2017 IAA PLANETARY DEFENSE CONFERENCE
MAY 15-19 2017 / TOKYO, JAPAN

Damage from Asteroid Airburst or Impact on Land, in Deep, and Shallow Water

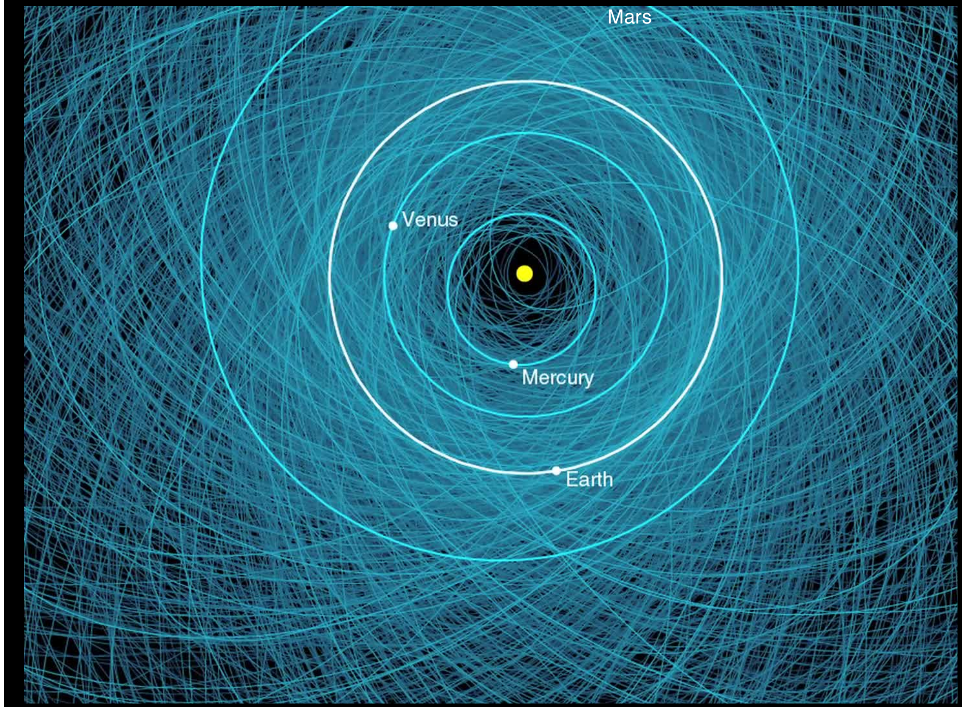
AMS Seminar, July 27th, 2017

Darrel Robertson
Lorien Wheeler
Donovan Mathias
NASA Ames Research Center

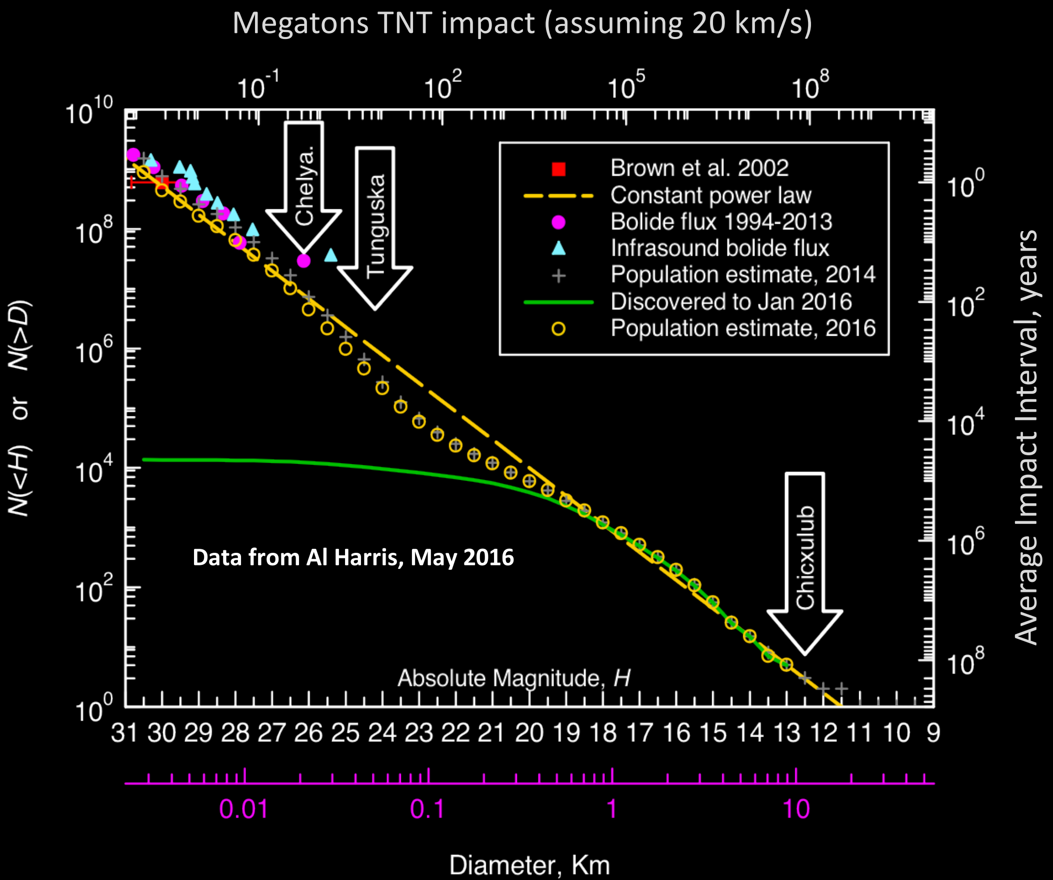
Asteroid Threat

- Estimated to be over 1 million Near Earth Asteroids larger than 30m
- Expect asteroid 30m or larger to strike Earth every 100 years
- Spaceguard Survey has only found ~16 000 as of 2017
- Of those found so far, ~1800 classified as hazardous

PHA map 2013



NASA JPL Center for Near Earth Object Studies (cneos.jpl.nasa.gov)



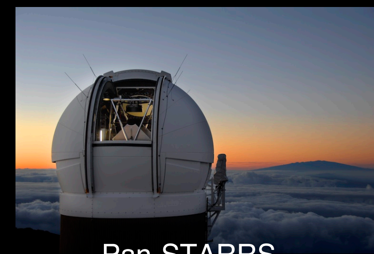
Chelyabinsk, Russia, 2013

Planetary Defense

NASA Planetary Defense Coordination Office (www.nasa.gov/planetarydefense)

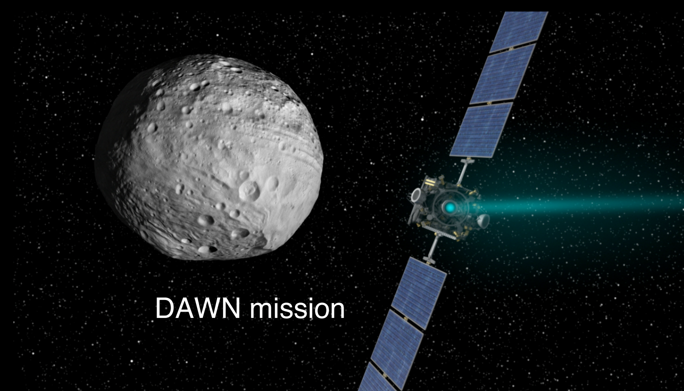
- Find
- Track and characterize
- Predict damage
- Evacuate or mitigate

Spacewatch

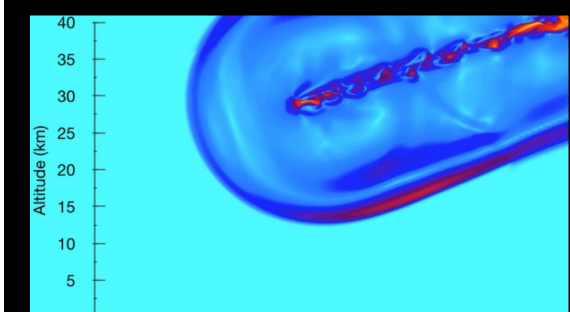


Pan-STARRS

NEOWISE

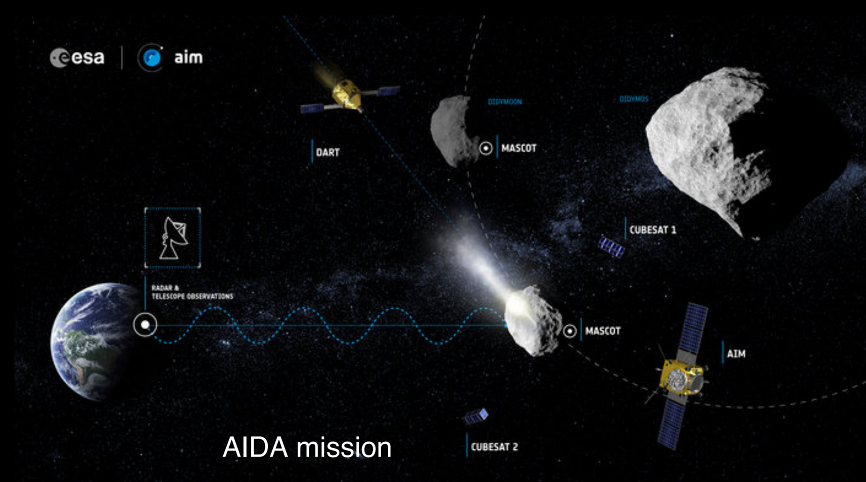


DAWN mission



Blast wave simulation (Aftosmis)

Los Alamos disruption simulation



AIDA mission

Asteroid Threat Assessment Project

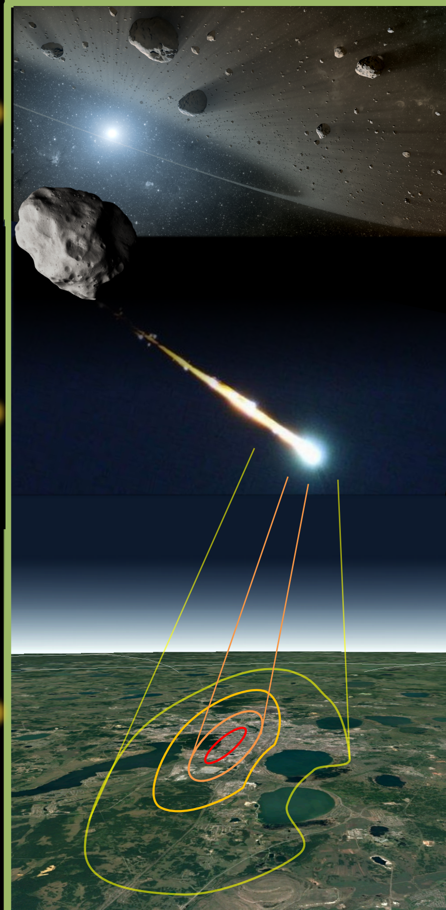
D. Mathias. "Asteroid Threat Assessment", International Space Development Conference 2016, San Juan, Puerto Rico, May 21, 2016

Characterization
- Physical Properties
- Orbital Trajectories

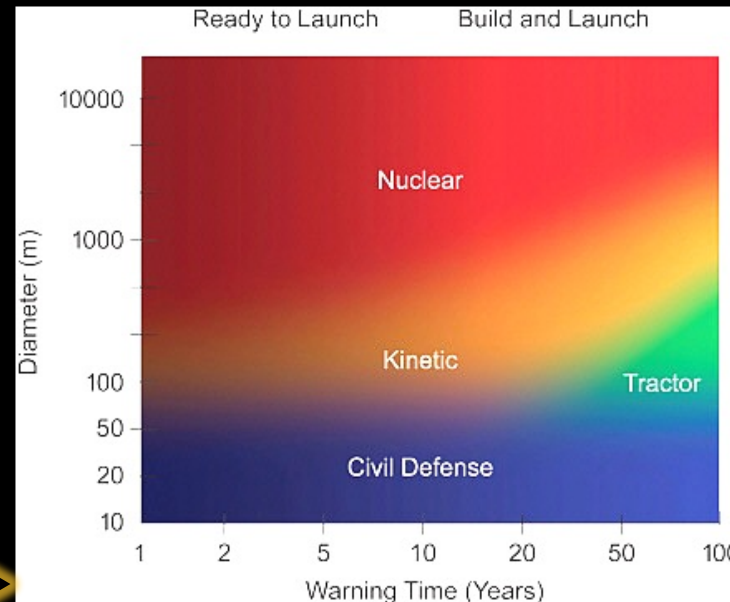
Atmospheric Entry & Airburst Modeling
- Entry Trajectories/Ablation
- Energy Deposition

Surface Impact Effects Modeling
- Ground Damage
- Tsunami Propagation

Physics-Based Impact Risk Modeling
- Quantitative Risk Metrics
- Sensitivity to Uncertainty



