Impact Cratering on Icy Satellites

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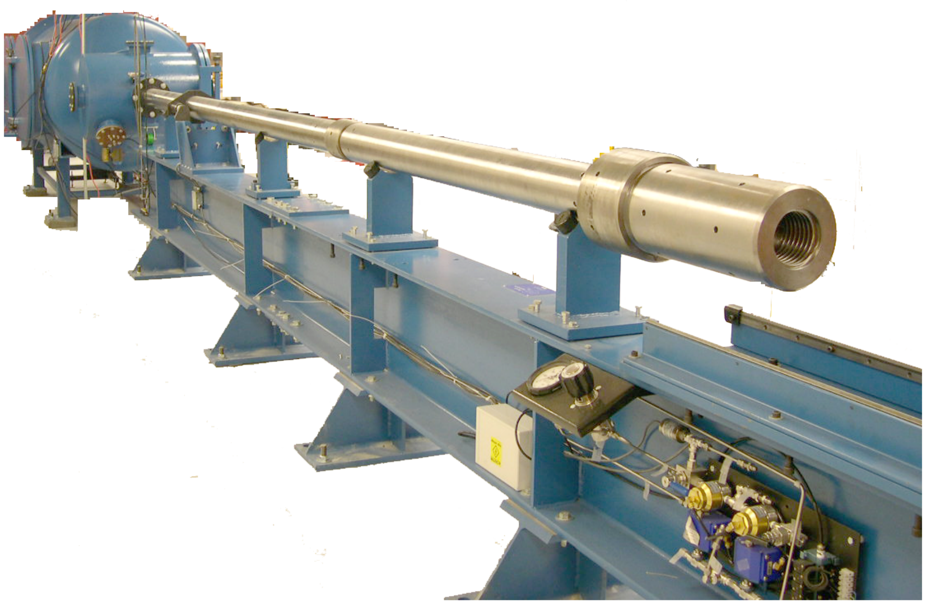
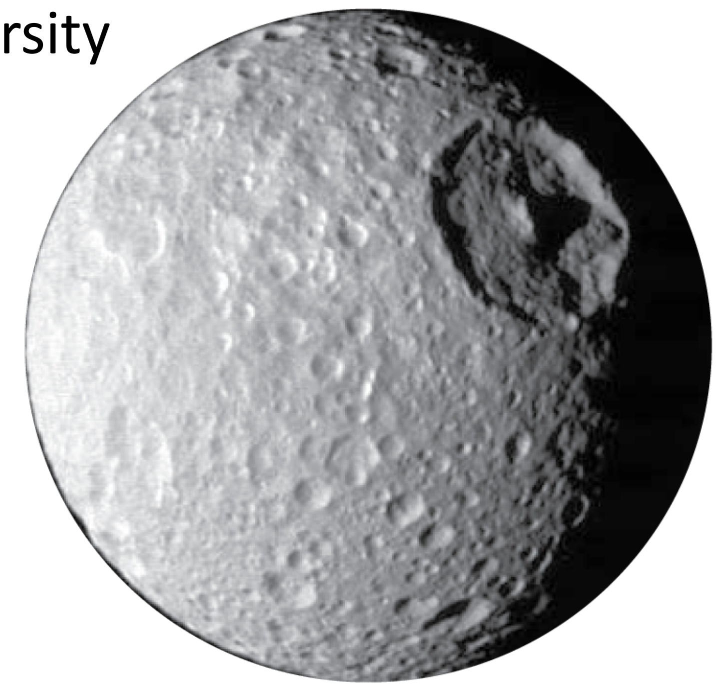




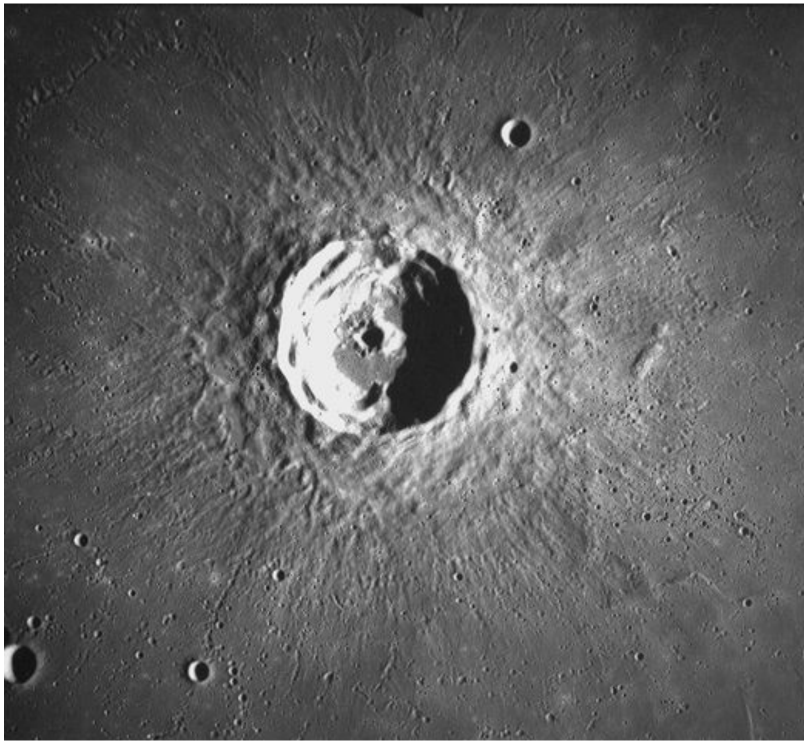
Collisions are an integral component of planet formation

Dust to planetesimals

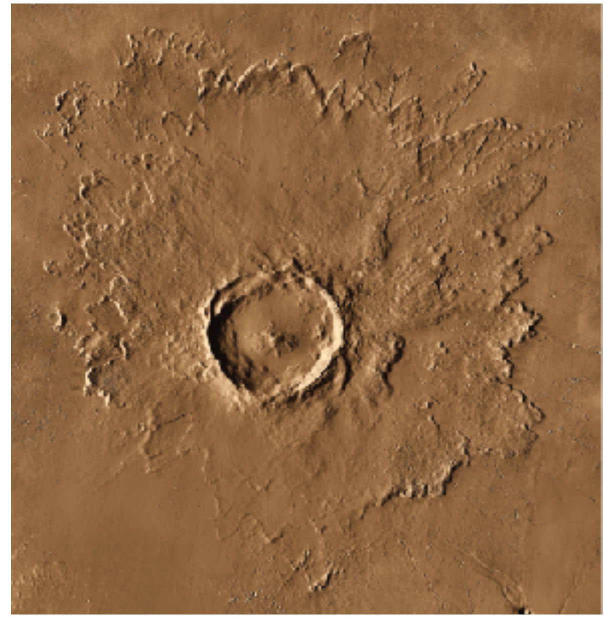
Giant impacts

Thank you Bill Hartmann and Don Davis

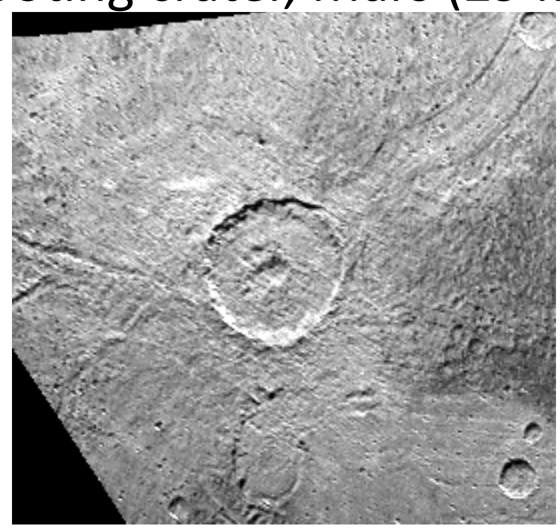
Impact craters reflect target properties



Timocharis crater, Moon (33 km)



Tooting crater, Mars (29 km)



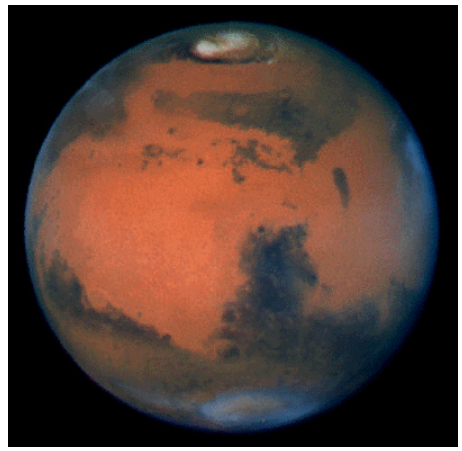
Isis crater, Ganymede (73 km)

Morphological differences:

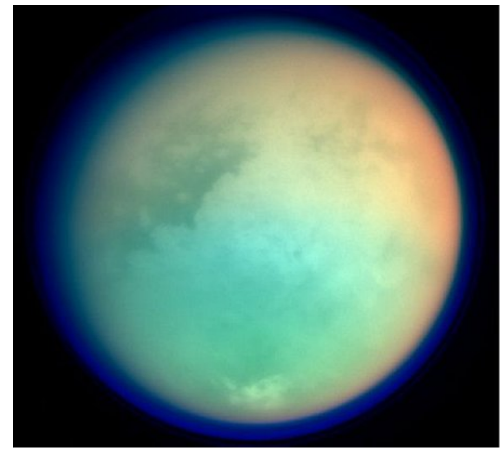
- Depth to diameter ratios
- Central features
- Ejecta structures

Craters expose subsurface stratigraphy and can create transient pools of liquid water

Deep Impact on comet Tempel 1



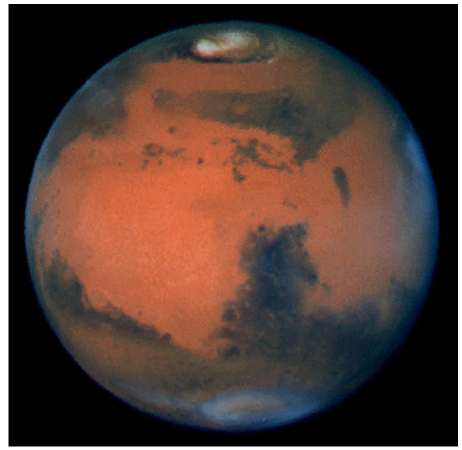
Mars



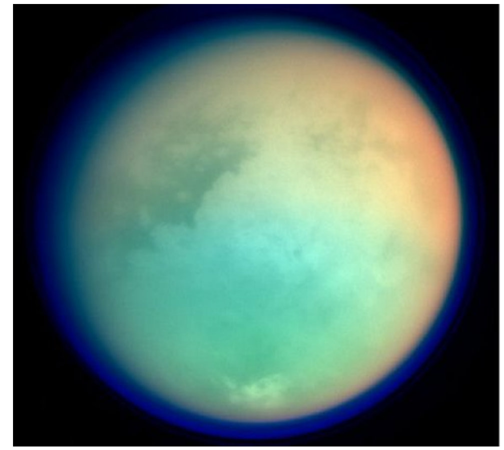
Titan

Craters expose subsurface stratigraphy and can create transient pools of liquid water

