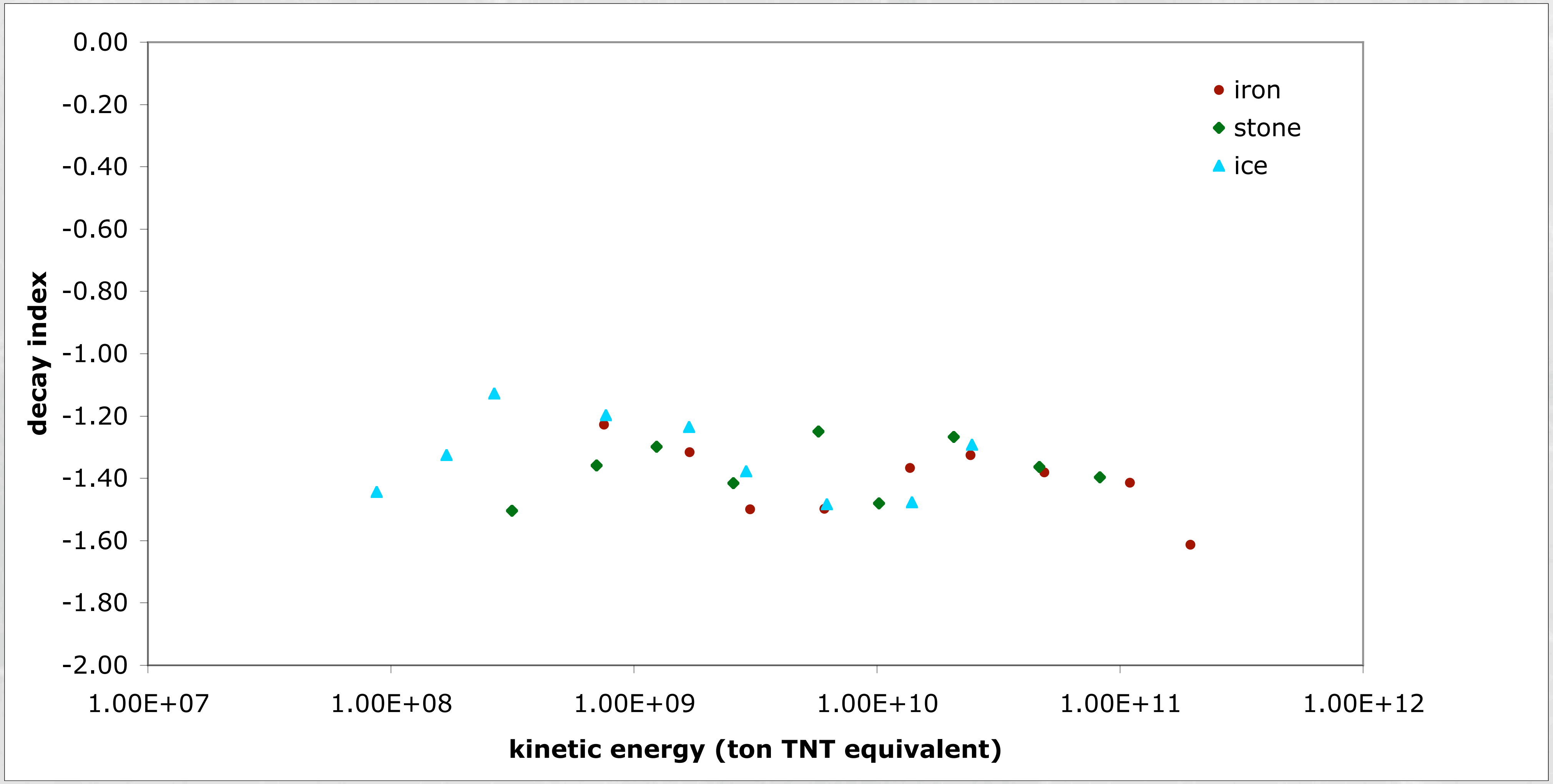


III. Wave Speed



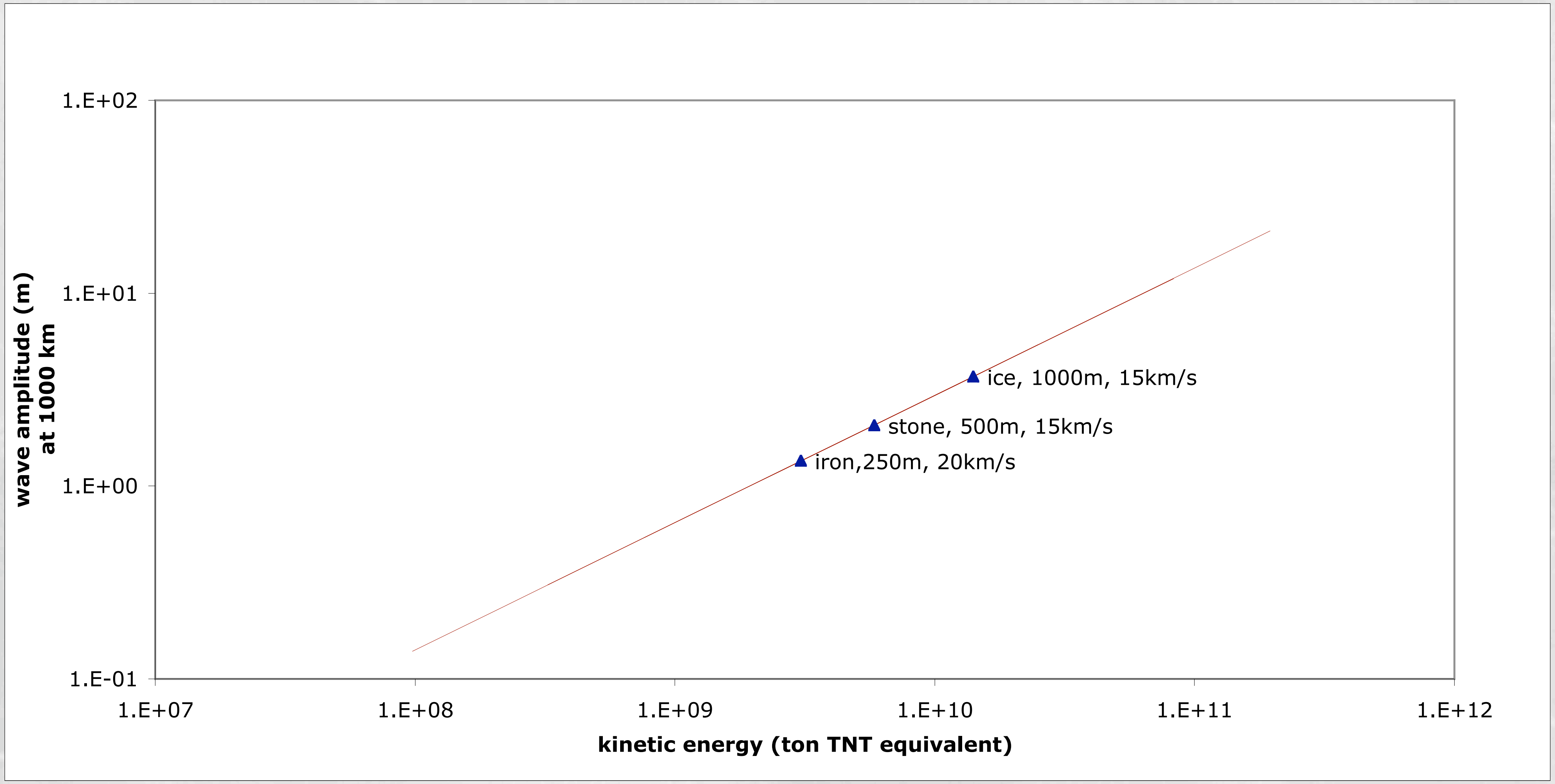
- Waves are slower than shallow-water speed $\sqrt{gD}$ = 221 km/s

IV. Wave Decay



- Wave height decays as $l^{-1.5}$ independent of energy or composition

What's our threshold for worry?



- Asteroids less than 500m in diameter do not produce ocean-wide disasters unless if they are of ordinary composition and speed
- Icy comets, at 60 km/s, could be dangerous at only 250m diameter

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Asteroid ocean impacts

- SAGE simulations of tsunamis generated by asteroid impacts show significant dissipation from well-resolved turbulence, cavitations, and internal shocks
- Risk of ocean-wide tsunami damage from asteroids < 500 m has been overstated
- Kinetic energy scaling is a better predictor than Froude number scaling for transient crater size and amount of water vaporized

Impact-generated waves are *unlike* classical tsunamis

- Their wavelengths are relatively short
- Their periods are relatively short
- They are highly turbulent and dissipative
- They do not propagate well over long distances
- *Nevertheless they can be dangerous if the impact is near a populated coastline*

What makes a classical tsunami?

- A disturbance that covers a substantial distance or lasts a considerable time
- Earthquakes, long run-out landslides
- Movement of the seafloor or pressure pulse communicated by the seafloor
- Explosions or impacts do not couple to water as efficiently as do slower movements of rock
- In general, for the same amount of free energy, subsonic disturbances make bigger water waves than supersonic ones