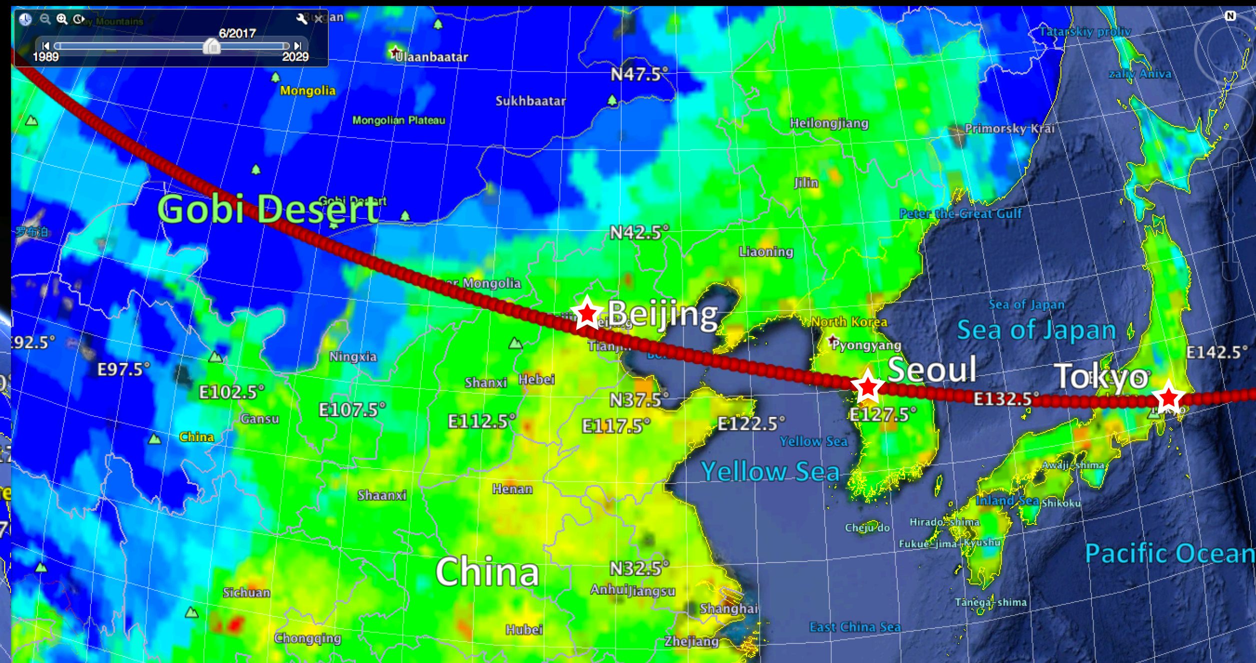
Impact Risk Assessment Tools

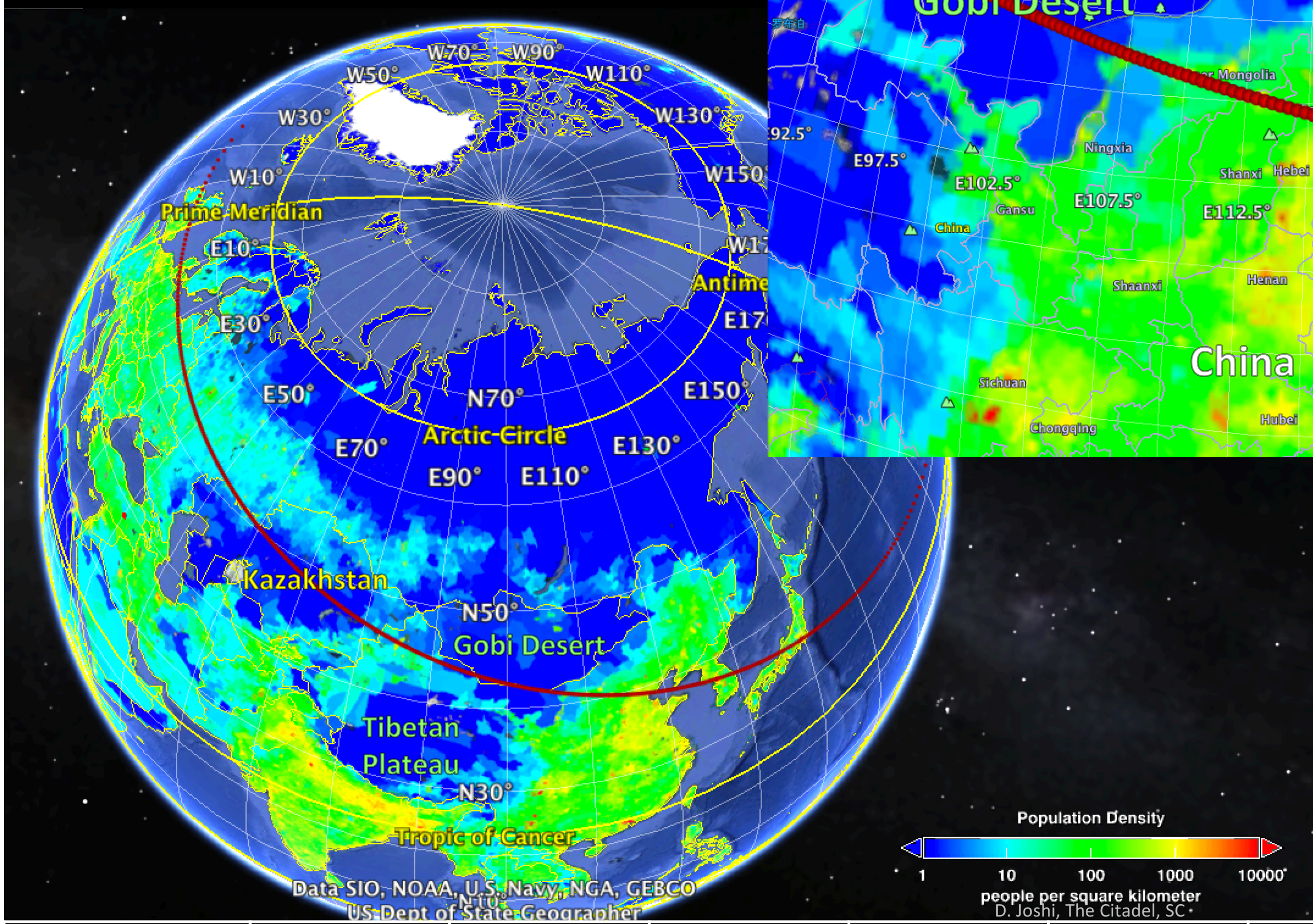


Credit: Tim Warchocki

Risk-Informed Decision Support
- Mitigation Planning
- Defense Strategies
- Response Decisions
- Policy Development

PDC Hypothetical Scenario

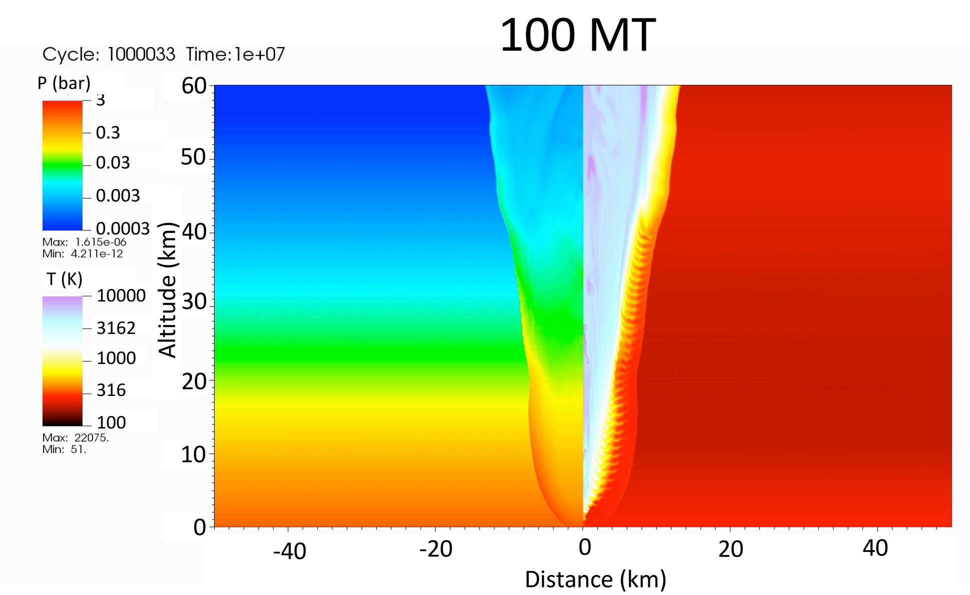


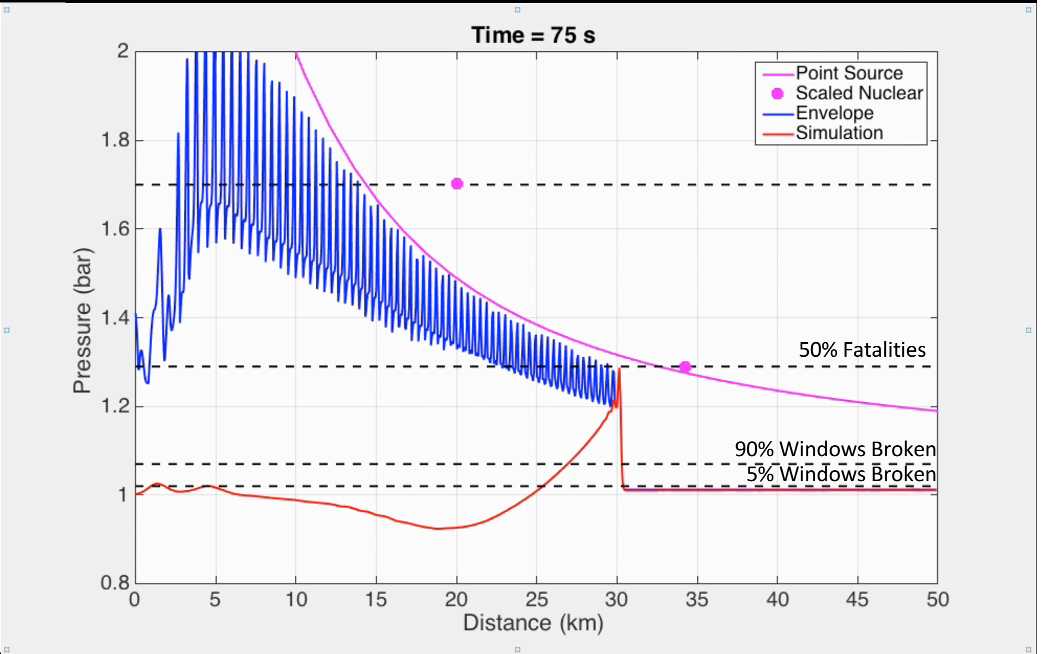


Diameter	100 m	100 m	100 m	250 m	250 m	250 m
Density	2000 kg m^{-3}	4000 kg m^{-3}	7000 kg m^{-3}	2000 kg m^{-3}	4000 kg m^{-3}	7000 kg m^{-3}
Velocity	17 km s^{-1}	17 km s^{-1}	17 km s^{-1}	17 km s^{-1}	17 km s^{-1}	17 km s^{-1}
Kinetic Energy	36 Mt	72 Mt	126 Mt	565 Mt	1130 Mt	1978 Mt

- Lowest population density in central Kazakhstan, Gobi Desert, and oceans

100MT Airburst

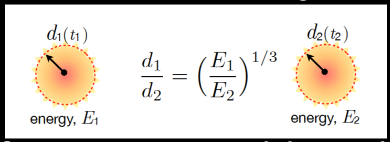




- 100MT vertical entry and airburst.
- Energy deposition from Wheeler Fragment-Cloud model.
- Blast wave very similar to 100MT point source or nuclear explosion

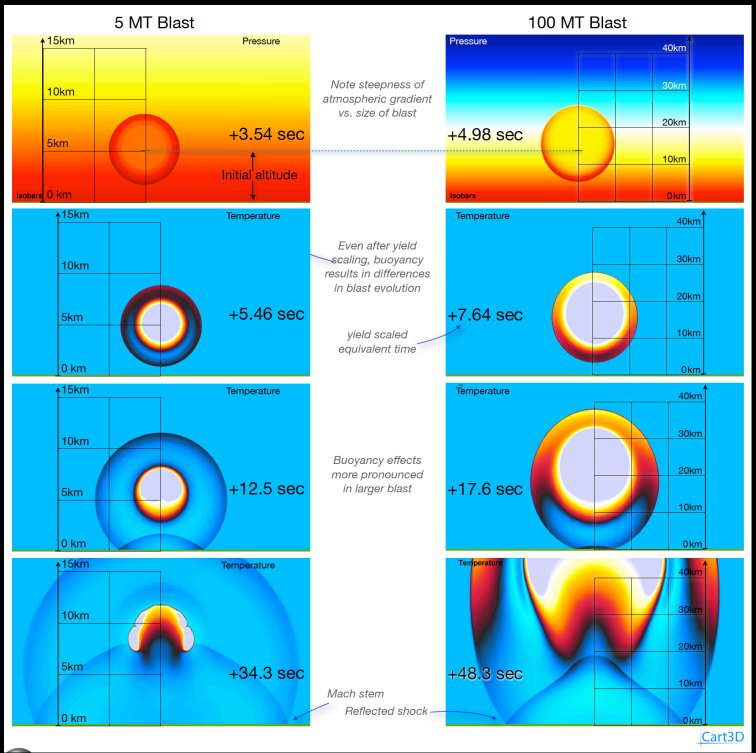
Large (>100MT) Airbursts

M. Aftosmis, D. Mathias, A. Tarano. "Simulation-Based Height of Burst Map for Asteroid Airburst Damage Prediction", IAA Planetary Defense Conference 2017, Tokyo, Japan.

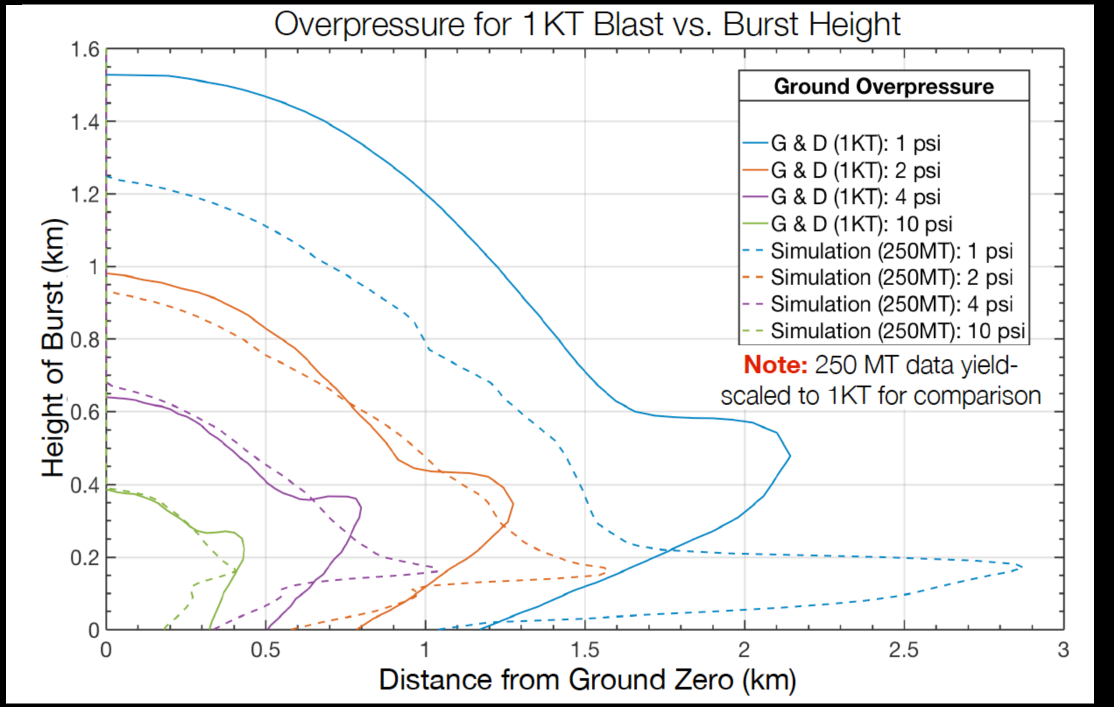


- Below 100 MT blast waves can be scaled using nuclear test data
- Above 100 MT atmospheric buoyancy breaks the self-similarity of point source blasts because distances of interest are no longer small compared to the scale height of the atmosphere (8 km).
- Similarity parameter $\frac{d^5\rho_0}{t^2E}$ establishes time scale equivalence between two blasts $\left(\frac{t_2}{t_1}\right)^2 = \frac{\rho_{02}E_1}{\rho_{01}E_2}\left(\frac{d_2}{d_1}\right)^5$
- Increase in time scale implies pressure gradient is steeper and acts over a longer period

Approximate equivalency relations of ground footprint of 5 and 100 MT blasts

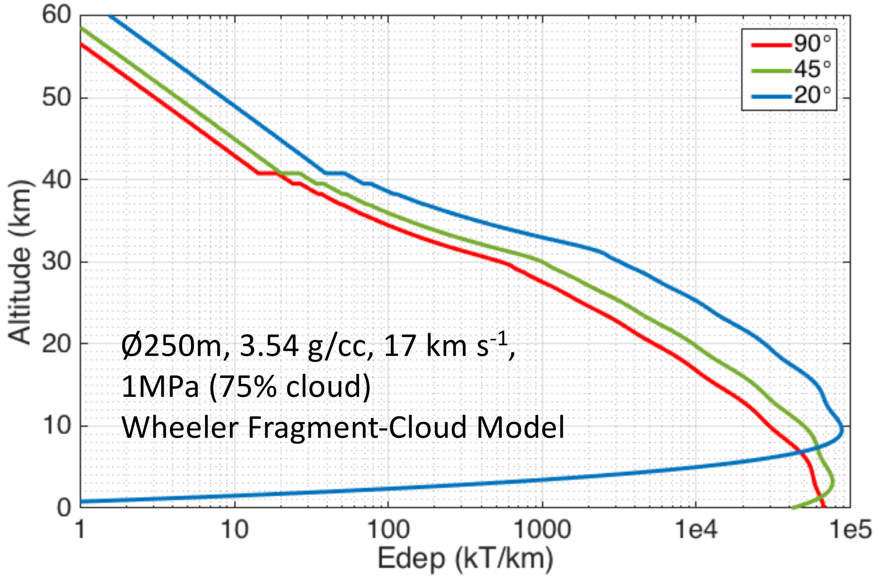


Buoyancy increases bulge associated with optimum height of burst.