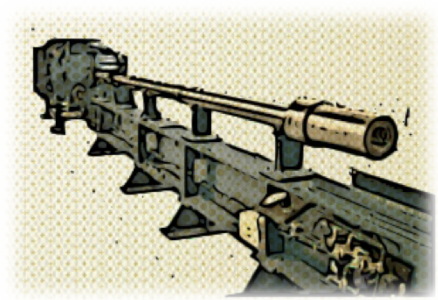
Deep Impact on comet Tempel 1



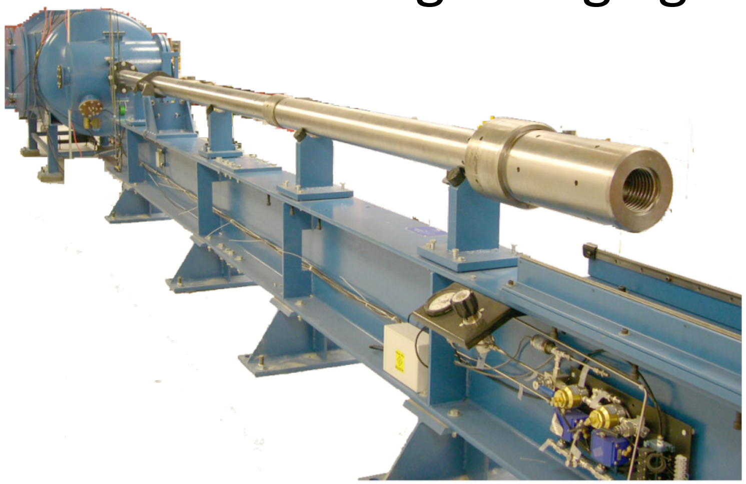
Mars



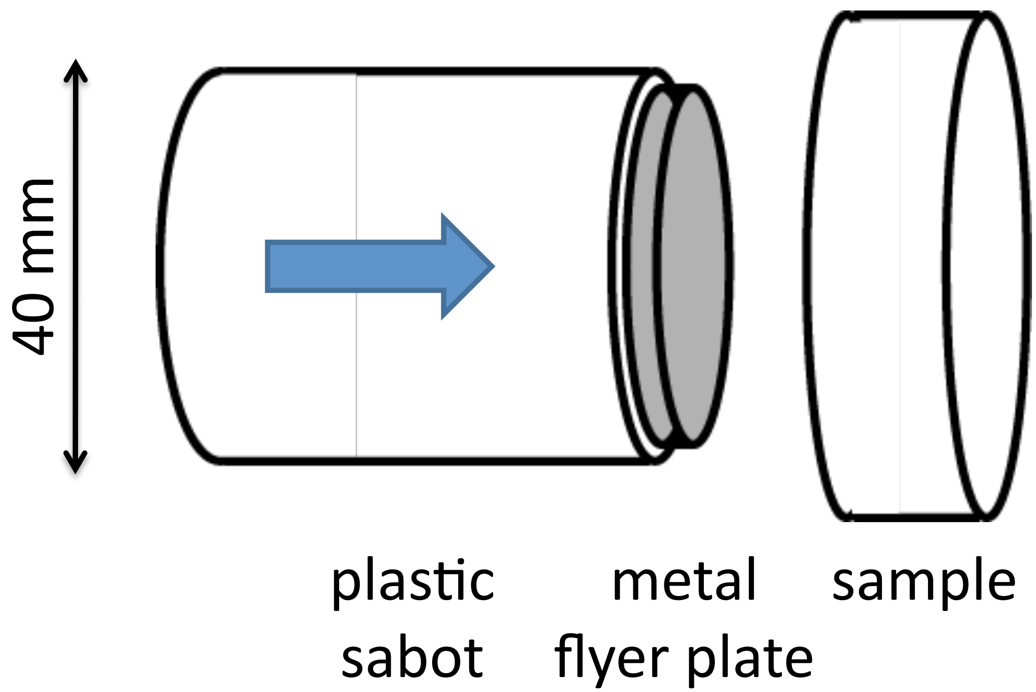
Titan



Harvard single stage gun



Shock wave experiments

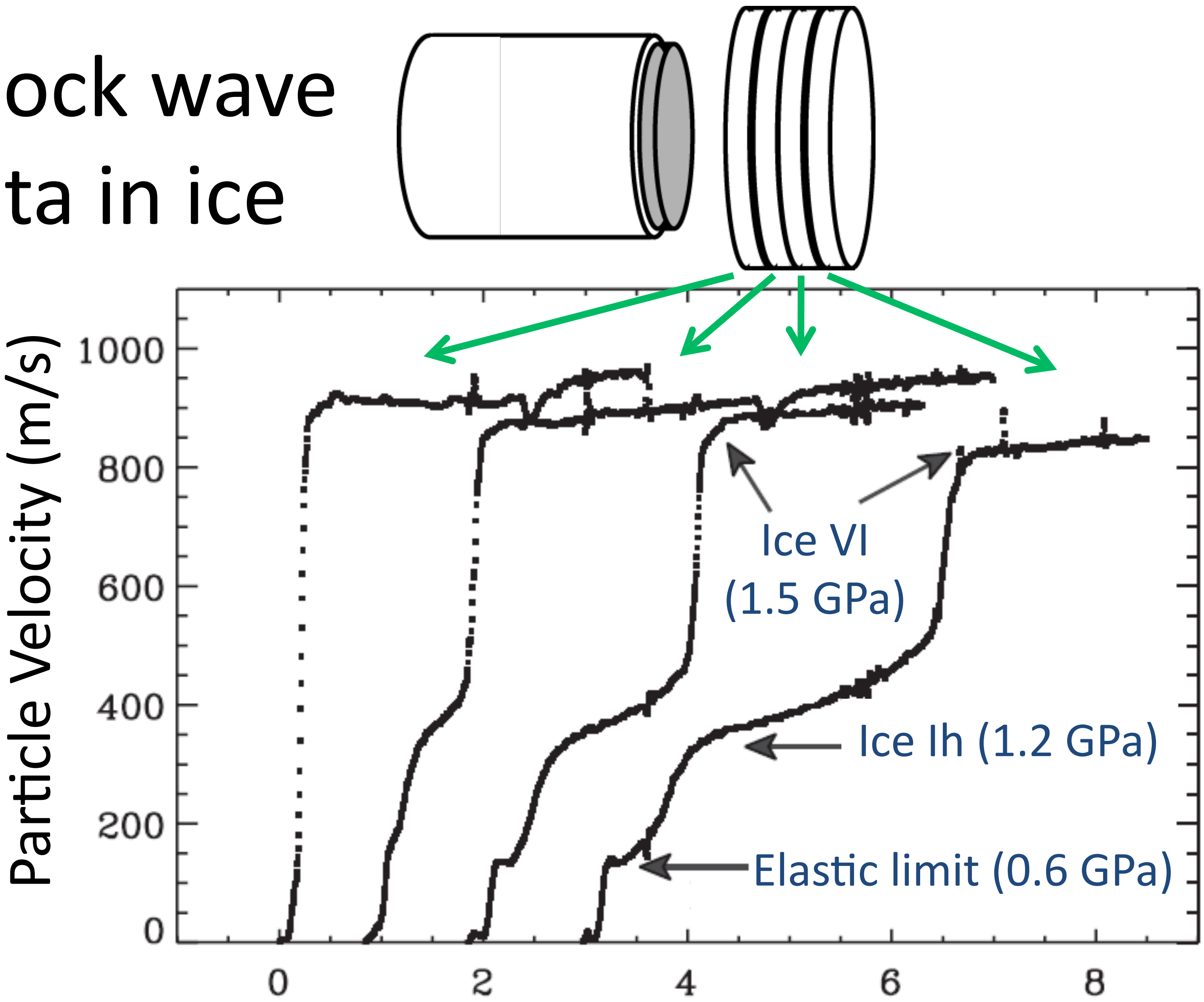


Measurements:

- Pressure & volume
- Temperature
- Strength
- Spectroscopy
- Sample recovery

Each experiment is over in a few microseconds.

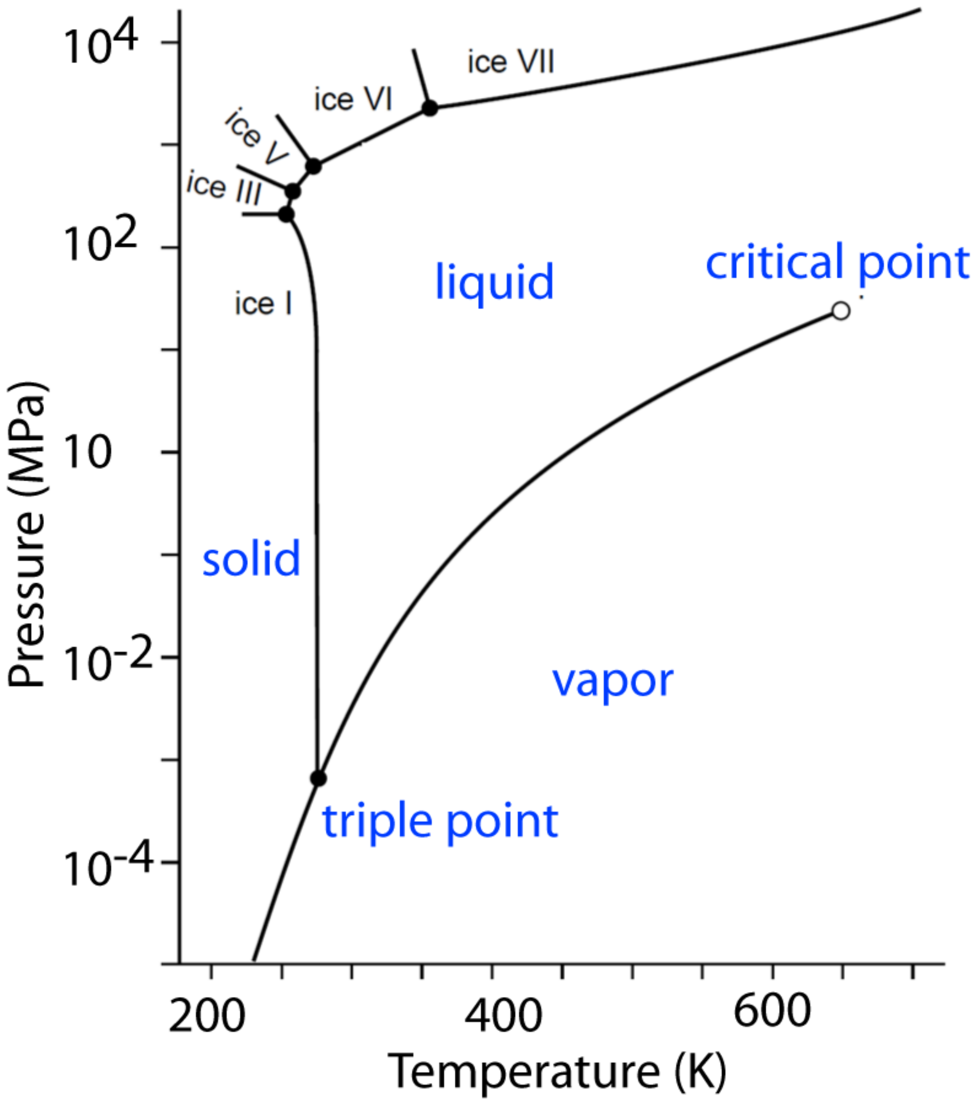
Shock wave data in ice



1 GPa = 10 kbar

Stewart & Ahrens 2003, 2005

H_2O phase diagram



21 known phases

12 stable phases:

vapor, liquid, 10 solid crystal structures

Triple point:

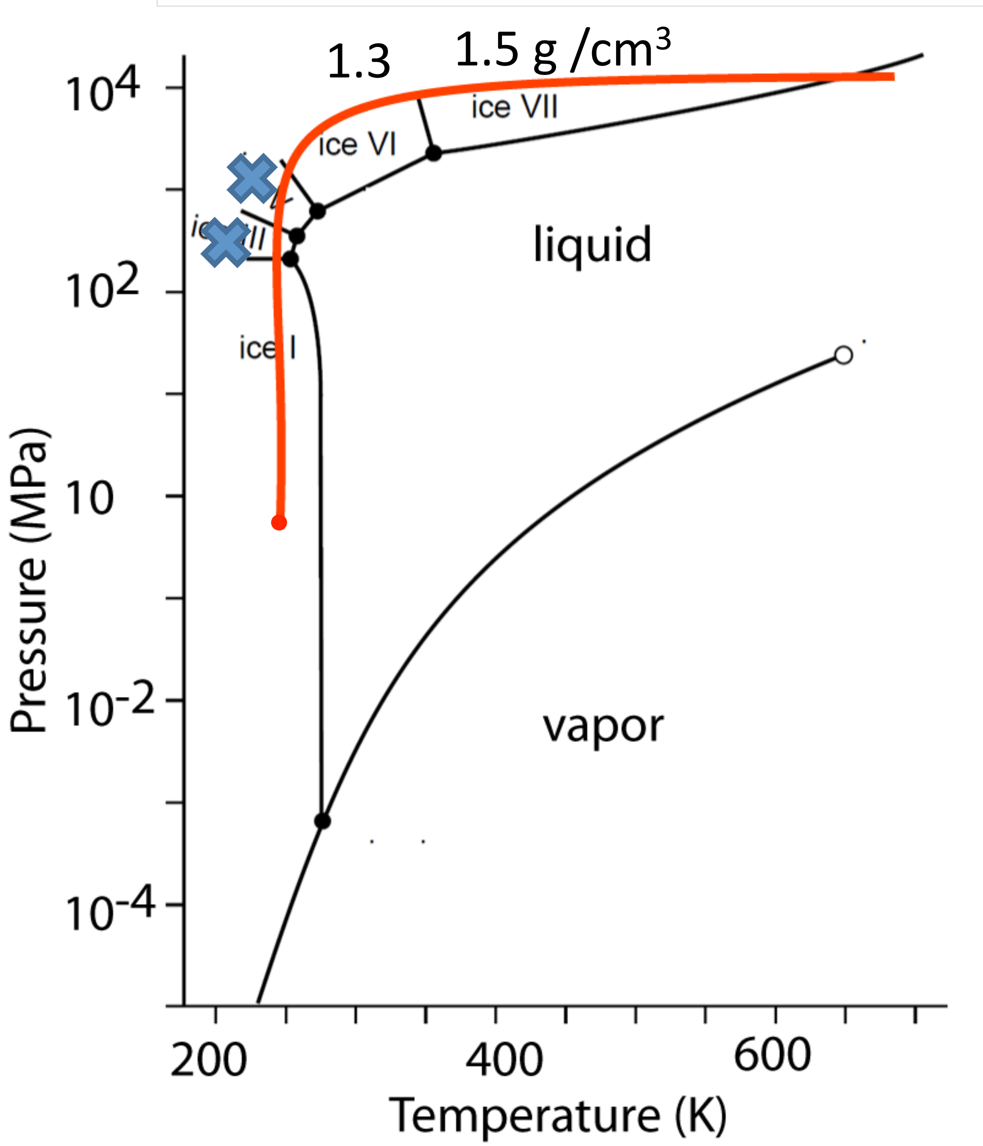
612 Pa, 273 K

Critical point:

22 MPa, 647 K

Wagner & Pruss 2002

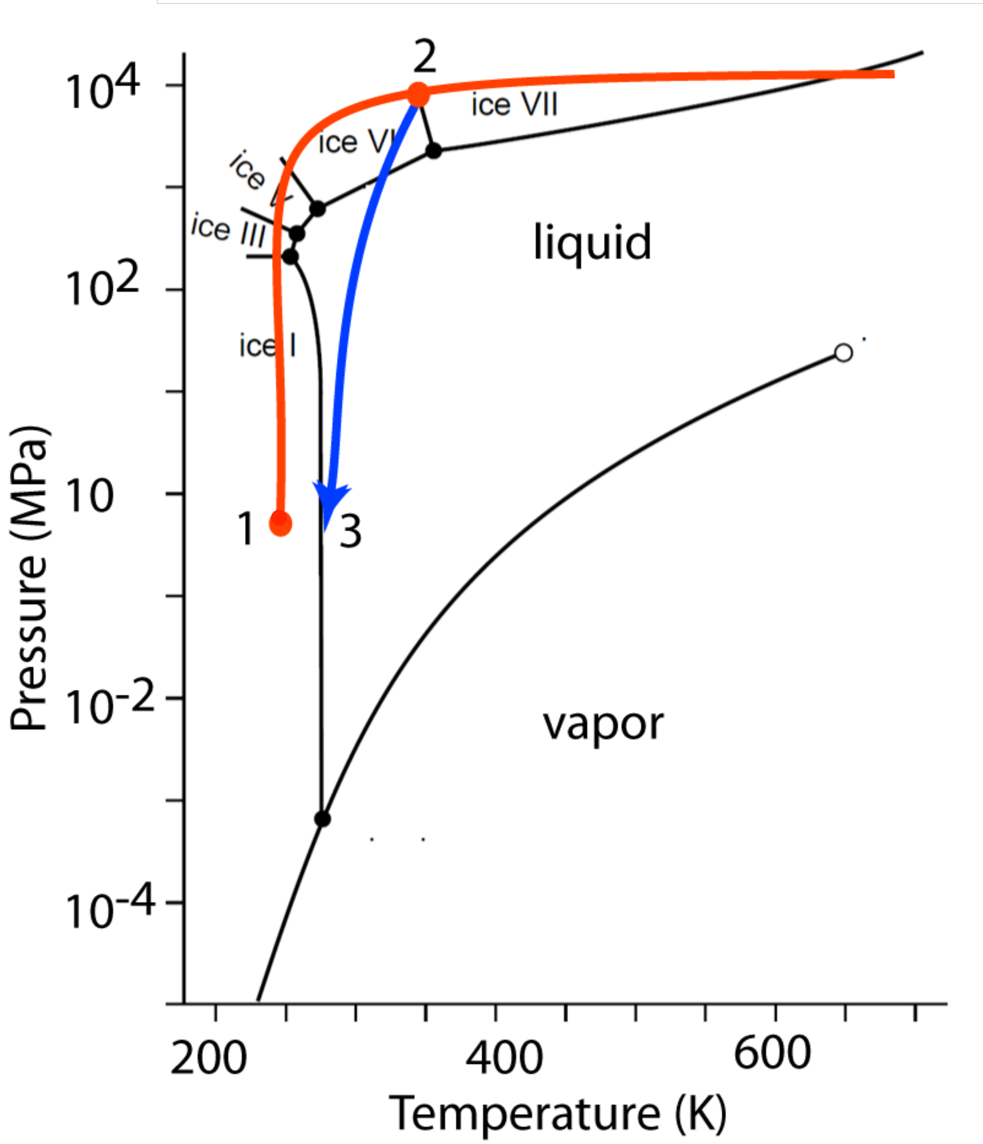
What happens when ice is shocked?



- Shock Hugoniot: the locus of possible shock states for a given initial condition
- Identified all phase transitions on the shock Hugoniot
- Low and high temperature (100 & 263 K) Hugoniots

Stewart & Ahrens 2003, 2005

What happens when ice is shocked?