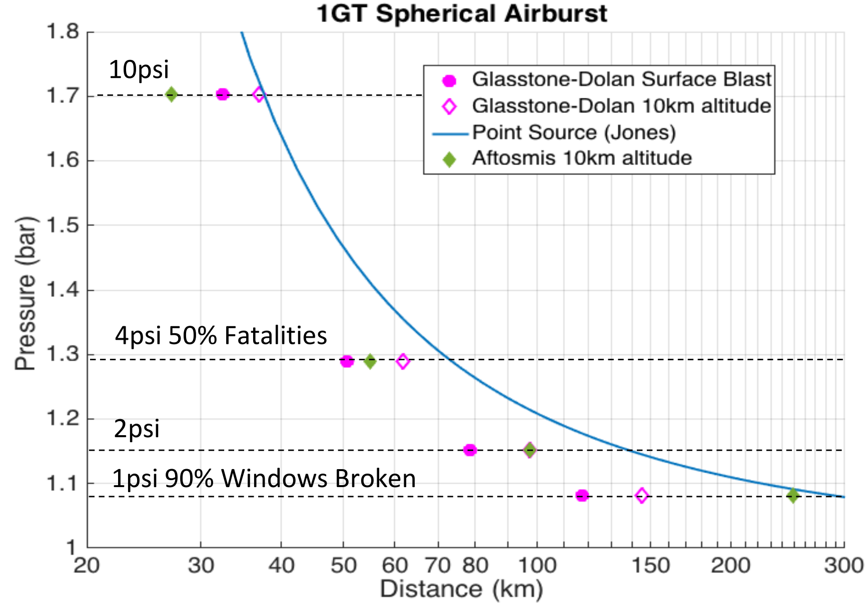


1GT Airburst

1GT stony asteroid



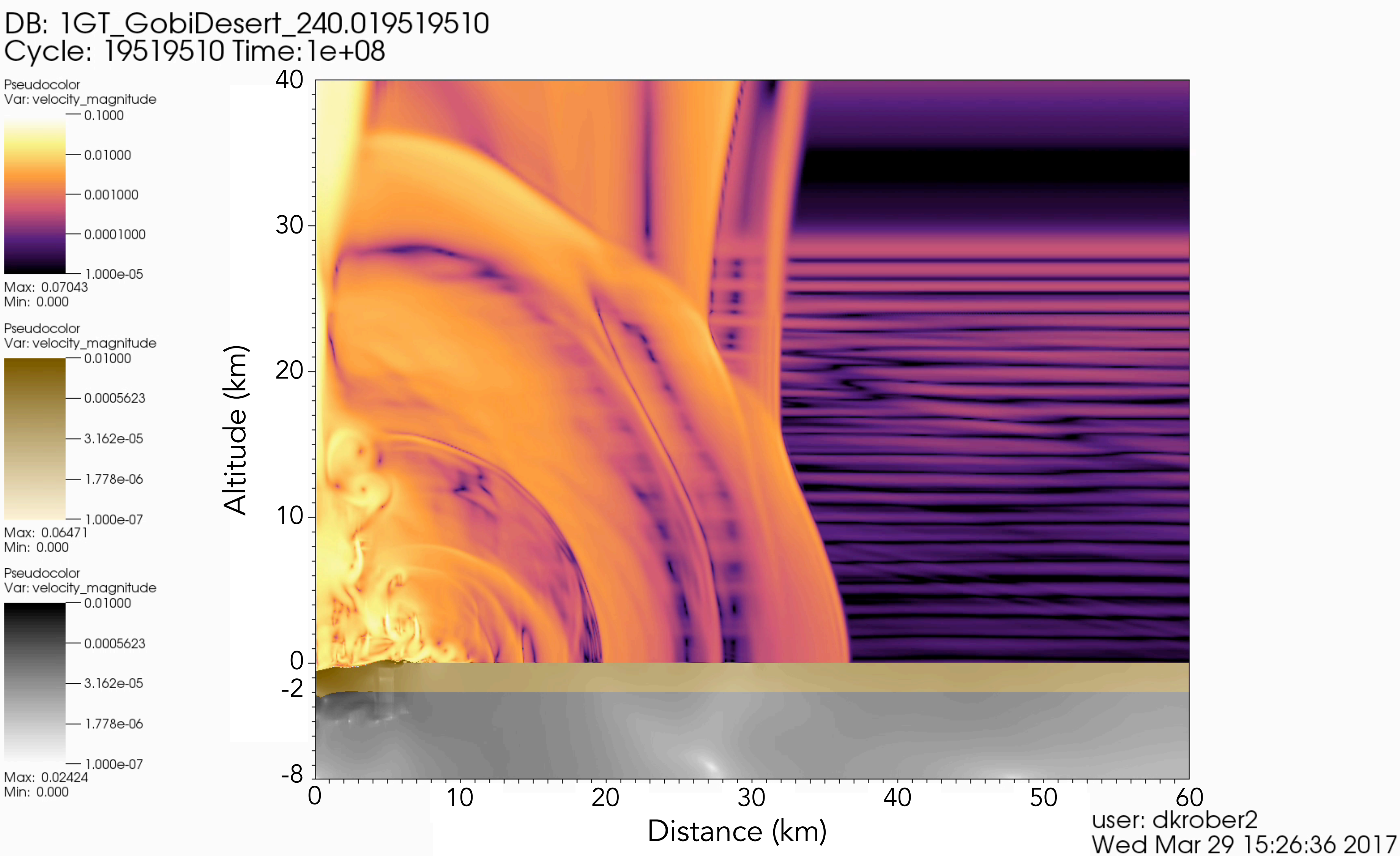
1GT Spherical Airburst



- 1GT entry and airburst.
- Shallow entry deposits most energy at 10km altitude
- Vertical entry brings 300MT to ground. 700MT deposited in air with peak at ground level.

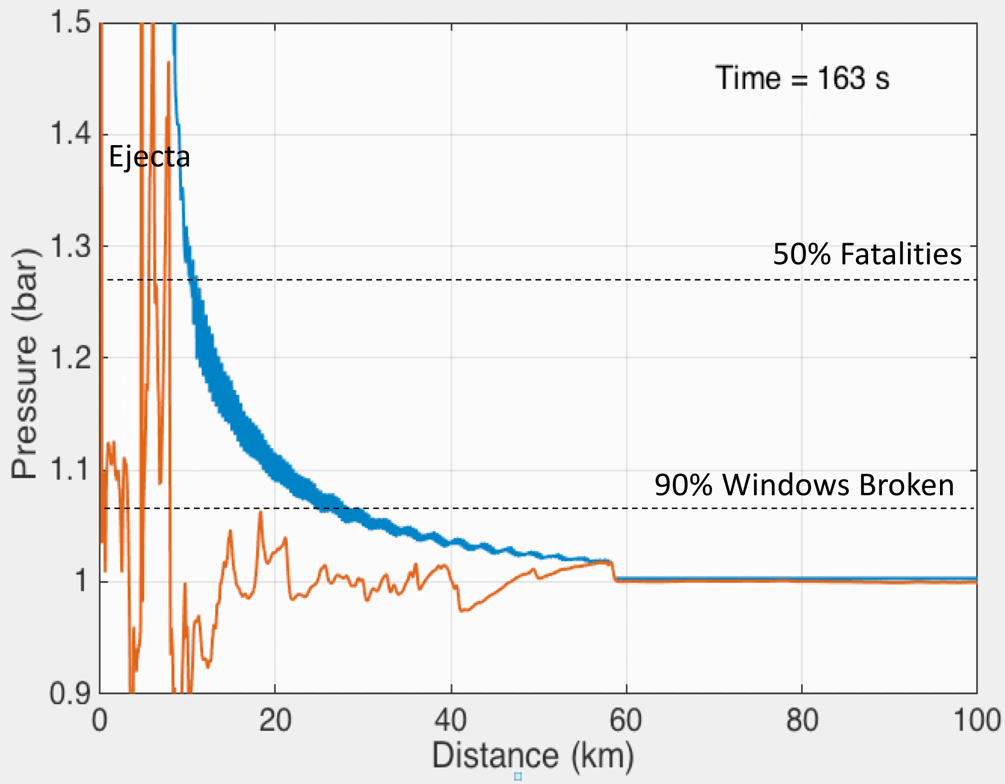
Jones, D. "Intermediate Strength Blast Wave", Physics of Fluids, Vol. 11, pp. 1664, (1968)
Glasstone & Dolan, "The Effects of Nuclear Weapons", US Department of Defense (1977)

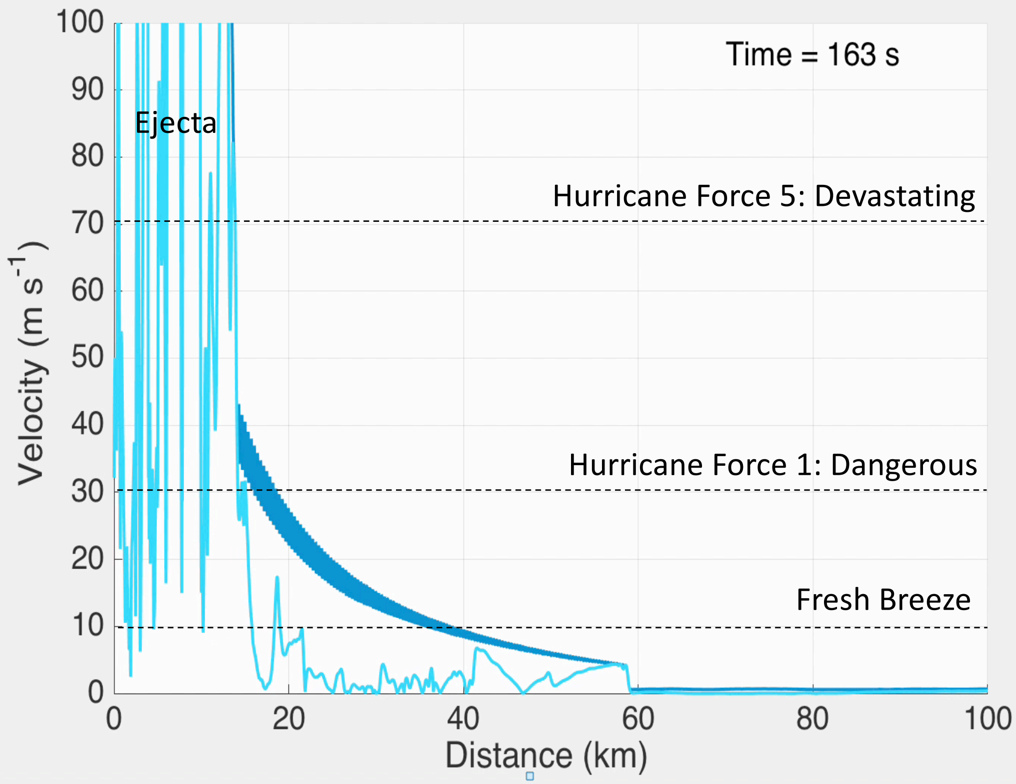
Land Impact



- 1GT iron so almost all energy delivered to ground

Blast Wave

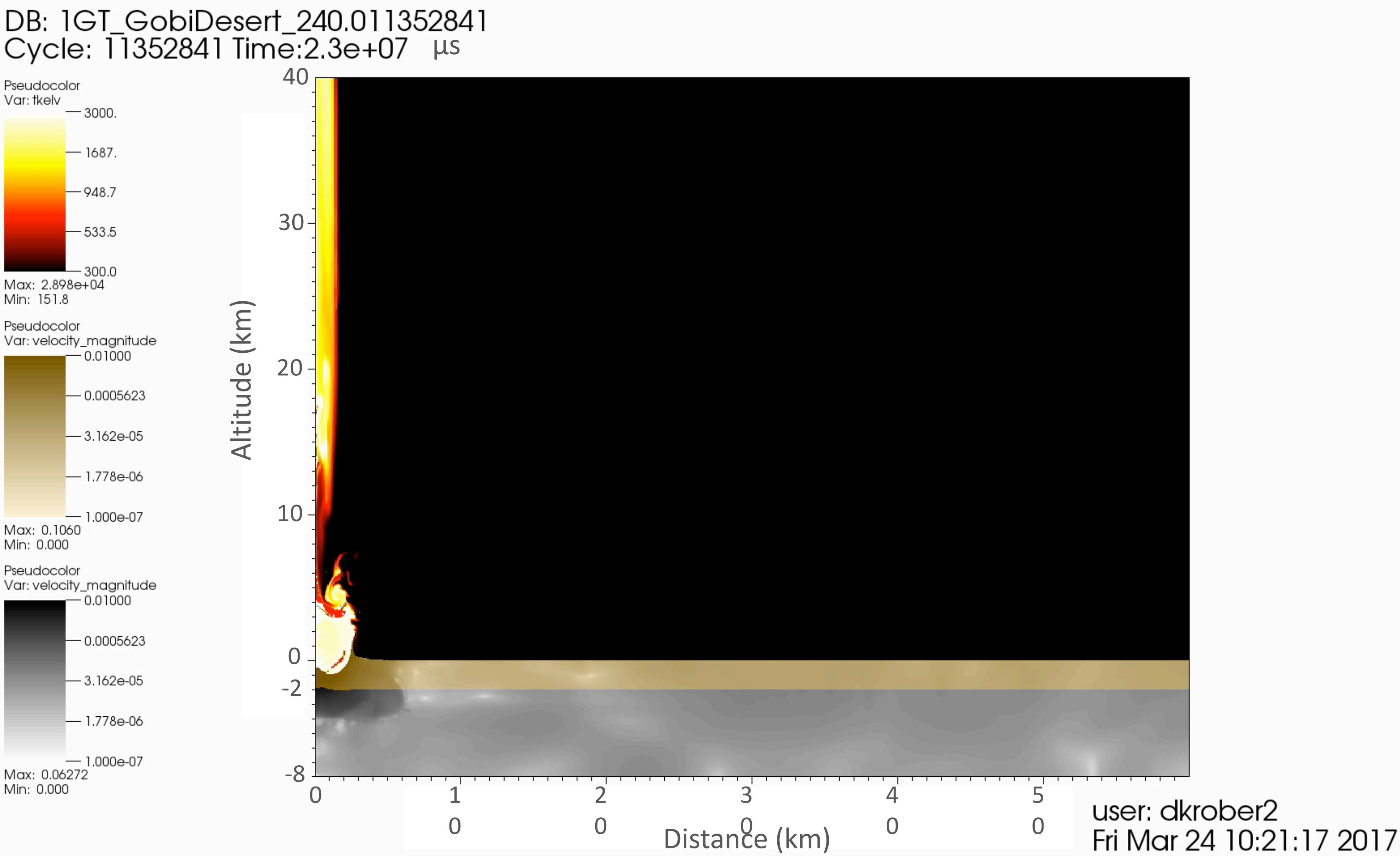




- Significantly less energy goes into blast wave in this simulation than in semi-empirical models or airburst case
- Results may be significantly different for stony asteroids that may deposit more energy into atmosphere than the iron modelled here that maximized energy delivered to ground.

Thermal Radiation

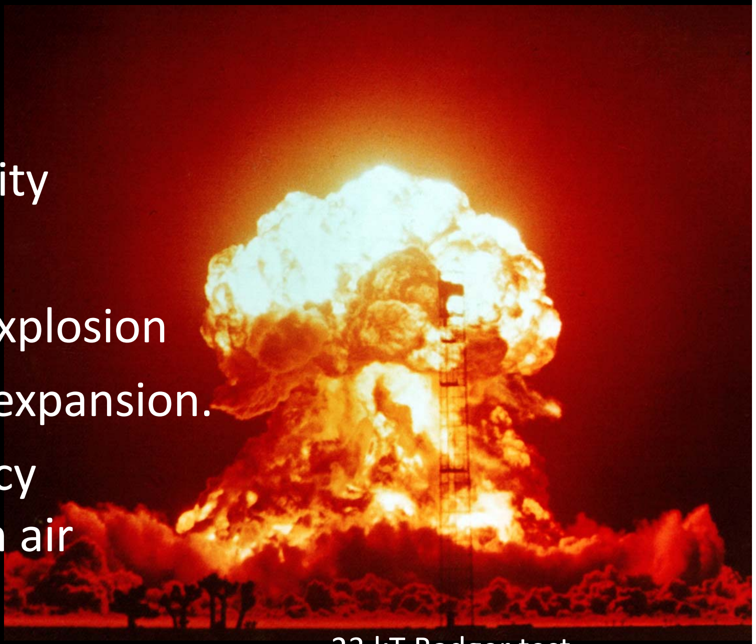
- Entry column ionizes air and impact vaporizes meteor creating hot gas at >10 000K. Entry column and impact fireball will strongly radiate.