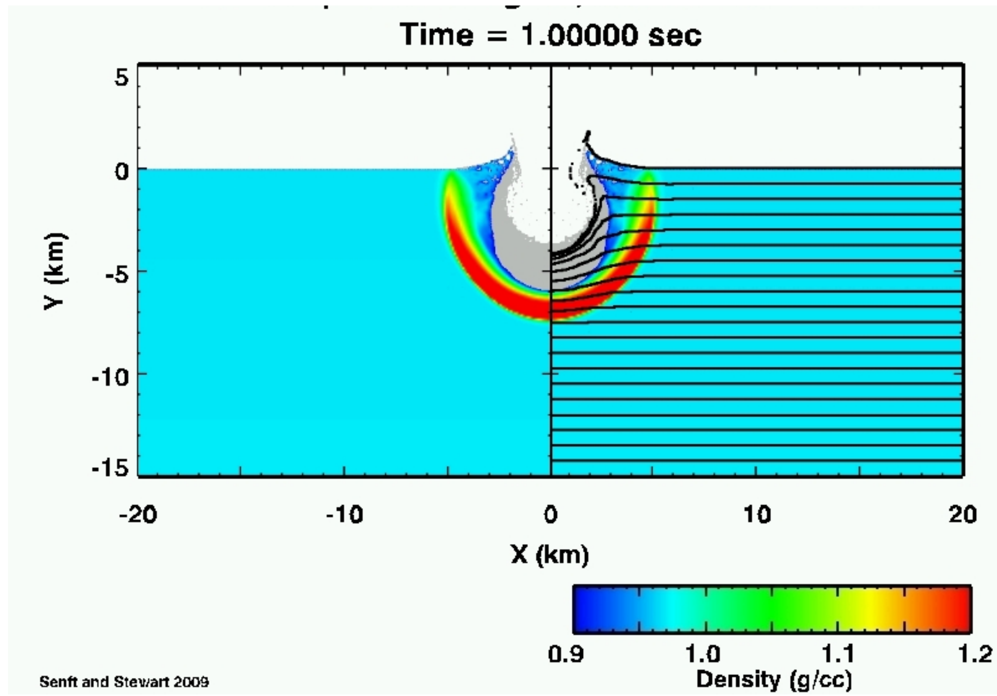
- Calculated the criteria for melting and vaporization upon release from shock
- Measured shock and post-shock temperatures
- Created a model equation of state with 5 phases

Stewart et al. 2008
Senft & Stewart 2008

Modeling impact events

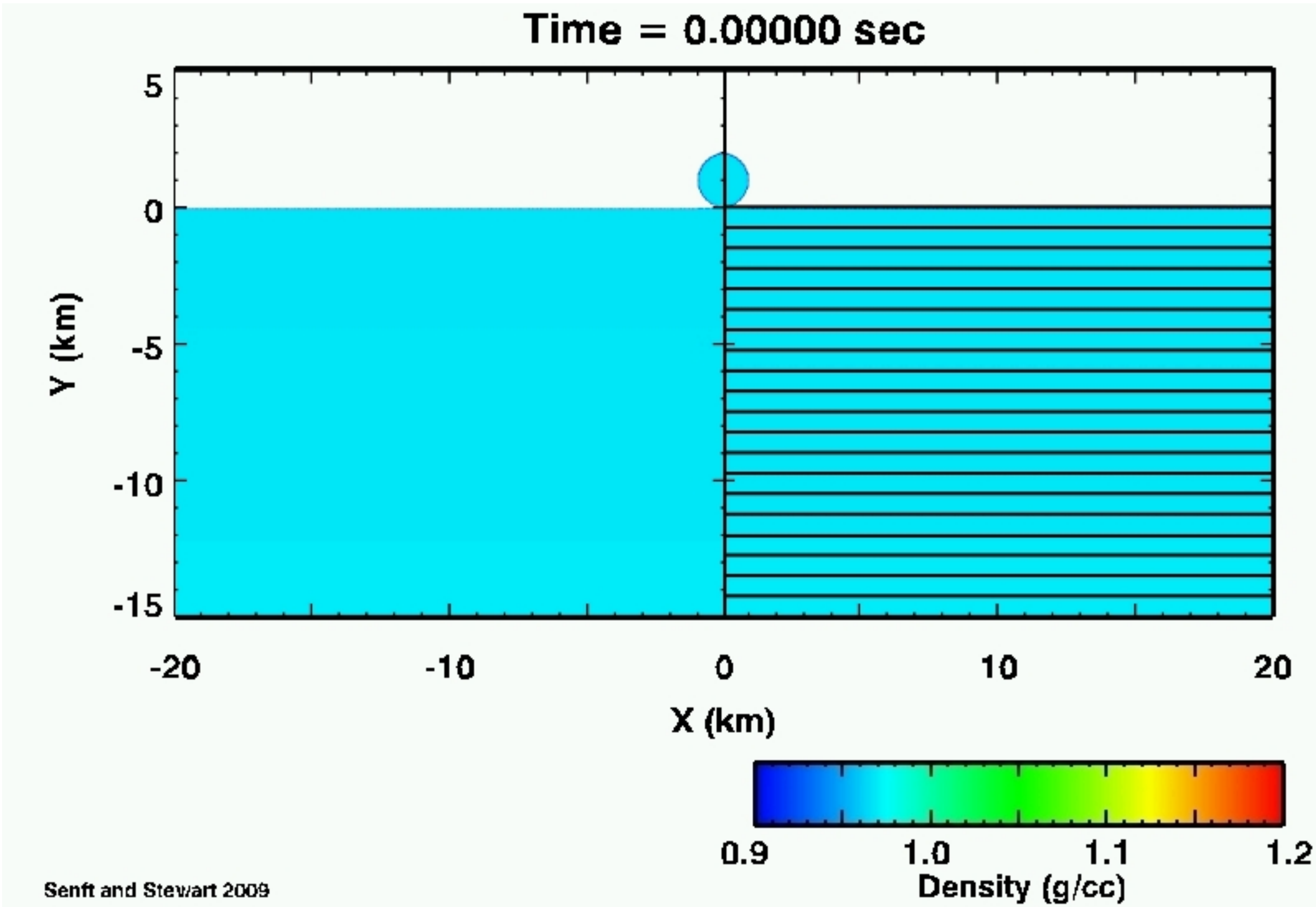
Shock physics code:

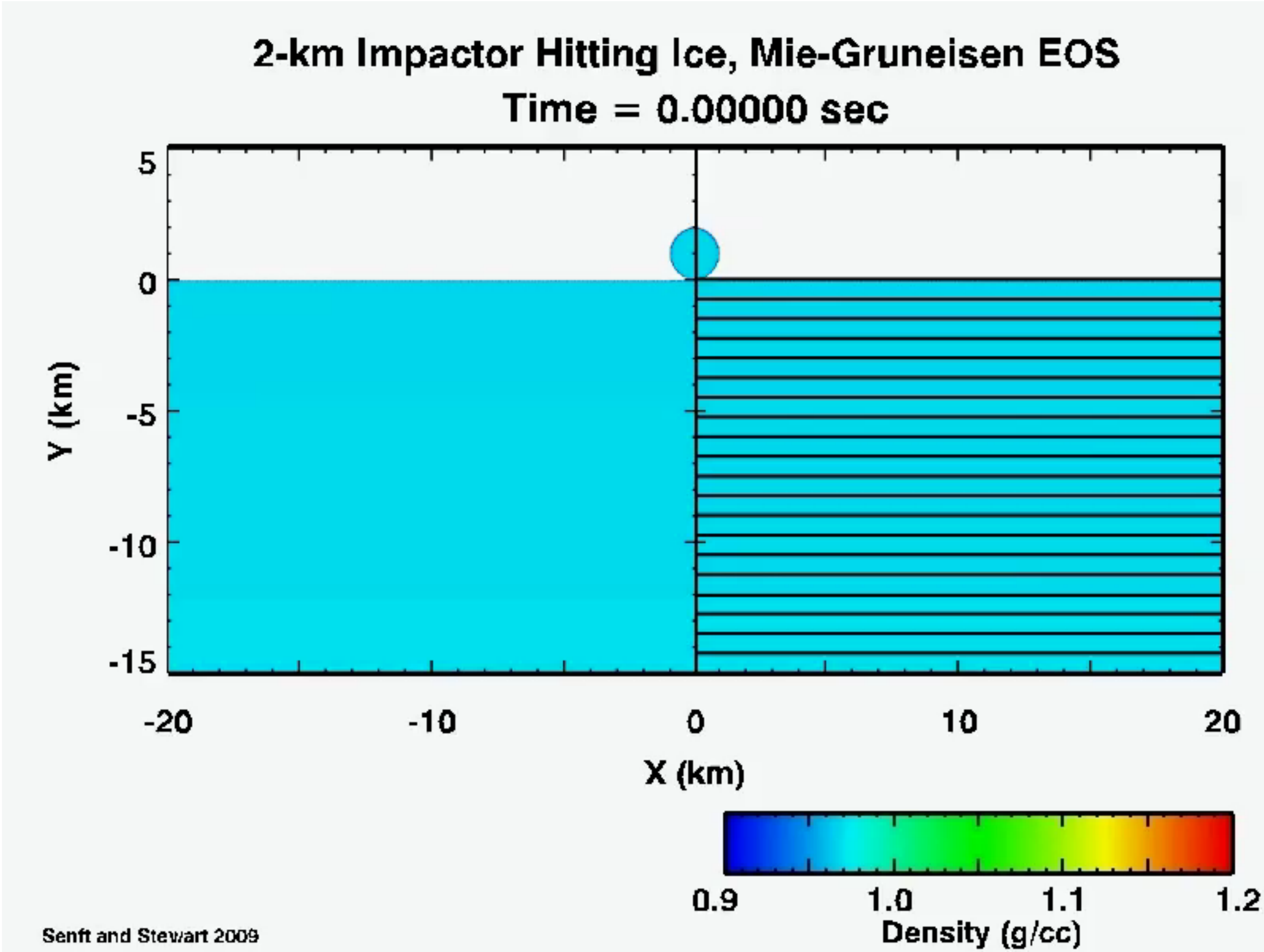
- Solves conservation equations
- Constitutive models
  - Shear strength
  - Tensile strength
  - Dynamic reduction in strength
- Equation of state



Senft & Stewart 2007, 2008, 2009

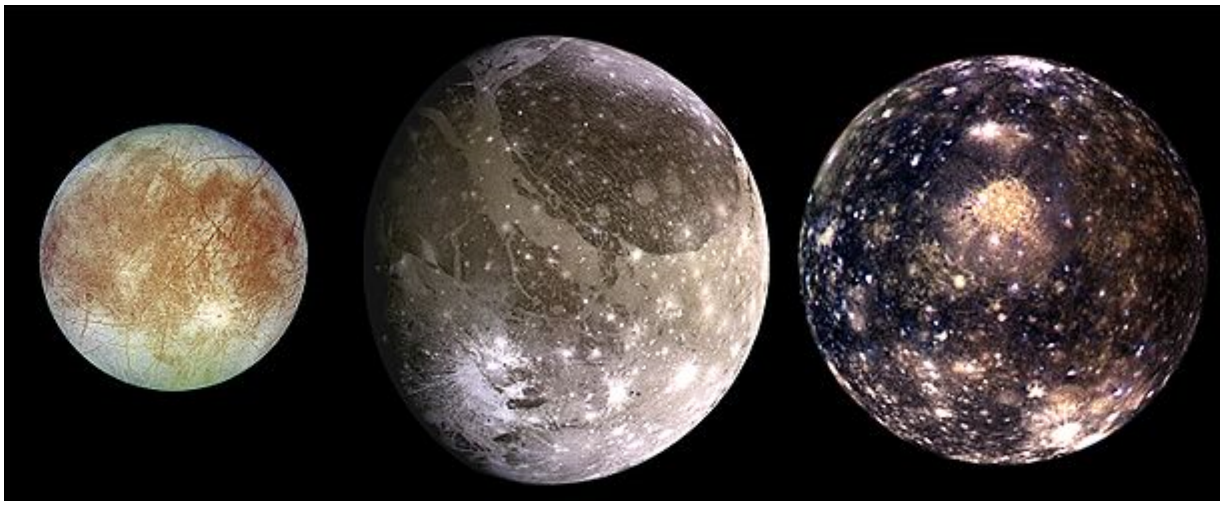
2 km diameter projectile at 15 km/s → 40 km diameter crater

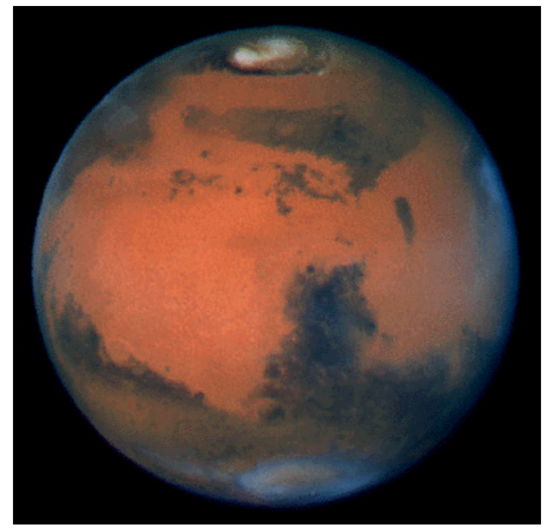




2-km Impactor Hitting Ice, Mie-Gruneisen EOS
Time = 0.00000 sec
Y (km)
5
0
-5
-10
-15
-20
-10
0
10
20
X (km)
0.9
1.0
1.1
1.2
Density (g/cc)
Senft and Stewart 2009

Cratering on icy bodies





Europa Ganymede Callisto Mars

Wide range of crater morphologies observed on icy satellites

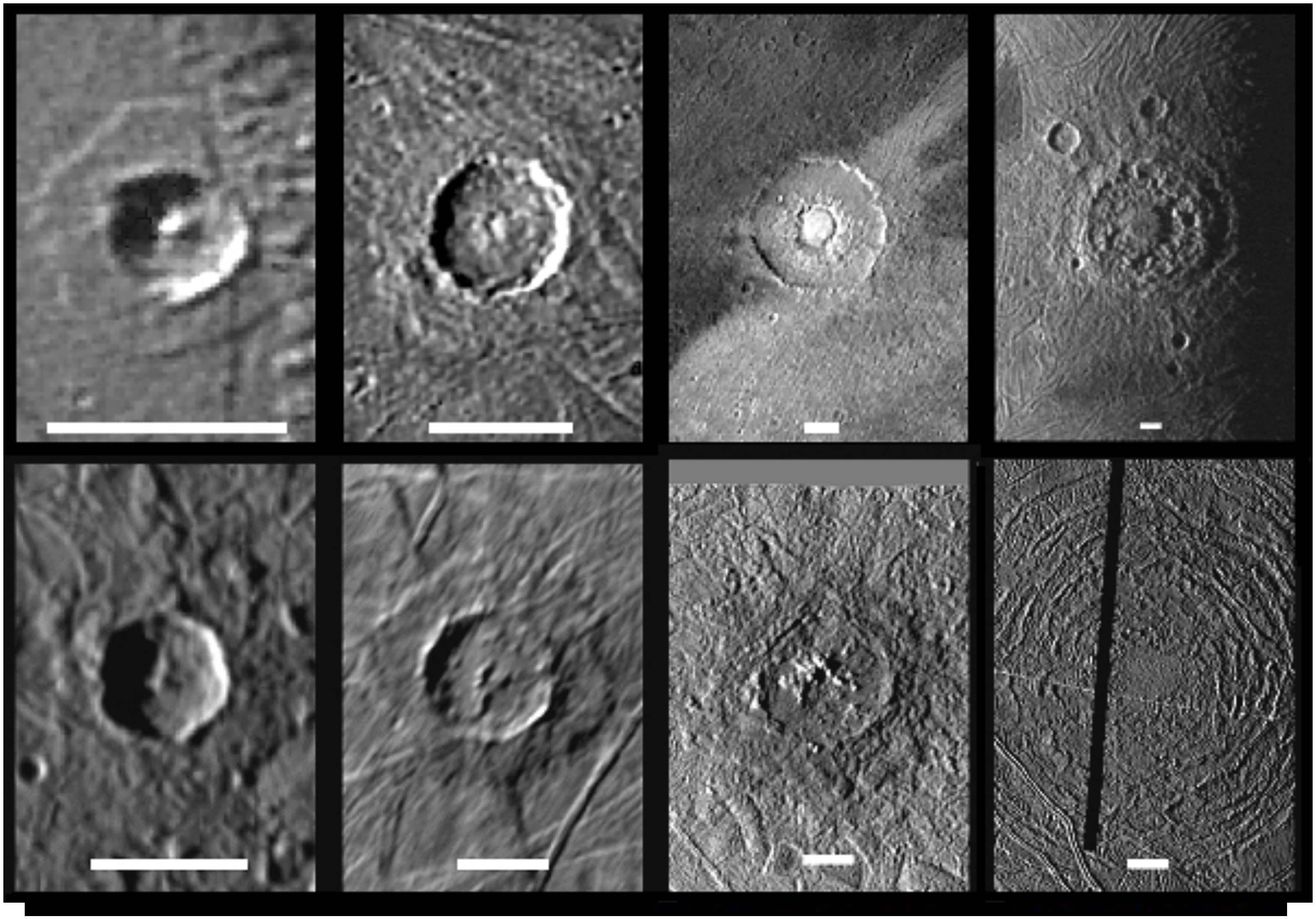
Ganymede & Callisto

30 km scale bar

Europa

10 km scale bar

Schenk 2002



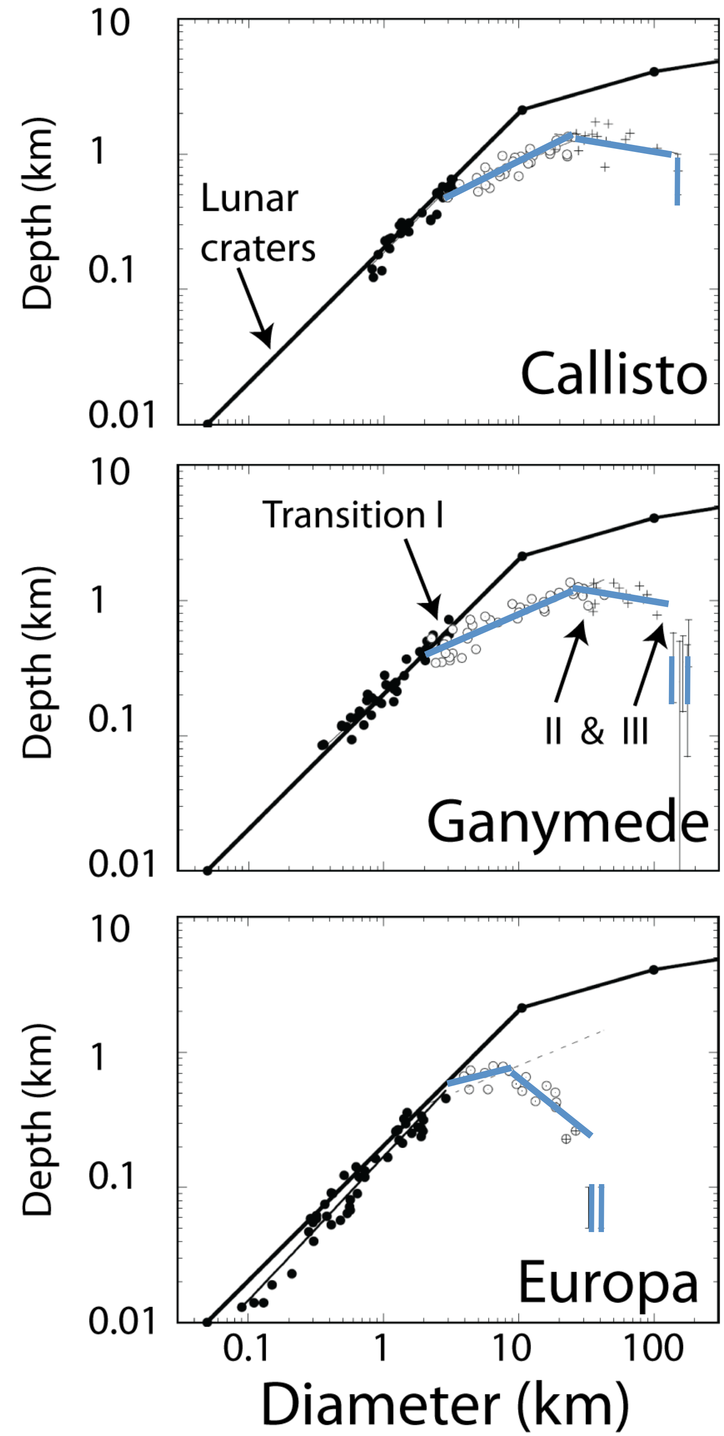