Thermal Radiation

Collins 2005 – Semi-empirical Model

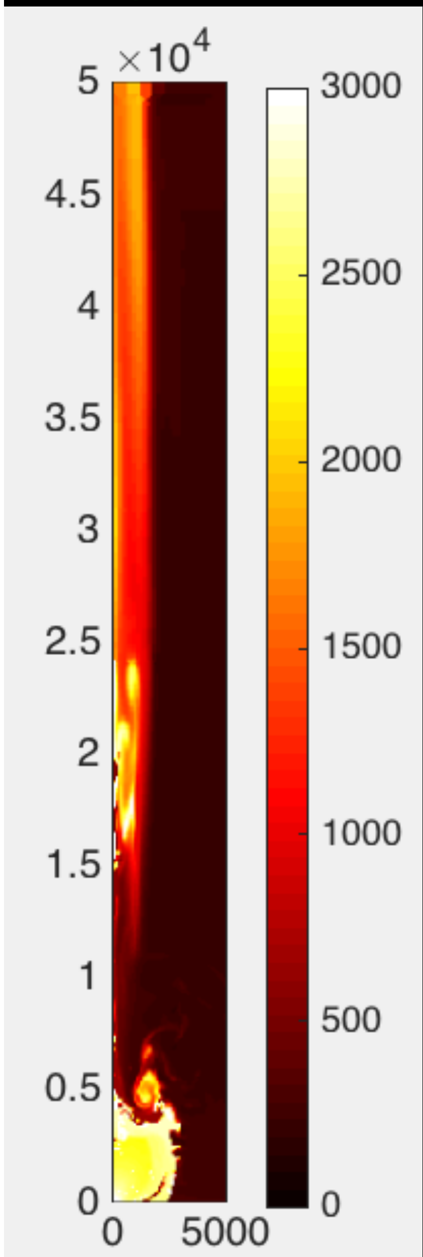
- Fireball radius at time of peak radiation $R = 0.002E^{1/3}$
- Time at peak radiation $T = R/v$ where v=impact velocity
- Luminous efficiency, $\eta=3\times10^{-3}$ (poorly constrained)
- Thermal exposure, $\Phi = \dfrac{\eta E}{2\pi r^2}$ where r=distance from explosion assuming hemispherical expansion.
- Duration $\tau = \dfrac{\eta E}{2\pi R^2 \sigma T^4}$ assuming T=3000K = transparency temperature of air (above which air becomes opaque)
- Exposure required to ignite a material $\dfrac{\Phi}{\sqrt{\alpha\tau}} = \dfrac{T_{ignition}}{\rho c_p}$ where α=thermal diffusivity, ρ =density, c_p=heat capacity
- Combining above yields scaling law $\Phi_{ignition} = \Phi_{1MT} E^{1/6}$

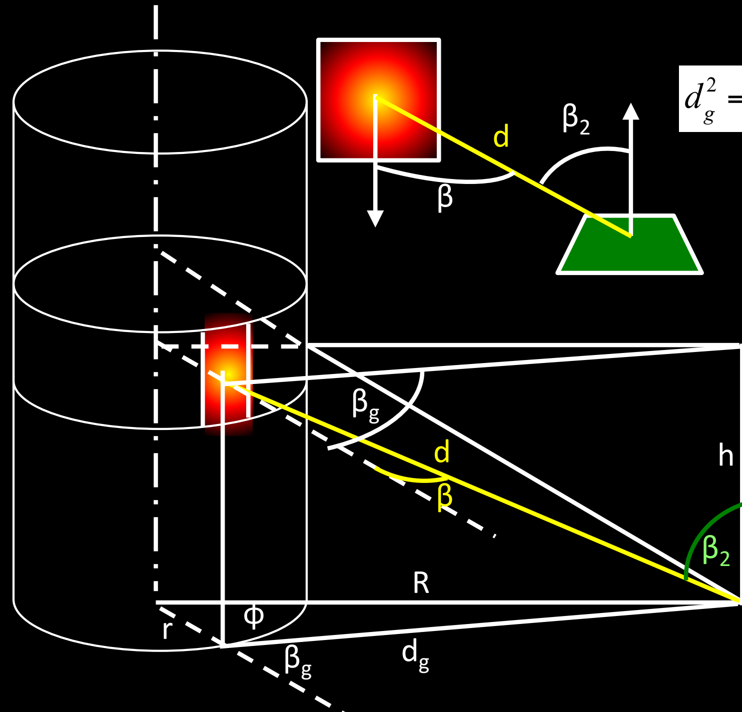


23 kT Badger test
Nevada 1953

	1st degree burns	2nd deg. burns Deciduous Trees ignite	Paper and Grass ignite	3rd. deg burns	Plywood ignites	Clothing ignites
ϕ_{1MT}(MJ m^{-2})	0.13	0.25	0.35	0.42	0.67	1.0

Radiative Transfer





$$d_g^2 = R^2 + r^2 - 2Rr\cos\phi$$ cosine rule

$$\frac{\sin\beta_g}{R} = \frac{\sin\phi}{d_g}$$ sine rule

$$\tan\beta = \frac{\sqrt{h^2 + d_g^2\sin^2\beta_g}}{d_g\cos\beta_g}$$

$$d = d_g\frac{\cos\beta_g}{\cos\beta}$$

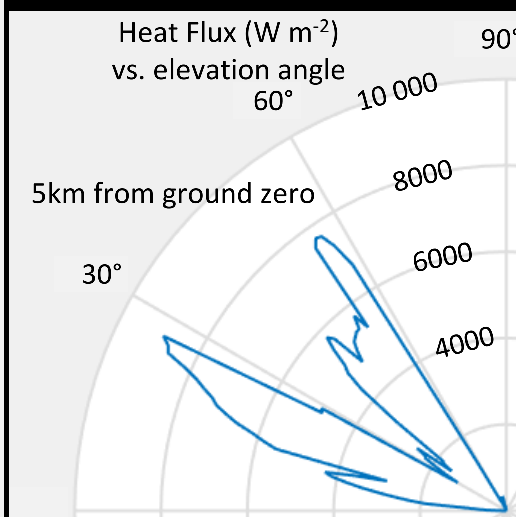
$$\cos\beta_2 = \frac{h}{d}$$

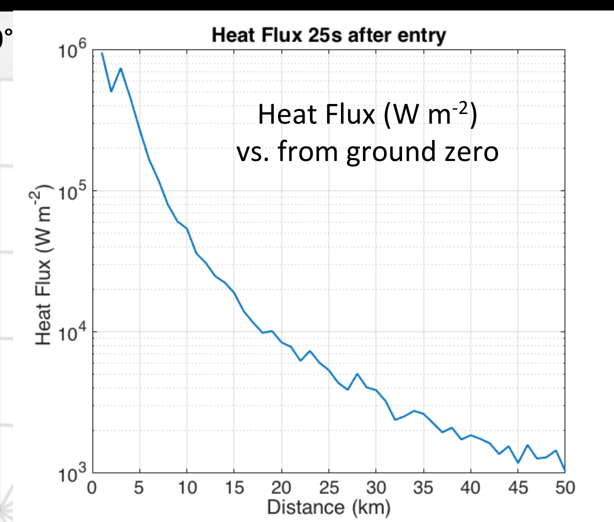
$$\cos\phi_{\max} = \frac{r}{R}$$

View Factor

$$F = \int_{-\phi_{\max}}^{\phi_{\max}} \frac{\cos\beta\cos\beta_2}{\pi d^2} r\, d\phi$$

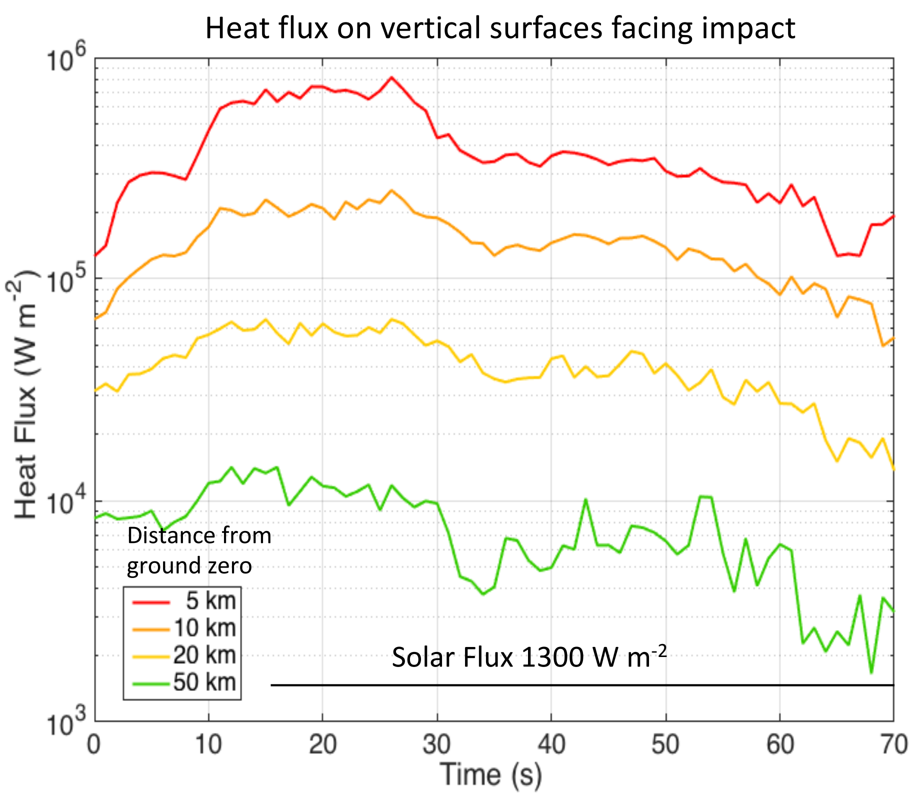
$$q_{incident} = \int_{h=0}^{\infty} \sigma T^4(h) F(h)\, dh$$

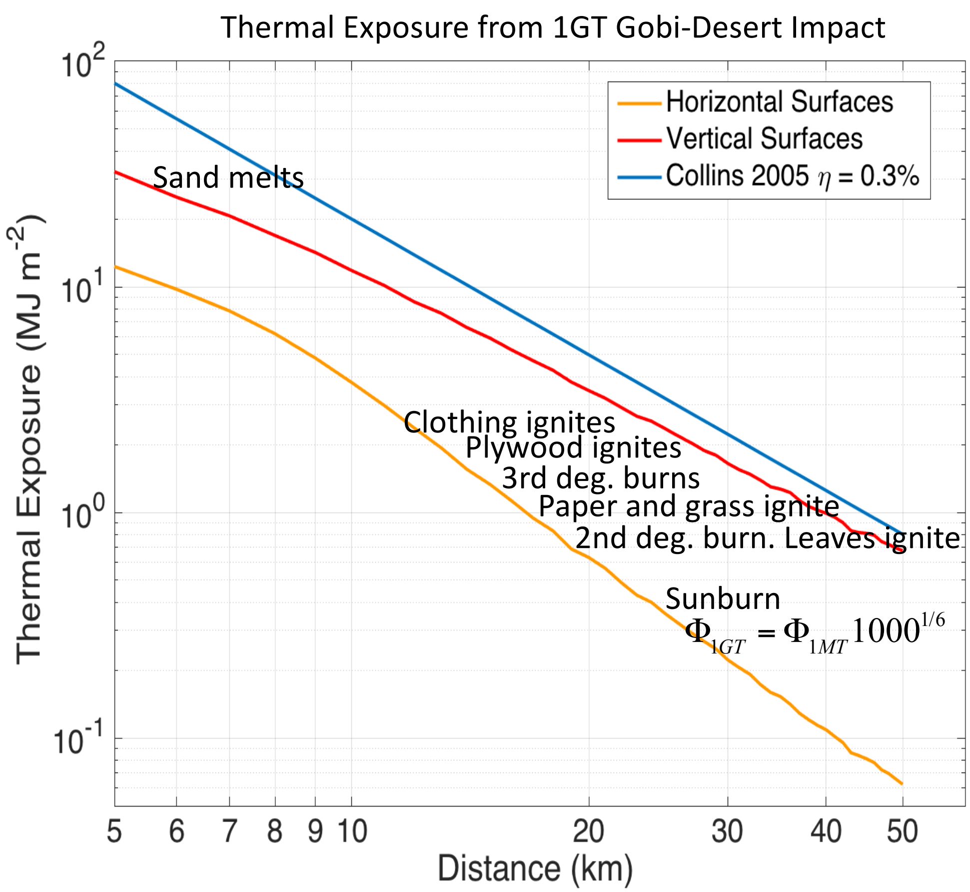




- Radiant flux from a hot surface $q'' = \varepsilon\sigma T^4$ W m^{-2} assume $\varepsilon = 1$ so black body.
- Water vapor and CO2 in atmosphere can absorb a significant portion of the radiation, but neglect for now. (Transmittance ≈1 at zero humidity)

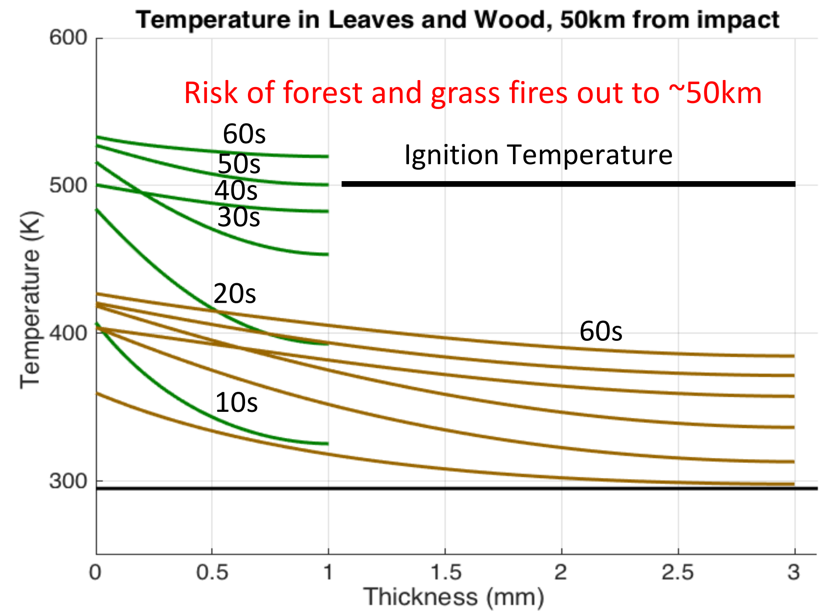
Heat Flux

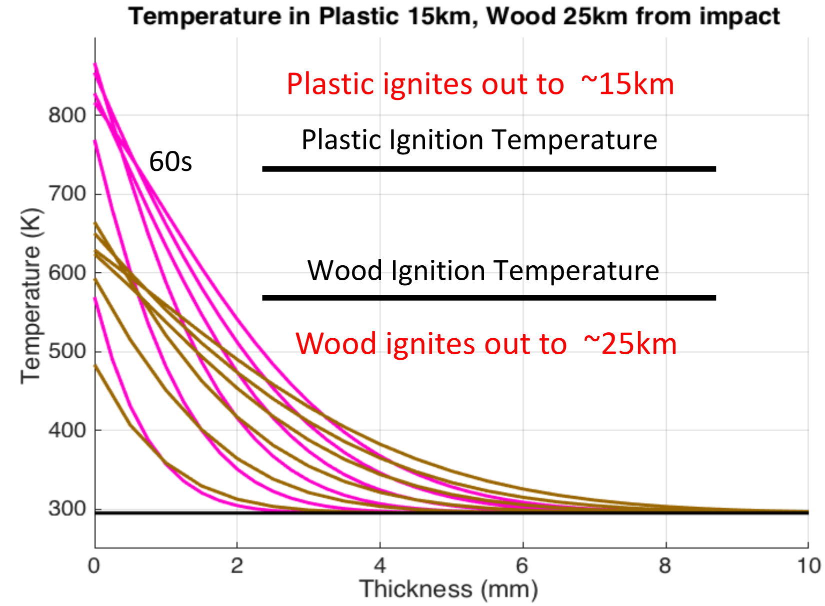

Heat flux on vertical surfaces facing impact
Heat Flux (W m-2)
Time (s)
Distance from ground zero
5 km
10 km
20 km
50 km
Solar Flux 1300 W m-2