Icy crater morphologies

Transition I: Simple to complex craters

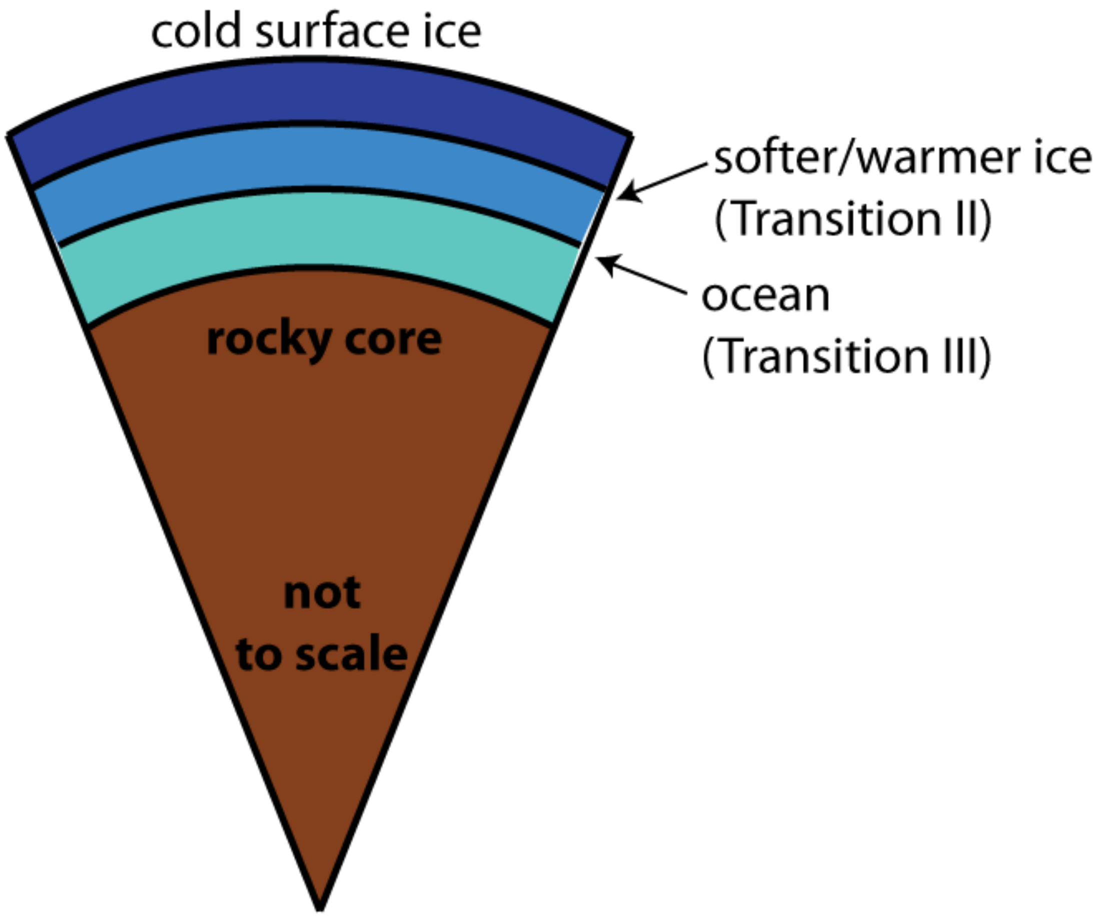
Transition II: Complex to central pits & domes (on Callisto & Ganymede)

Transition III: Central pits & domes to anomalous domes and multi-ring basins

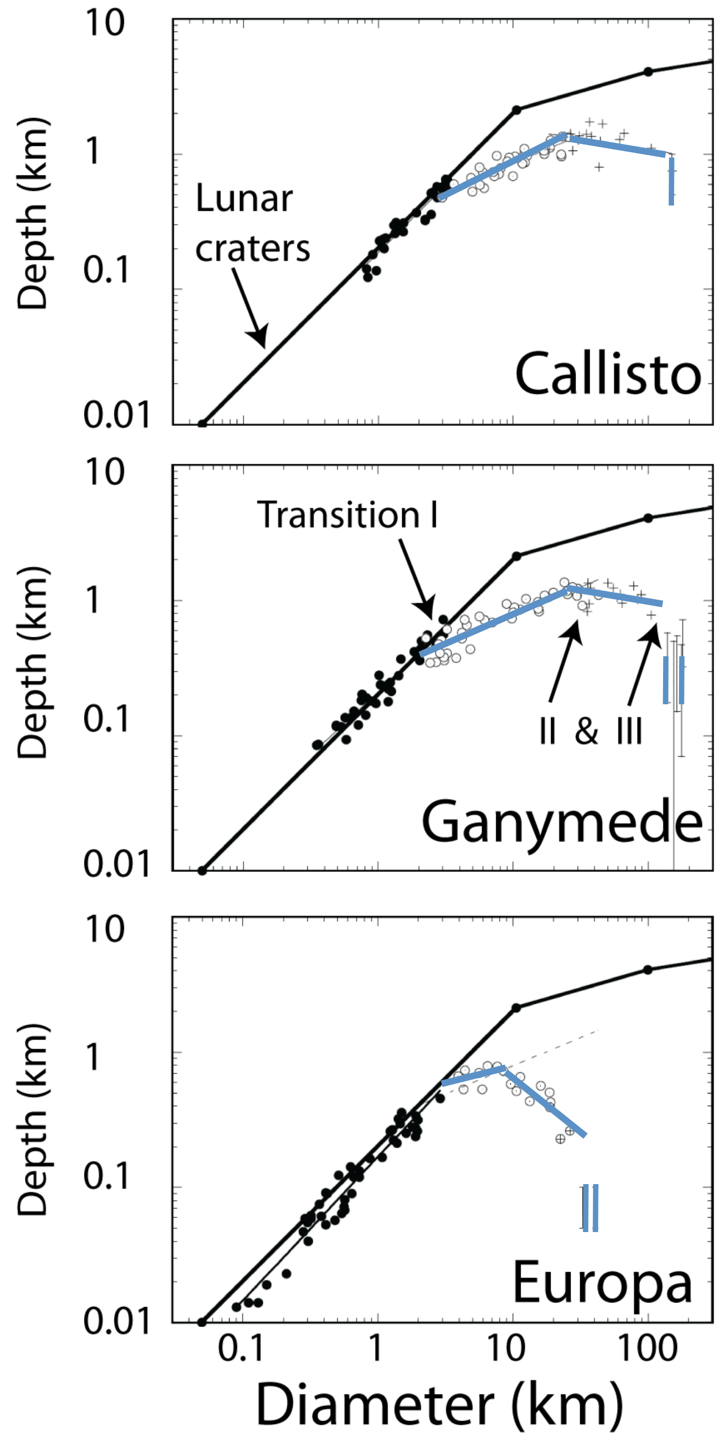
Schenk 2002



Interior structure inferred from craters



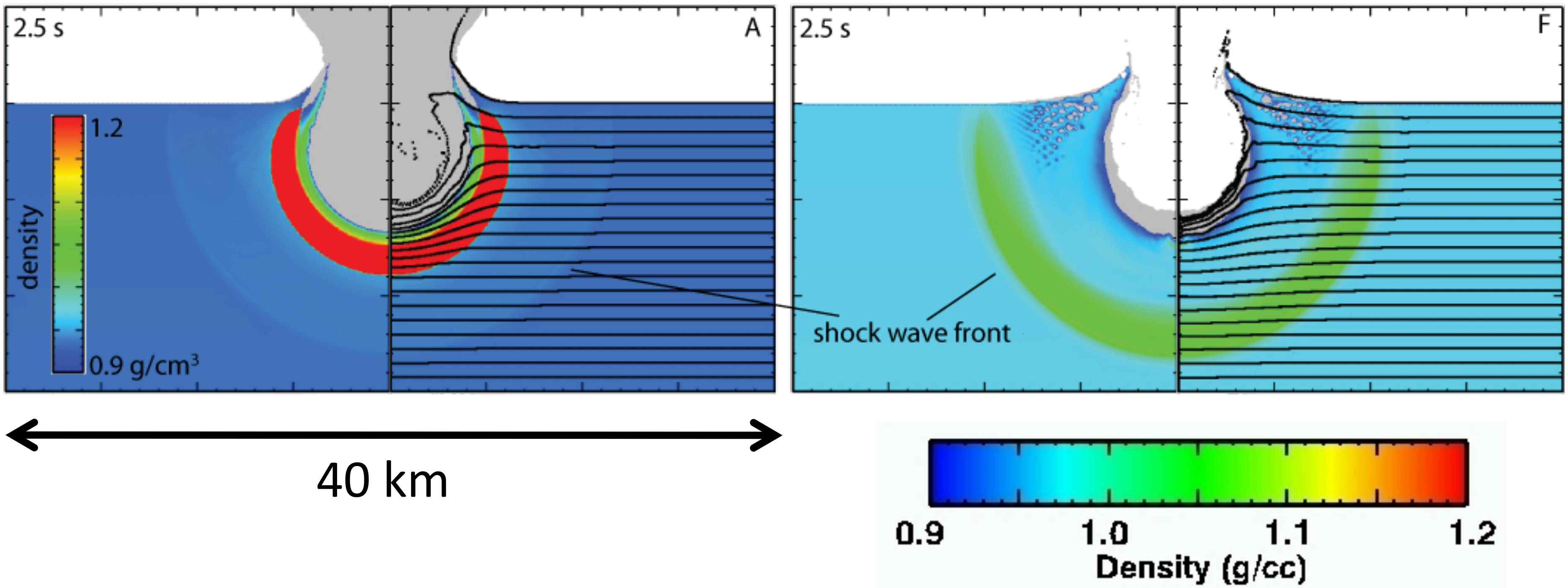
Schenk 2002



Cratering simulations with the 5-phase H_2O equation of state (EOS)