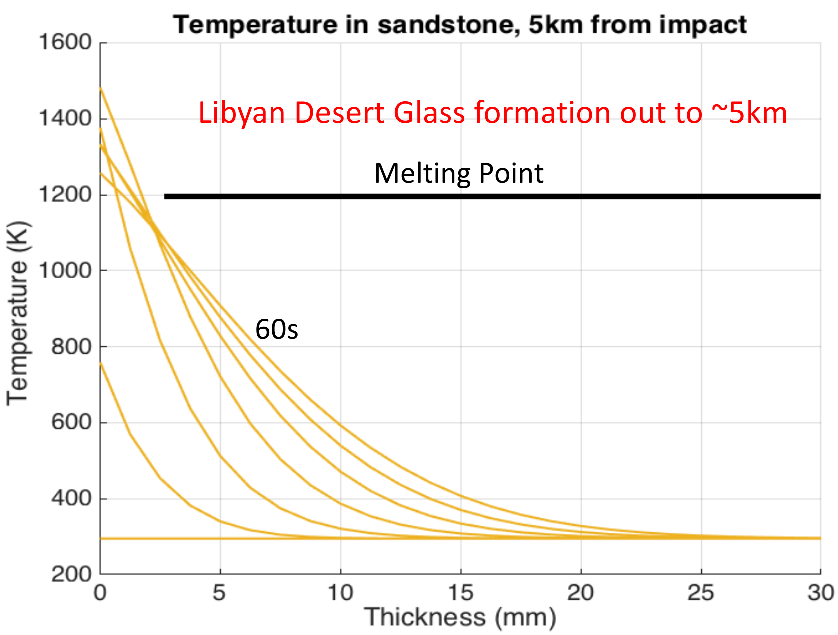

Thermal Exposure from 1GT Gobi-Desert Impact
Thermal Exposure (MJ m-2)
Distance (km)
Horizontal Surfaces
Vertical Surfaces
Collins 2005 η = 0.3%
Sand melts
Clothing ignites
Plywood ignites
3rd deg. burns
Paper and grass ignite
2nd deg. burn. Leaves ignite
Sunburn
$\Phi_{1GT} = \Phi_{1MT} 1000^{1/6}$

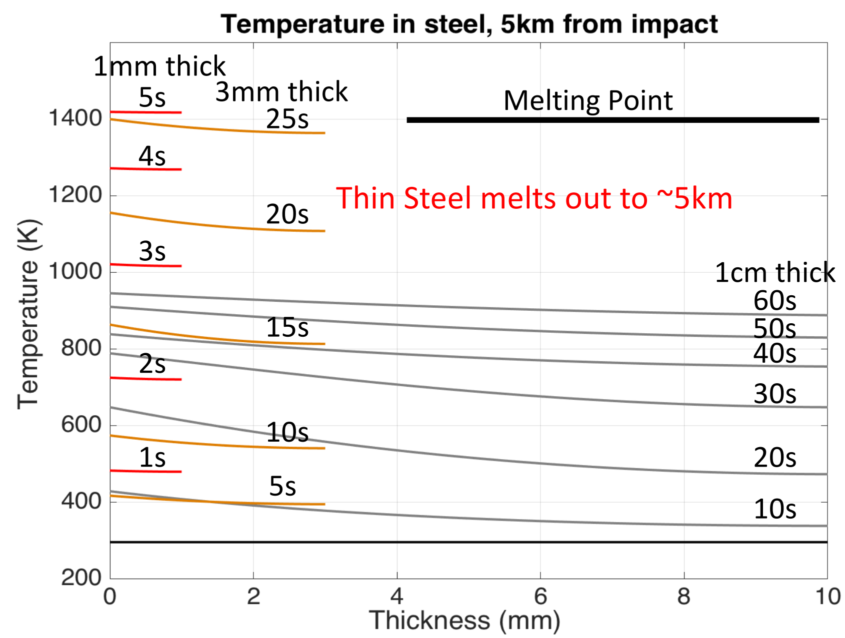
Ignition and Melting

Values provide good match Collins 2005 model from scaled nuclear data

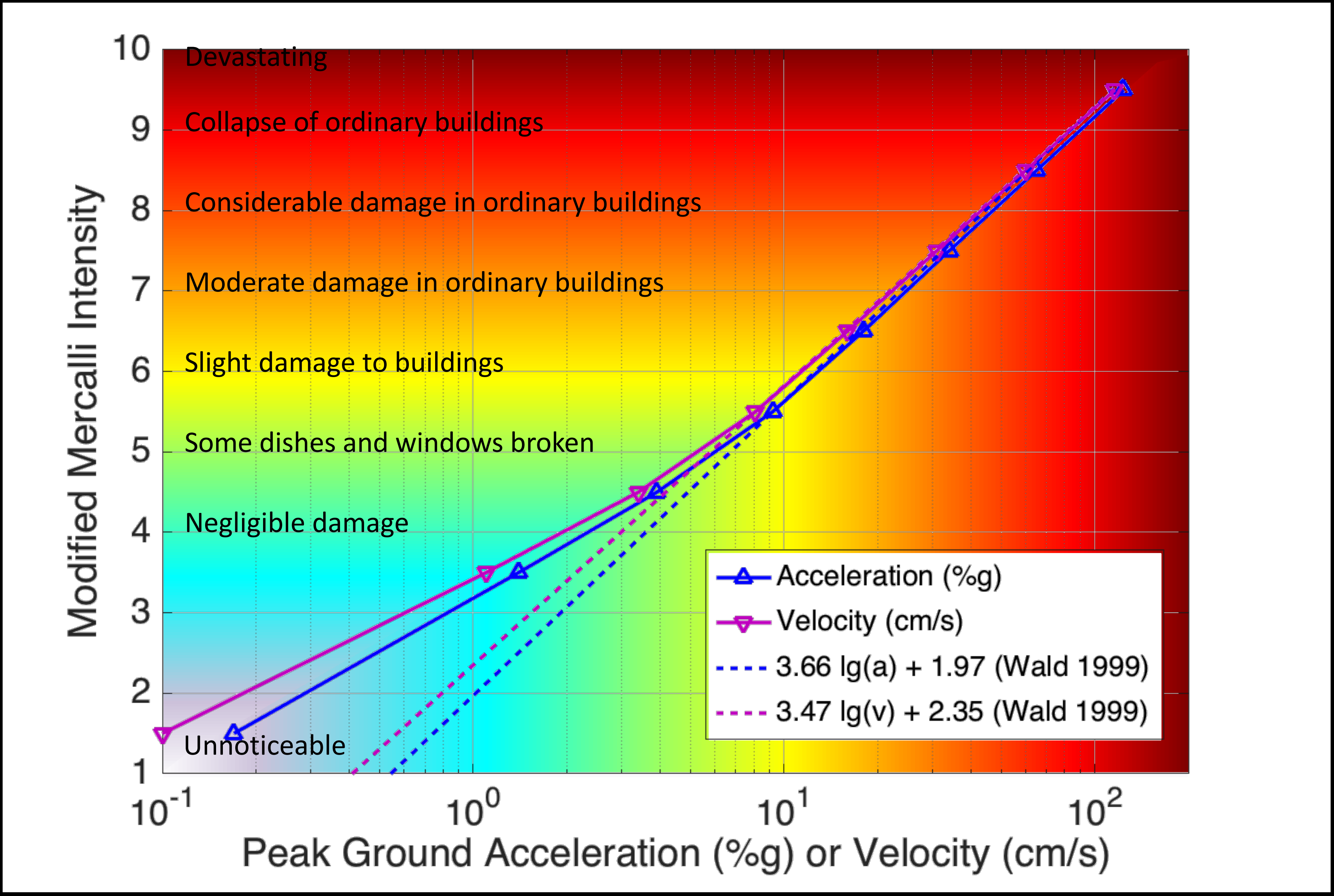






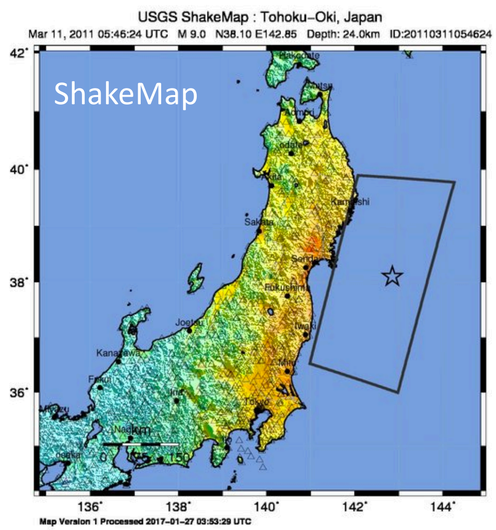


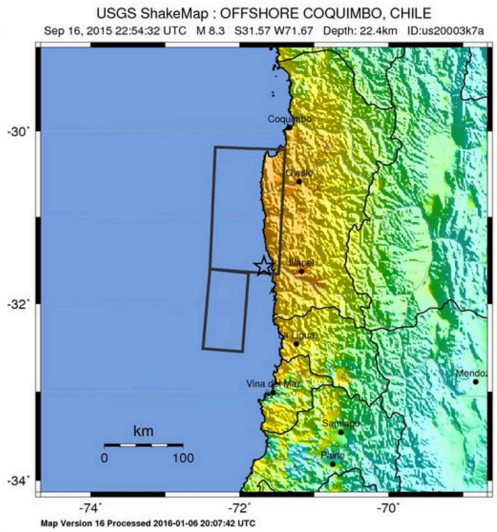
Earthquake Damage

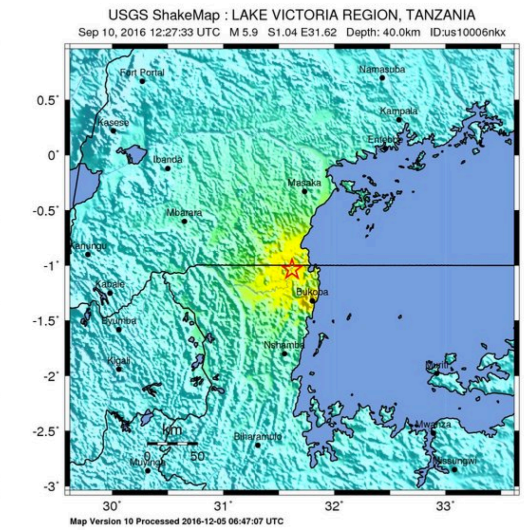


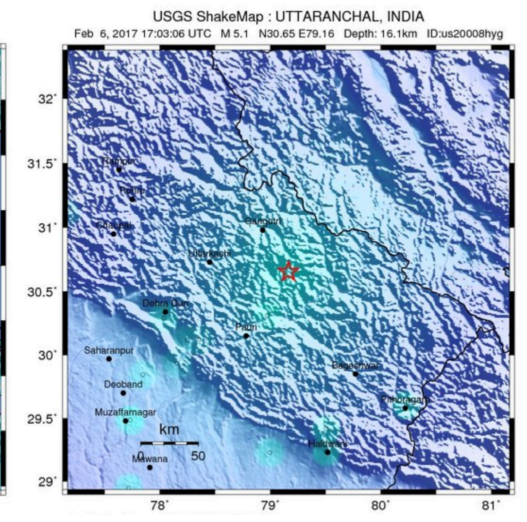
https://earthquake.usgs.gov/earthquakes/search/

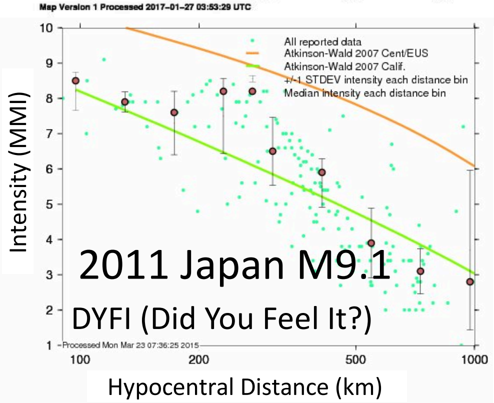
Earthquake Magnitude

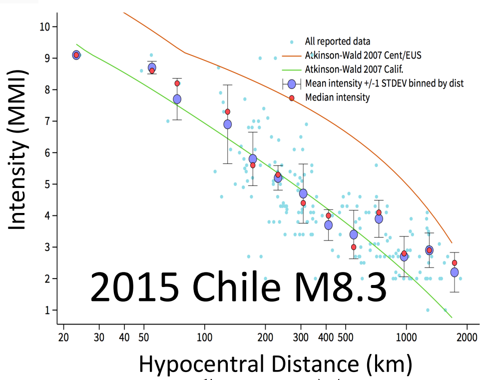


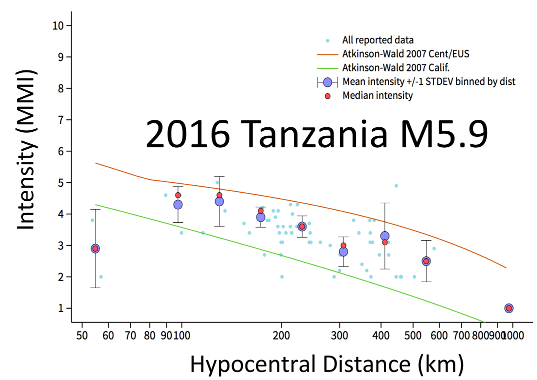


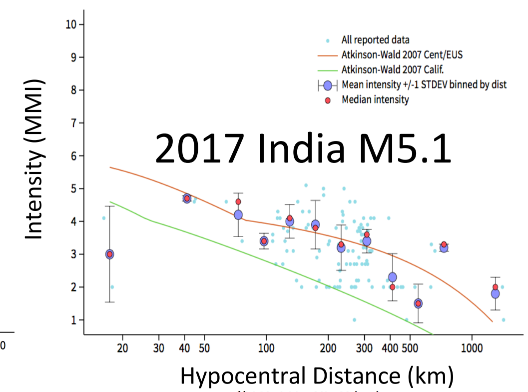












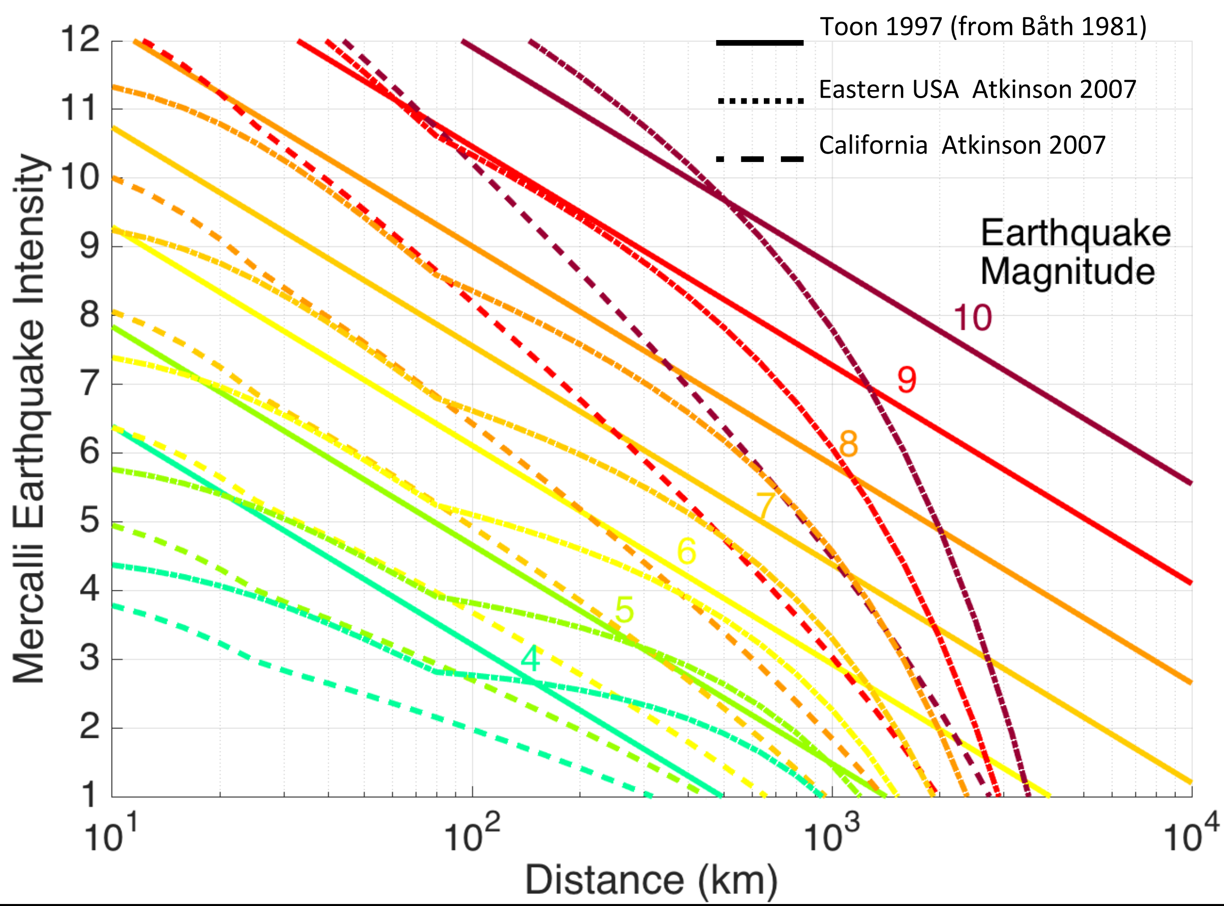
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Damage	None	None	None	Very slight	Light	Moderate	Moderate/ heavy	Heavy	Very heavy
Peak Acc	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Vel	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16 -31	31-60	60-116	>116

Peak Acc = Peak ground acceleration (g), Peak Vel = Peak ground velocity (cm/s)

https://earthquake.usgs.gov/earthquakes/search/

- Intensity decreases approximately logarithmically with distance, but depends on how fractured ground is from previous earthquakes.
- Highly fractured ground in earthquake prone zones (e.g. California, Japan) absorbs much more energy than in more stable areas (e.g. Eastern USA).