5-Phase EOS

Simple single phase EOS

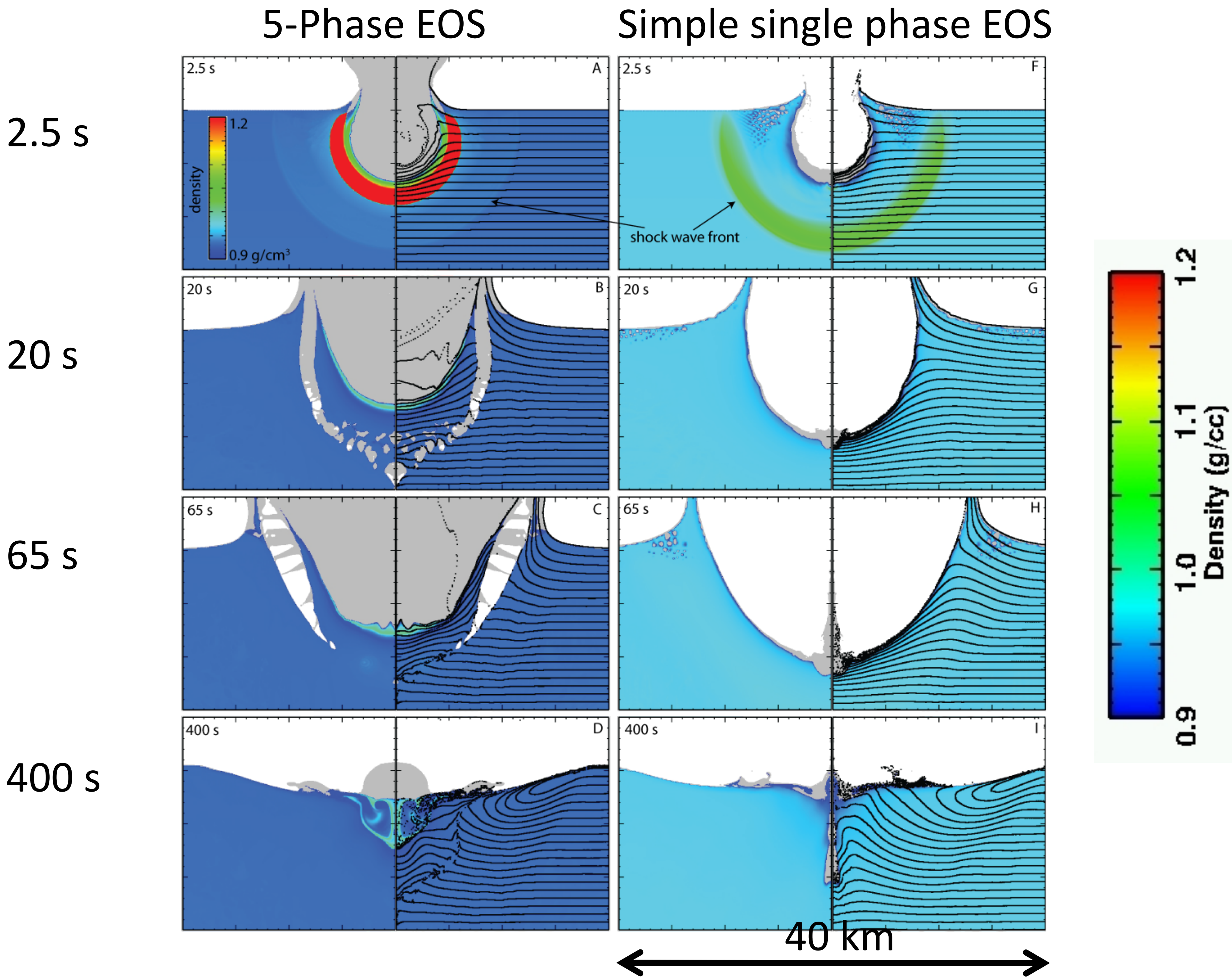


D=2 km, V=15 km/s, T=120 K, Ganymede gravity

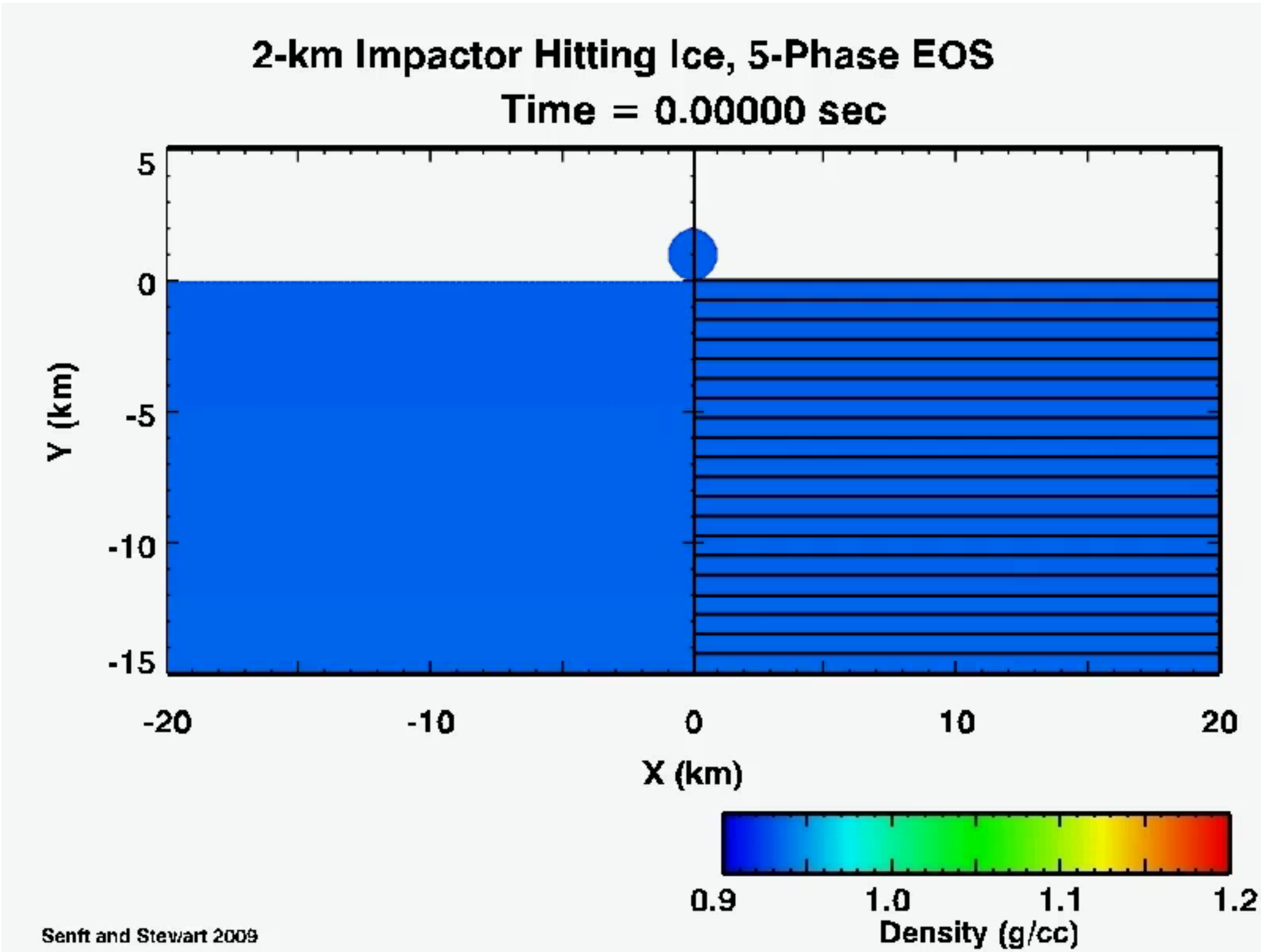
Black points are Lagrangian tracer particles

Gray density <0.9 g/cm^3

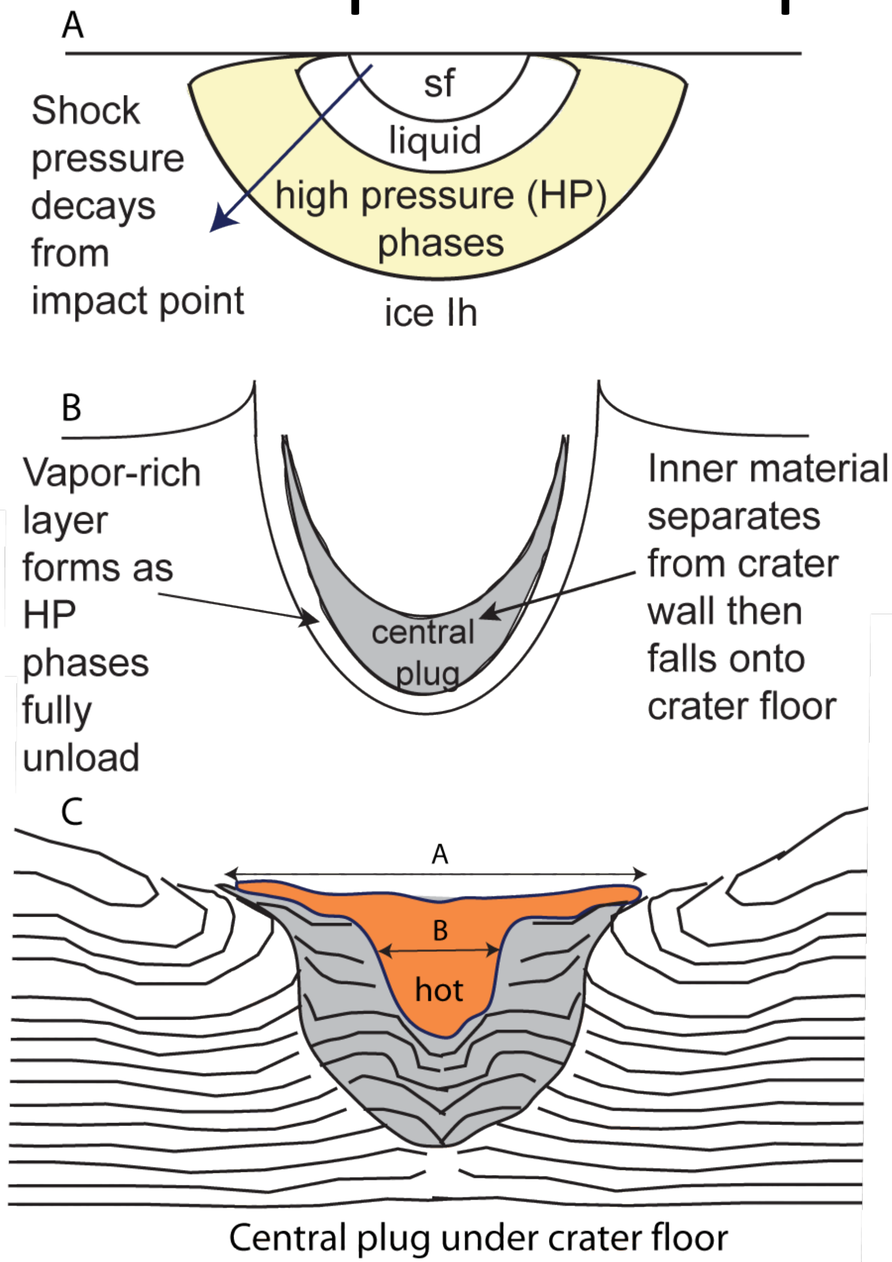
Senft & Stewart, in revision



5-Phase EOS
Simple single phase EOS
2.5 s
20 s
65 s
400 s
A
B
C
D
F
G
H
I
1.2
density
0.9 g/cm³
shock wave front
40 km
0.9
1.0
1.1
1.2
Density (g/cc)