Earthquake Intensity vs. Distance



- Toon 1997 from Båth 1981

  M = Earthquake magnitude

  ε = coupling efficiency

  E = impact energy (Mt)

  A = area (km^2)

  I = intensity

  (modified Mercalli scale)

  r = distance (km)

$$M = 7.2 + 0.71 \lg(\varepsilon E)$$

$$A = 3 \times 10^{9} (\varepsilon E)^{0.63} 10^{-0.63 I}$$

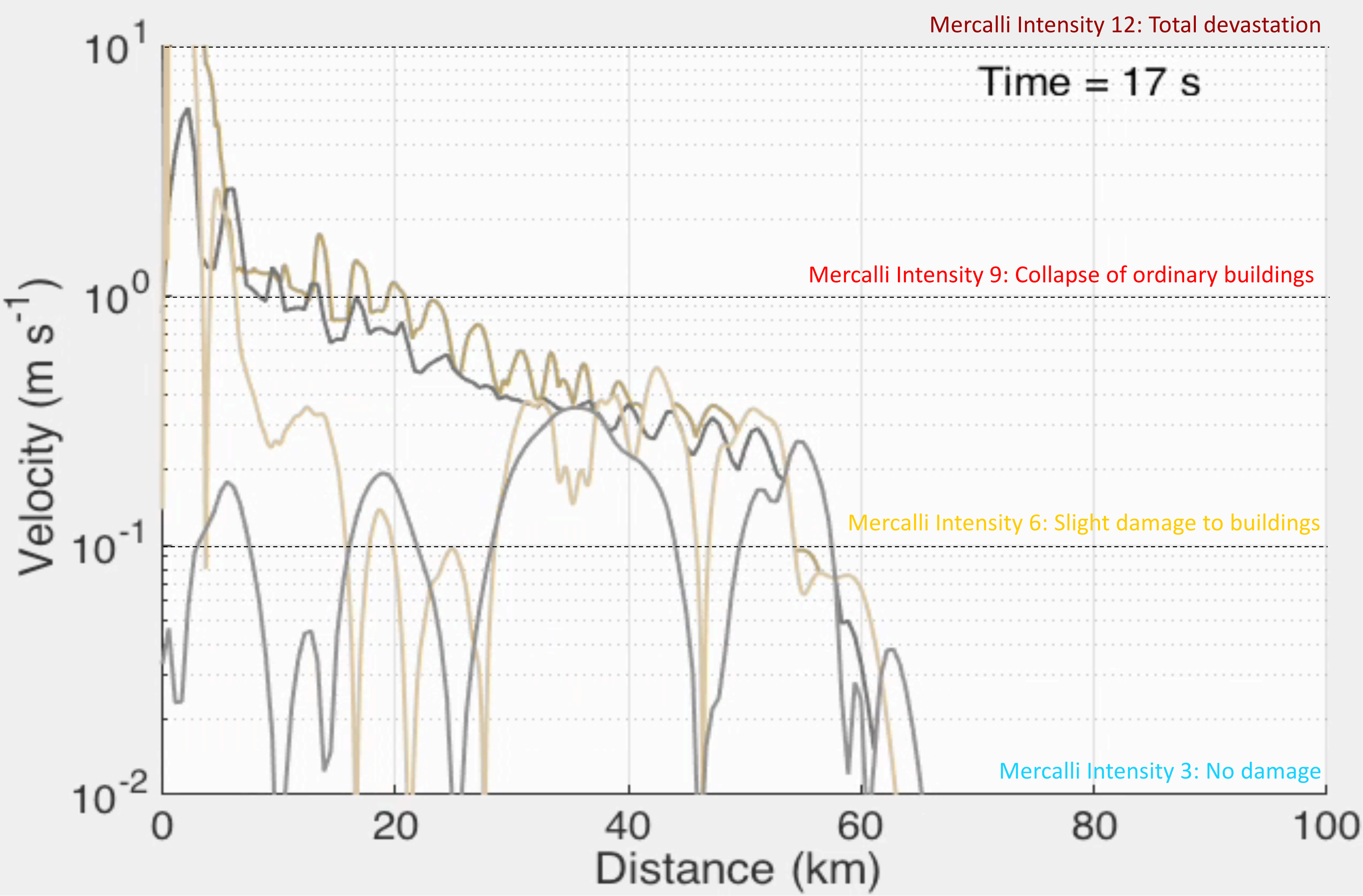
$$I_{Bàth} = 1.45M - 3.18 \lg(r) + 3.77$$

- Atkinson 2007 refitted using simpler equations only valid for 5 < I < 10

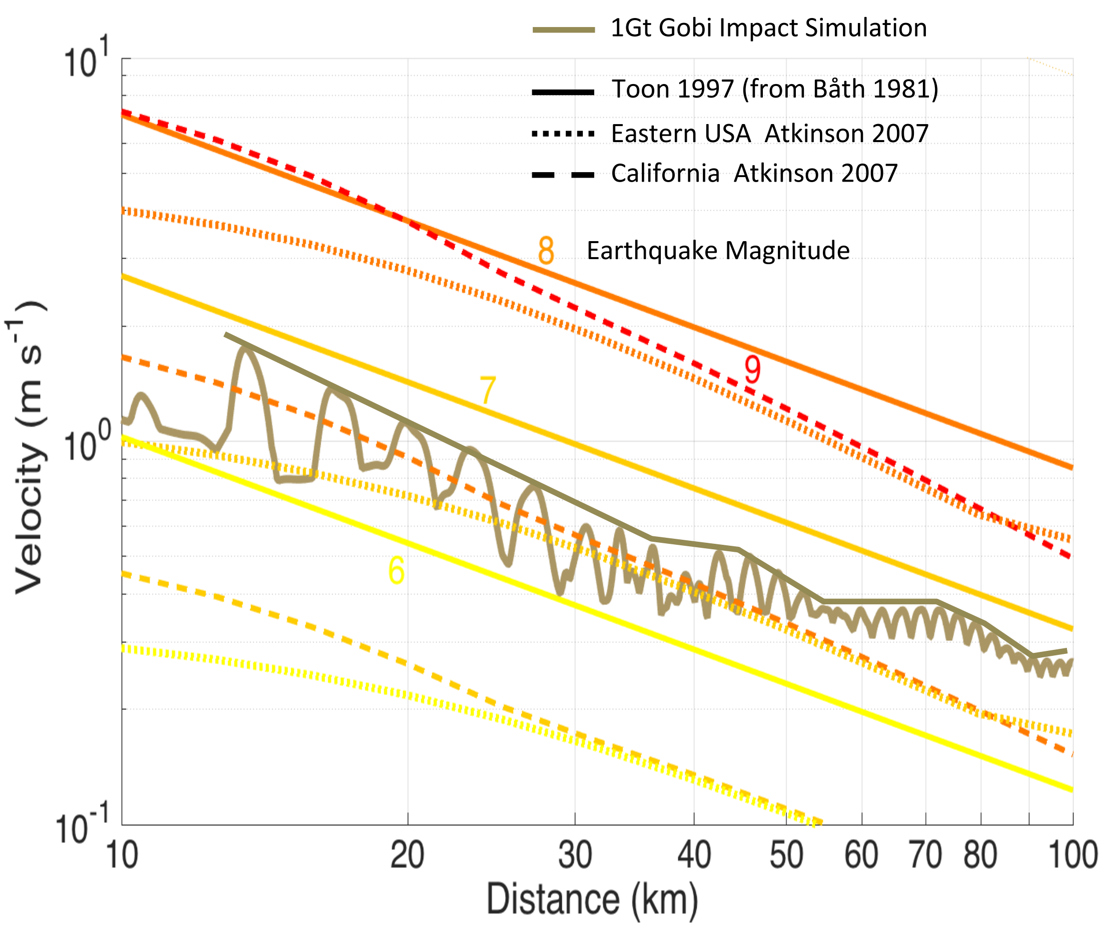
$$I_{CA} = 1.76M - 4.18 \lg(r) + 0.52$$

$$I_{East} = 1.70M - 2.27 \lg(r) - 0.0021 r - 0.29$$

1GT Gobi Impact Earthquake



Earthquake Coupling Efficiency



- 1GT Gobi Desert impact equivalent to ~M8 earthquake in CA or ~M7 in Eastern USA.
- 40km from impact, ground velocity

  0.5 m/s => I=8.2

  => Magnitude 6.6 (Båth eqn.)

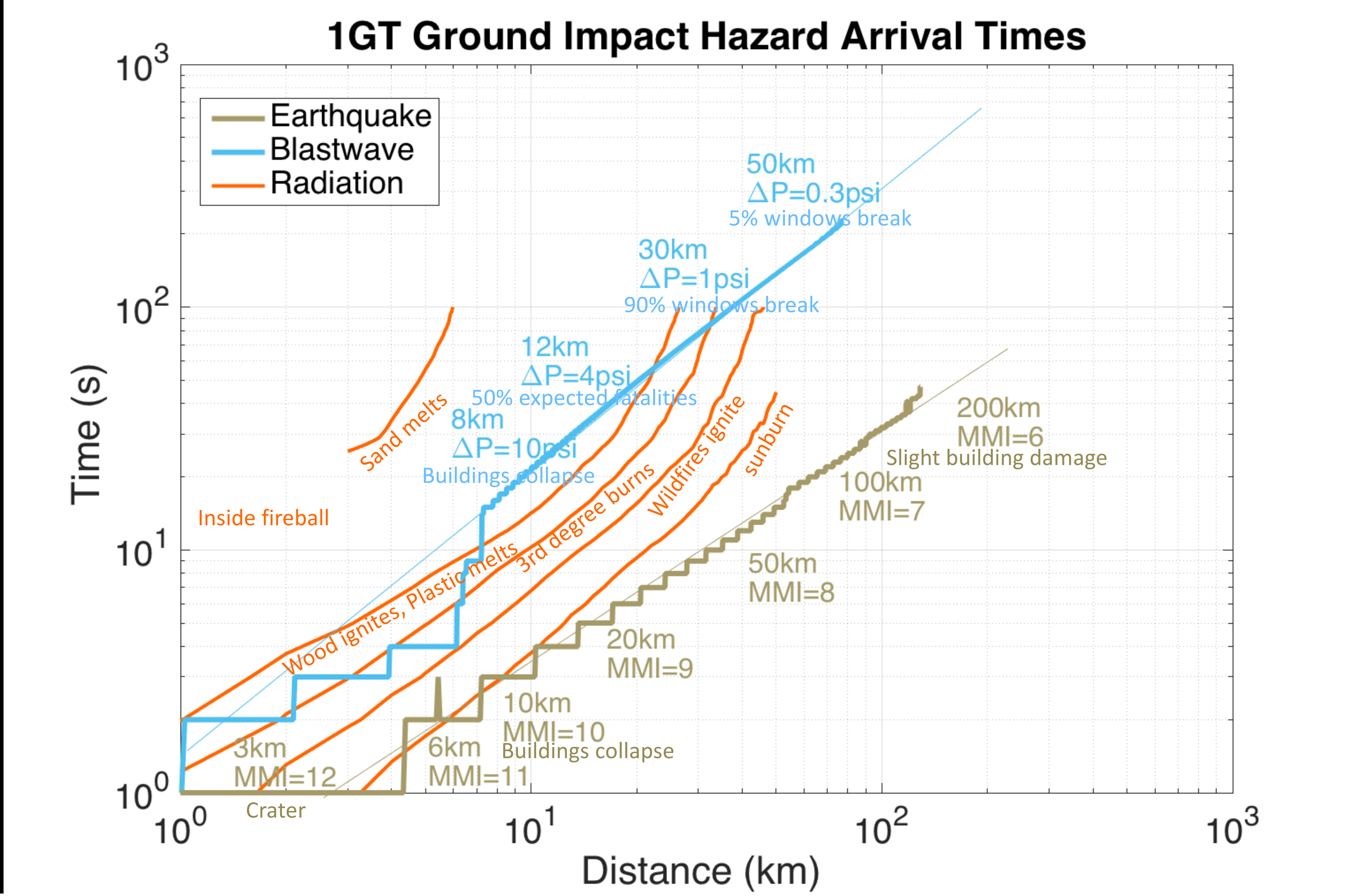
  => εE = 0.14 MT

  => ε = 1.4×10^{-4}

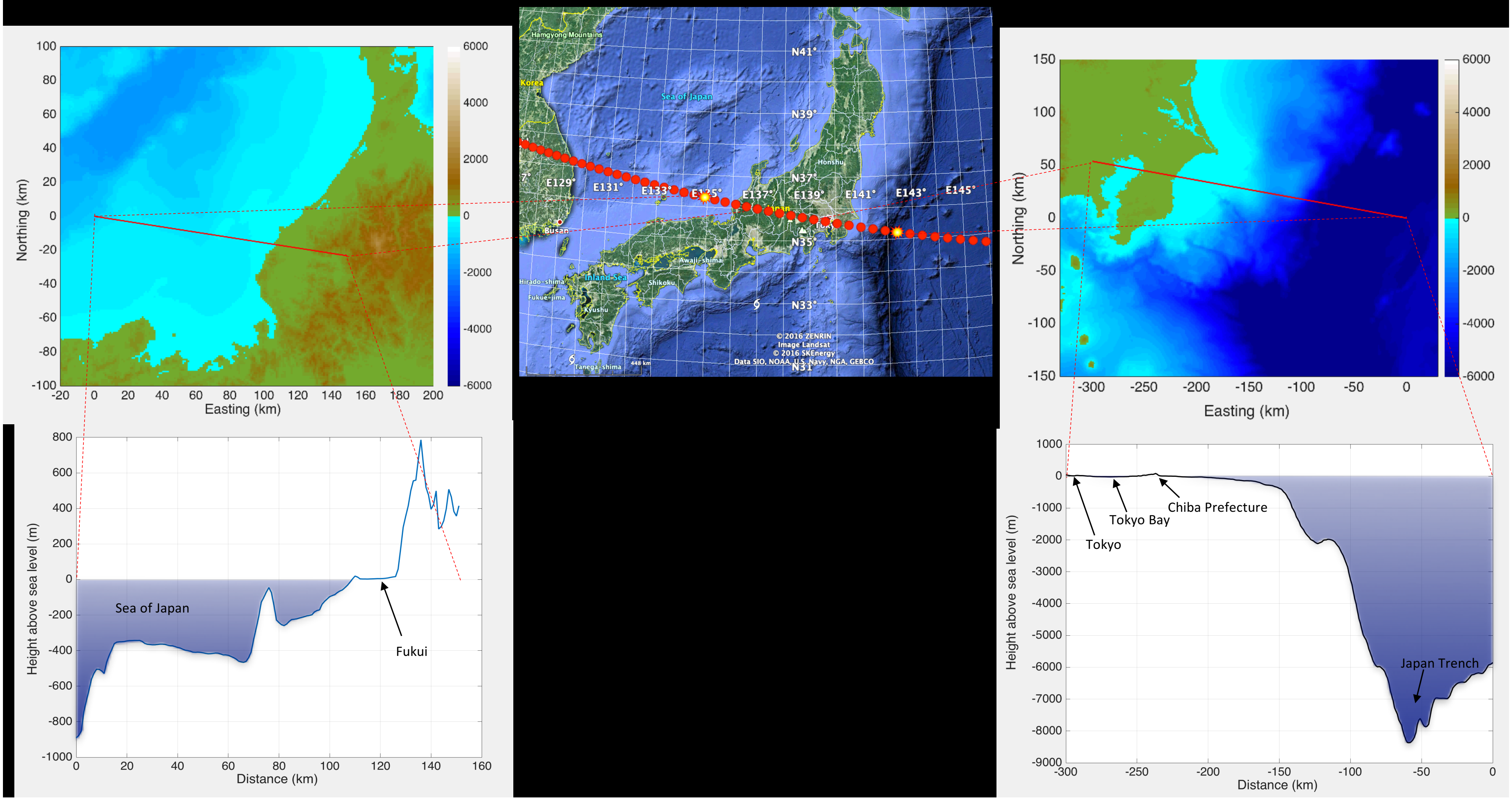
  Coupling efficiency = 0.014%

  Toon 1997 used ε = 10^{-4} (0.01%).

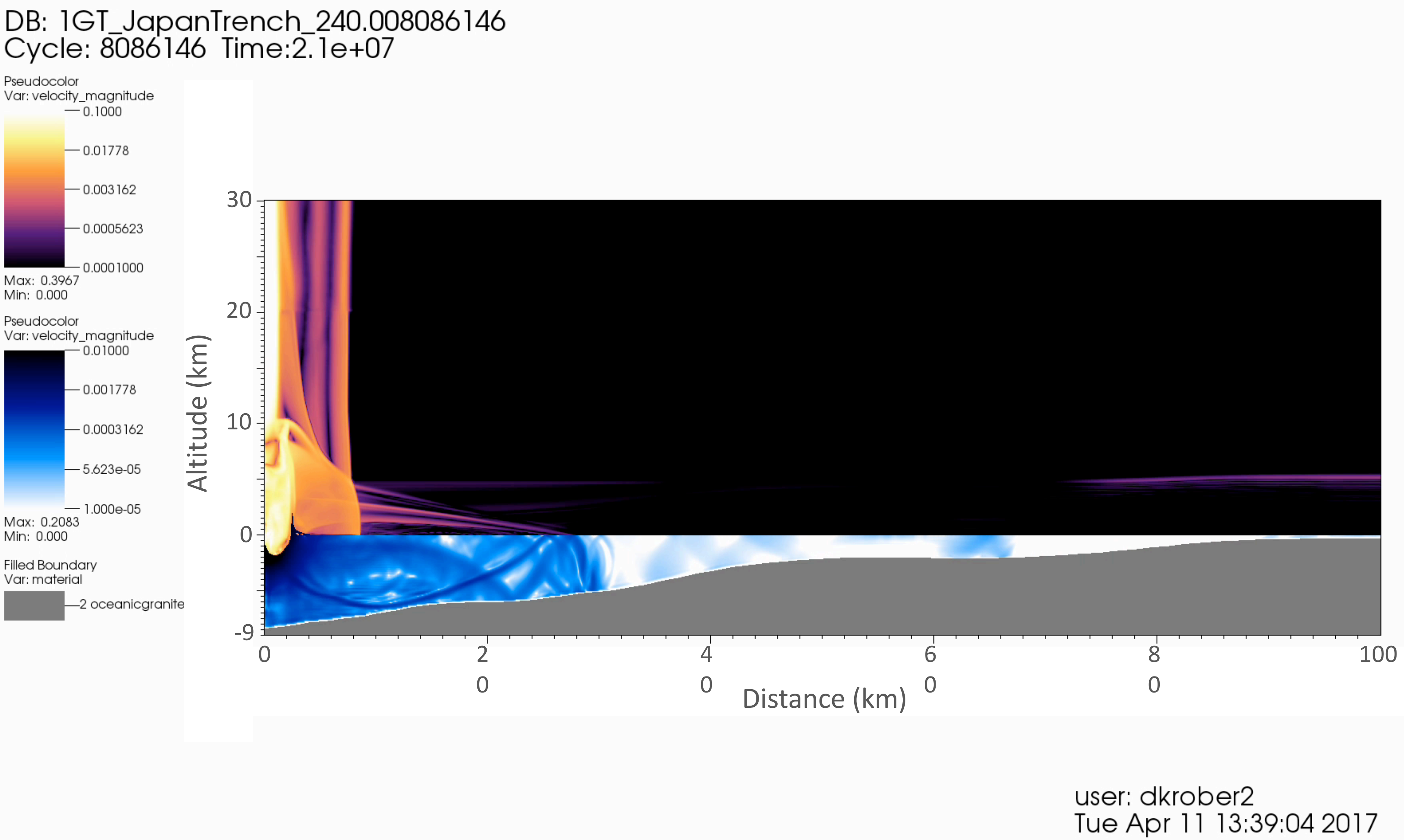
Hazard Space-Time Graph



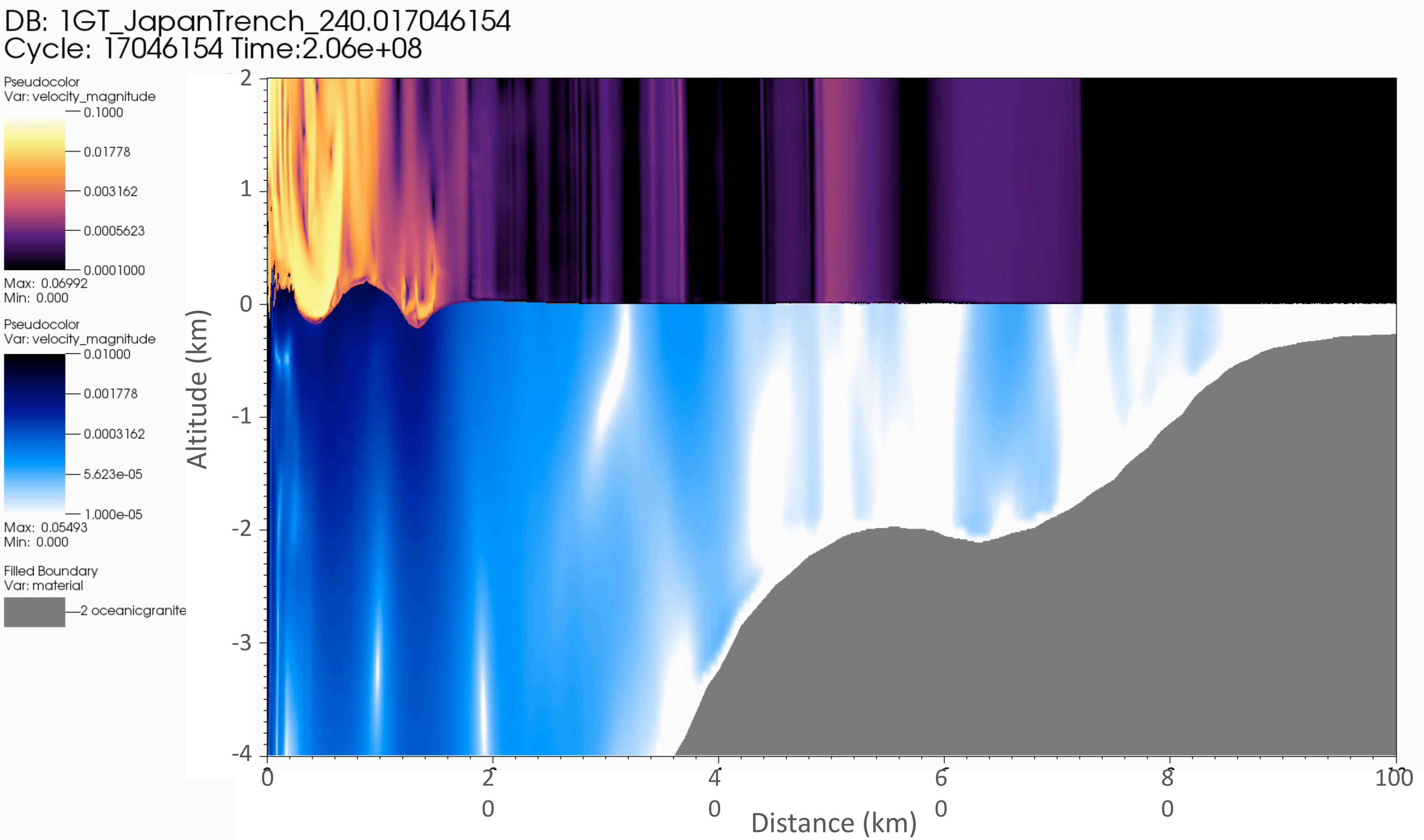
Japan Sea & Trench



Deep Water Impact

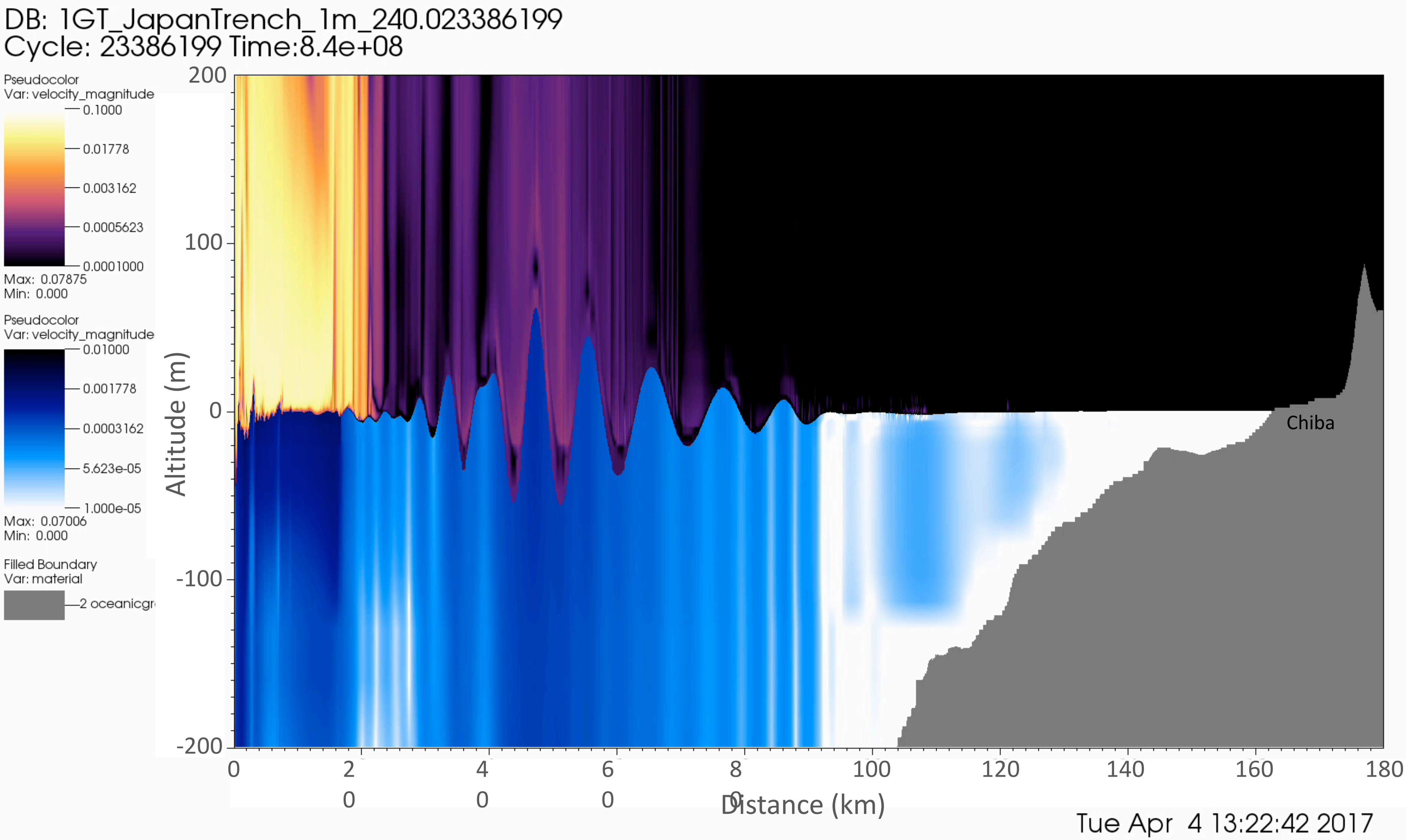


Vertical x10

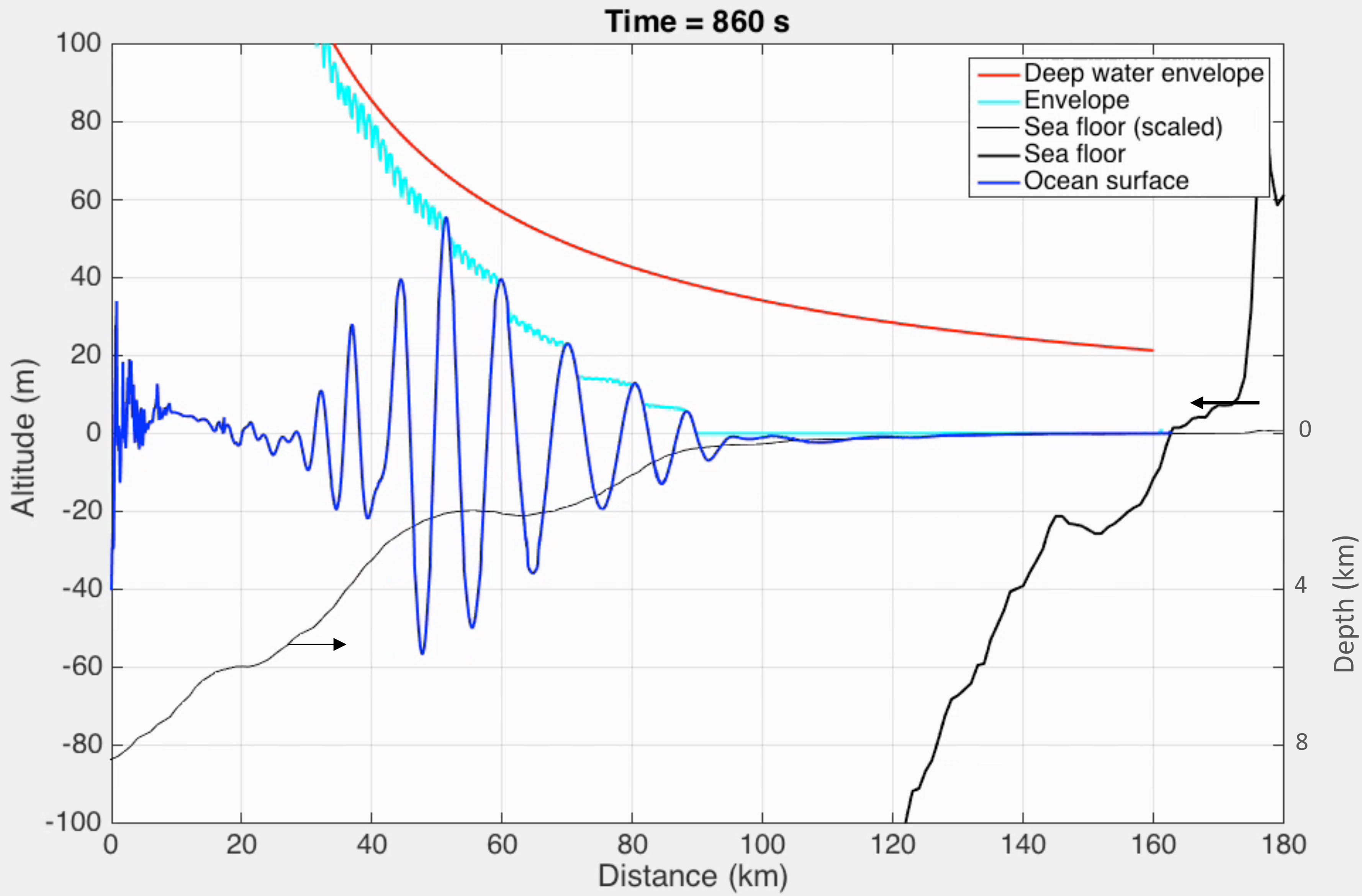


Vertical x250

- Wave reflect and dissipate on continental slope

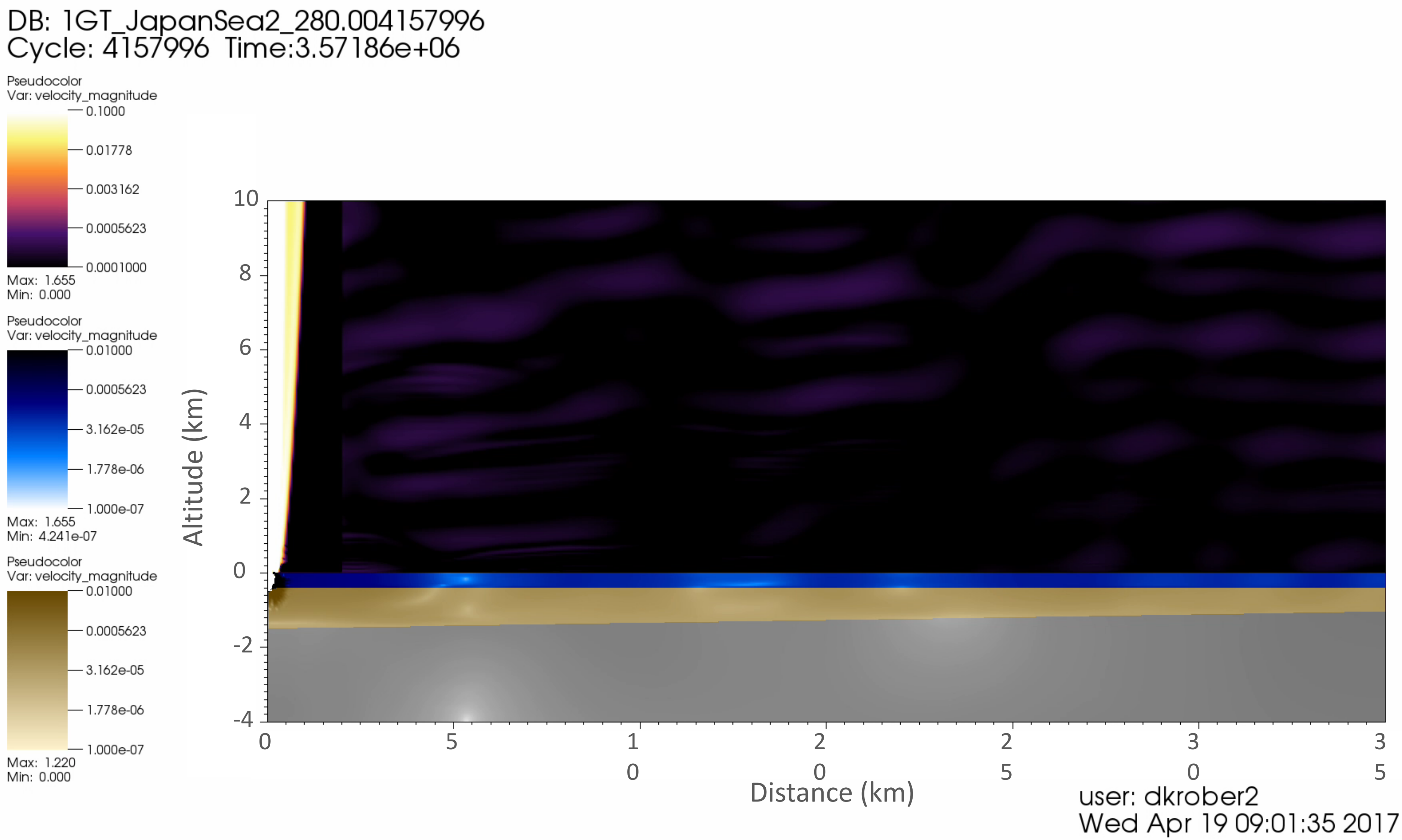


Tsunami Wave

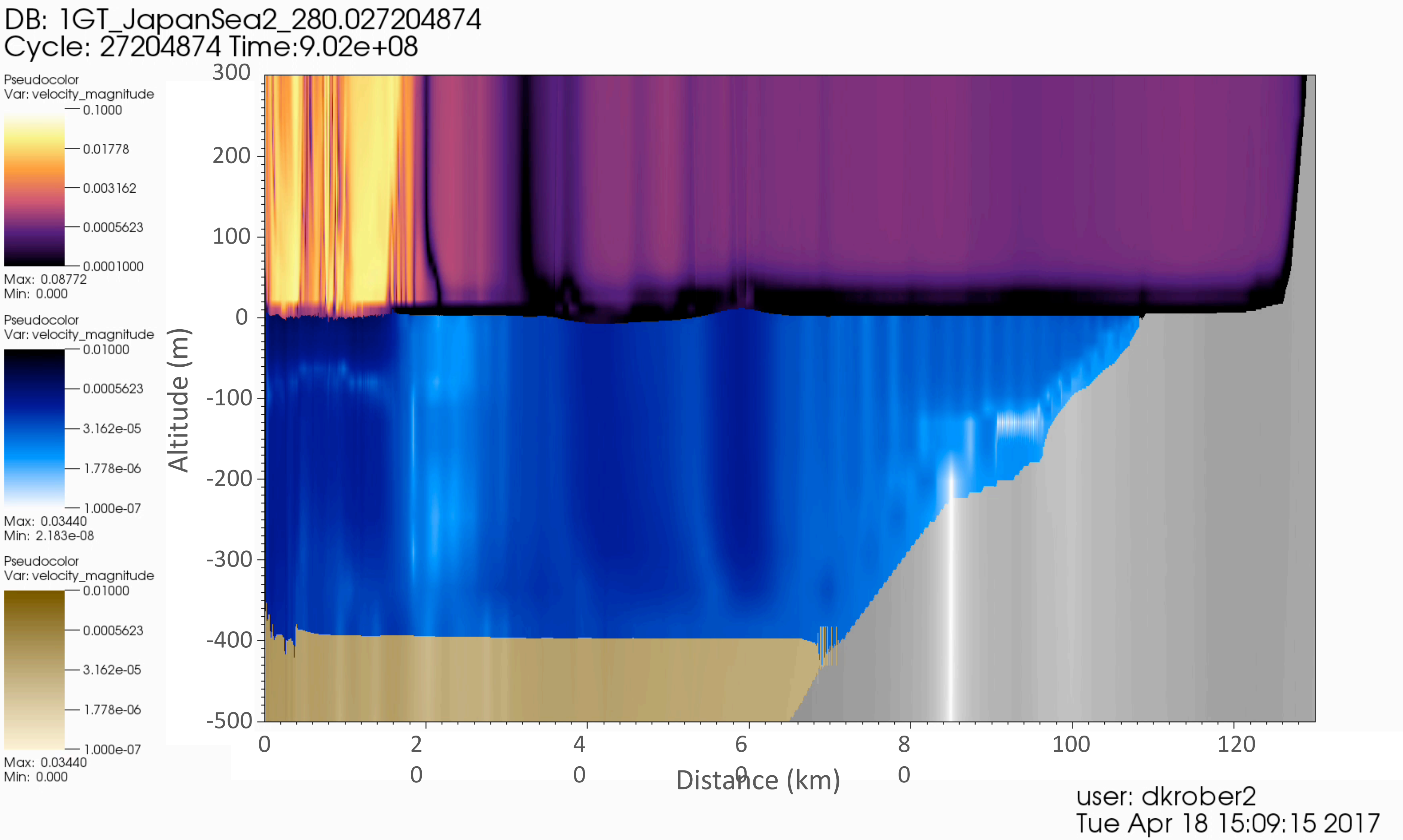


Japan Sea x1

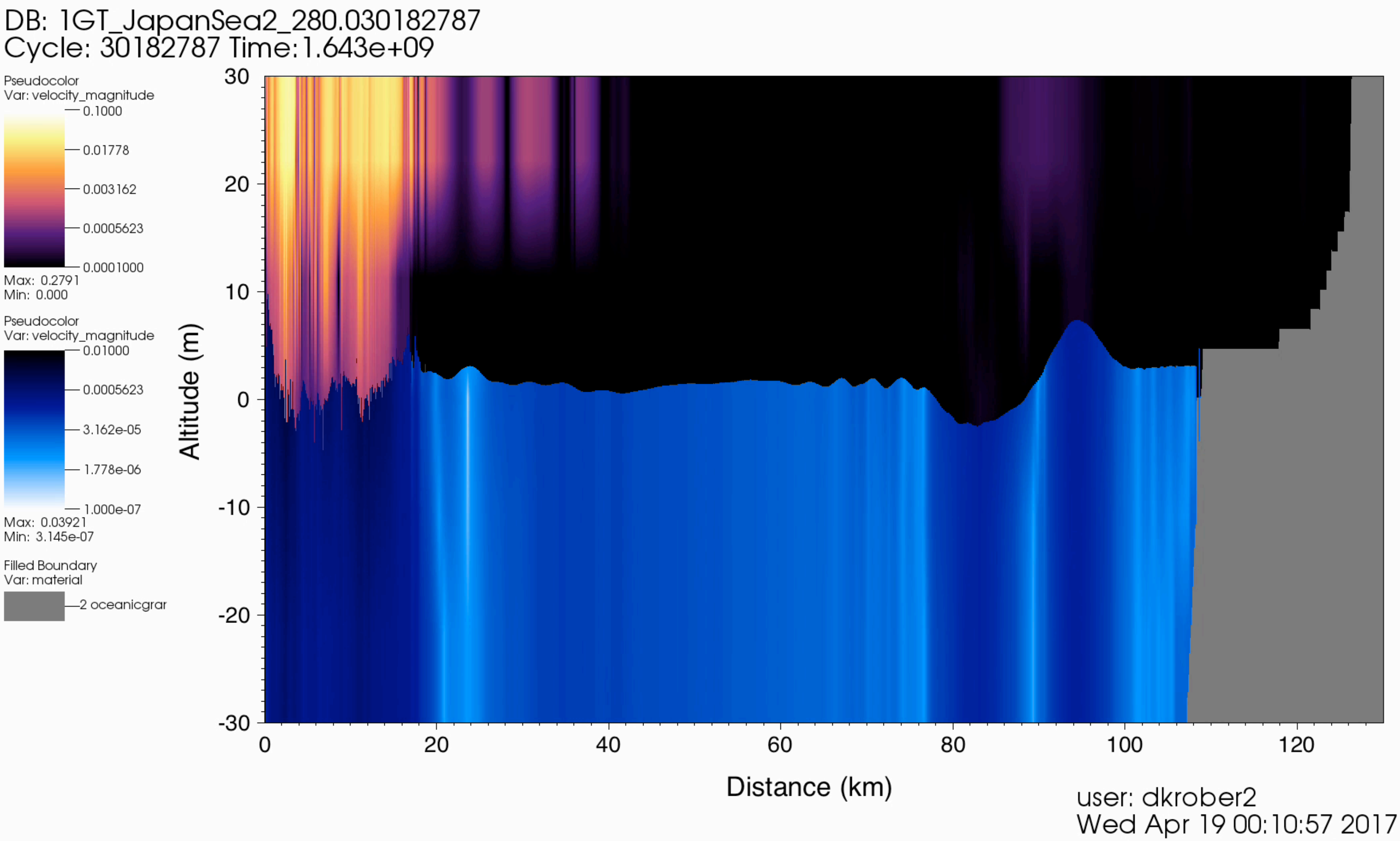
30



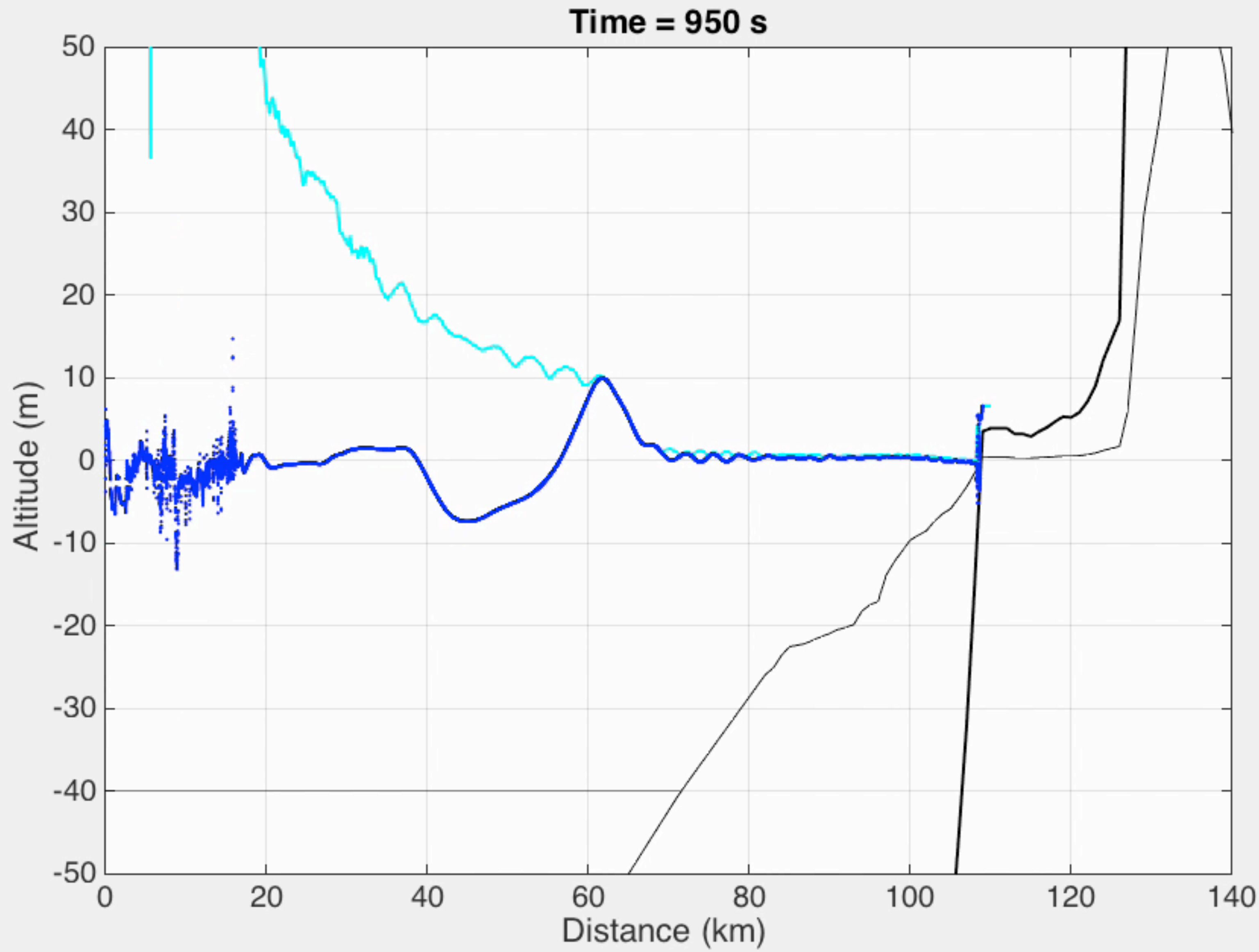
Japan Sea (over limestone) x100



Japan Sea x1000



Japan Sea Tsunami



Conclusions

- Gobi Desert may be an acceptable location to allow a 1GT impact
- Deep water may also be acceptable if far enough from shore and there is a low likelihood of triggering an undersea landslide.
- Shallow water inadvisable

Future Work

- Different ground properties
- Intermediate depth water (2 – 4 km)
- Entry of rubble pile asteroid
- Non-vertical entry angle (will require 3-D)

Novaya Zemlya Nuclear Test

3.5 kT, detonated just below the surface

https://www.youtube.com/watch?v=2fyrHW5djuA