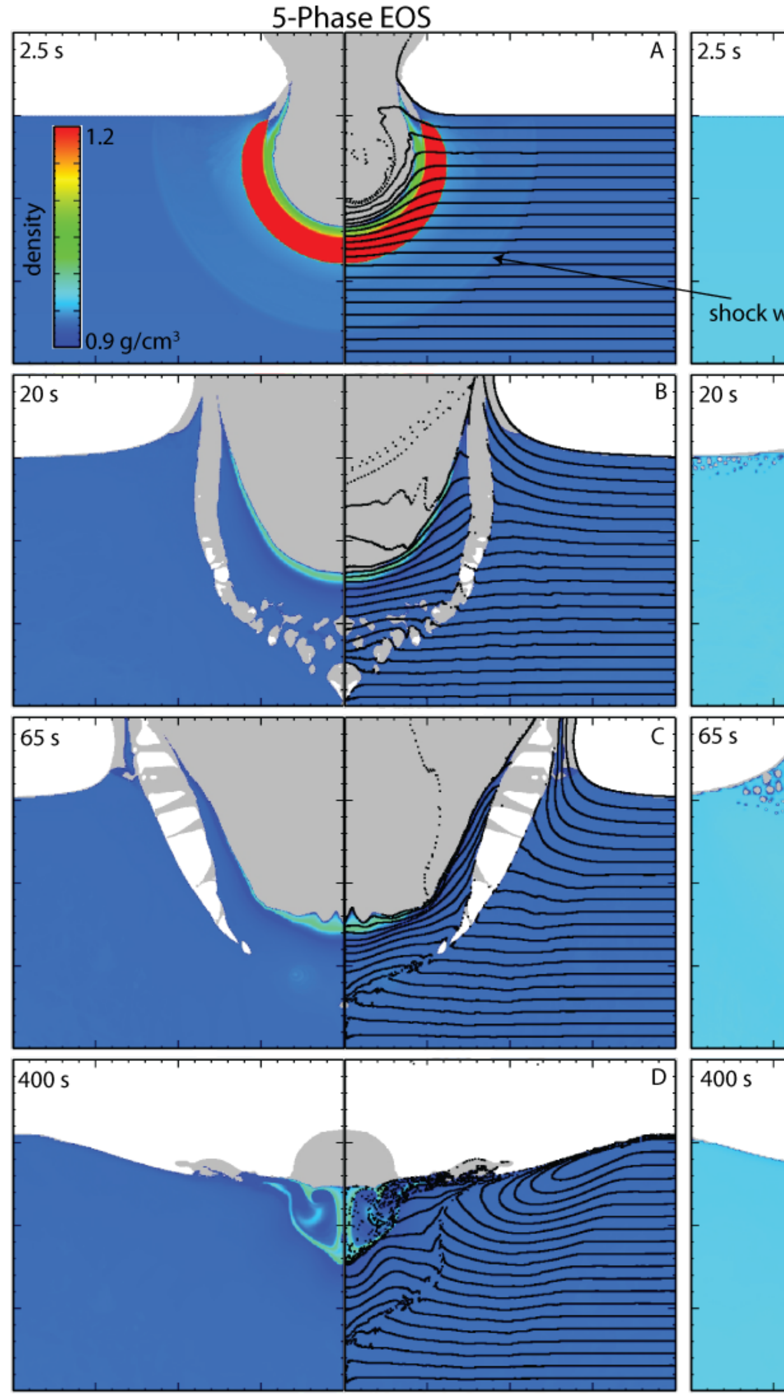

2-km Impactor Hitting Ice, 5-Phase EOS
Time = 0.00000 sec
5
0
-5
-10
-15
Y (km)
-20
-10
0
10
20
X (km)
0.9
1.0
1.1
1.2
Density (g/cc)
Senft and Stewart 2009

Central feature is a product of phase changes

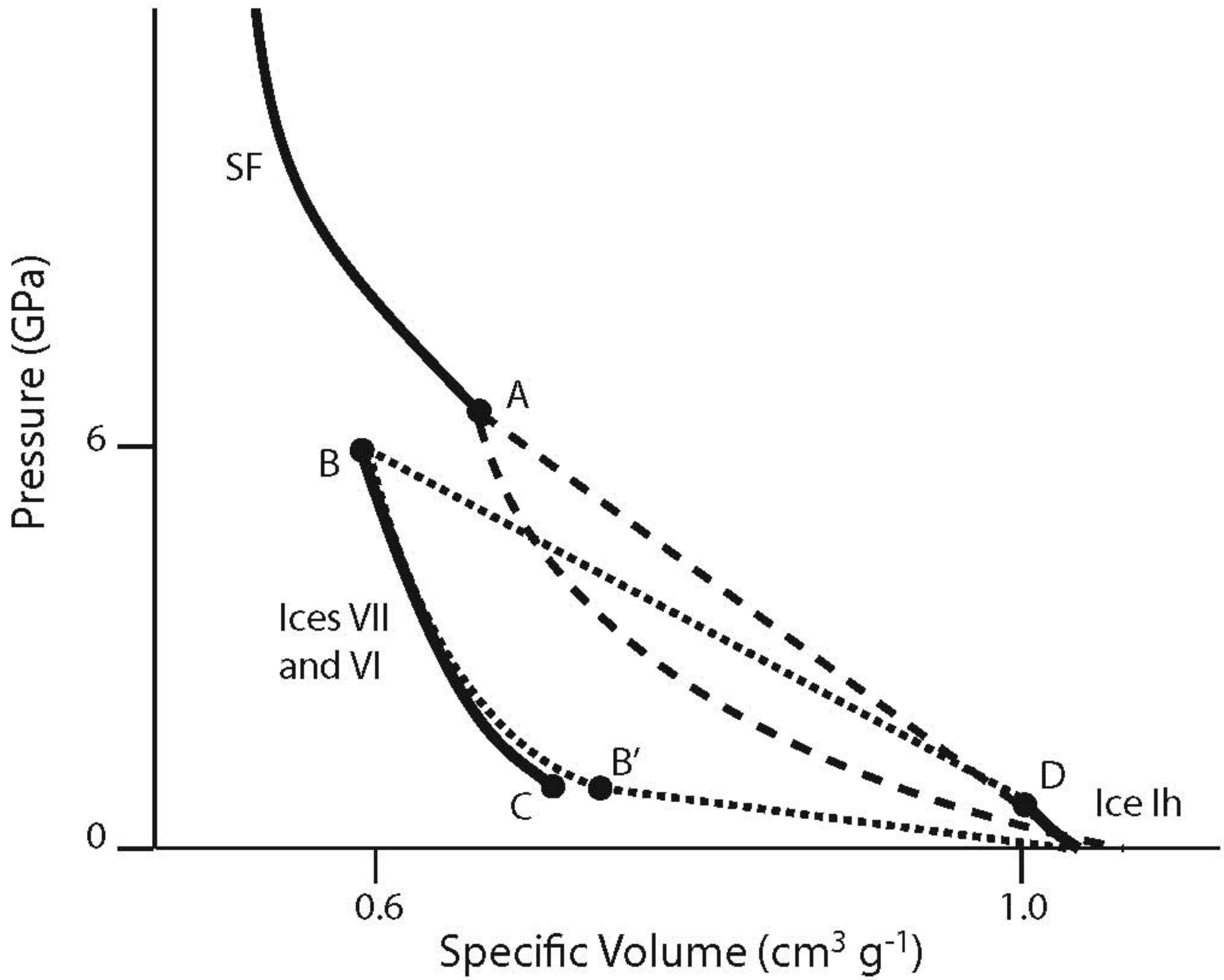


Phase changes in ice leads to *discontinuous excavation*

- Ice is shocked to different phases with distance from impact
- Different unloading paths leads to a discontinuity in material velocities
- Most highly shocked material is slower – it is concentrated within the collapsing crater
- Shock-induced phase changes modify the dynamics of excavation flow

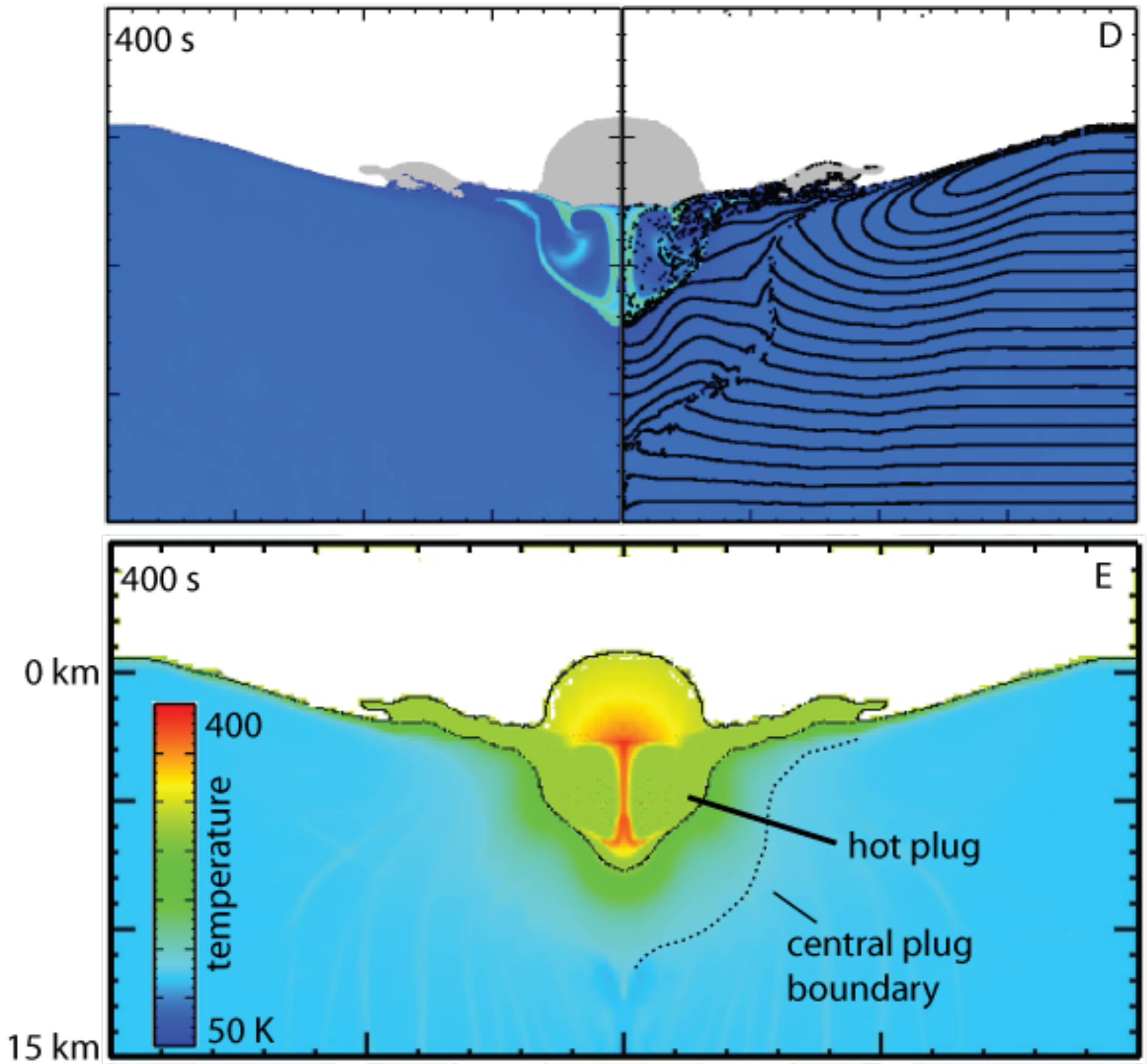


Different Loading and Release Paths

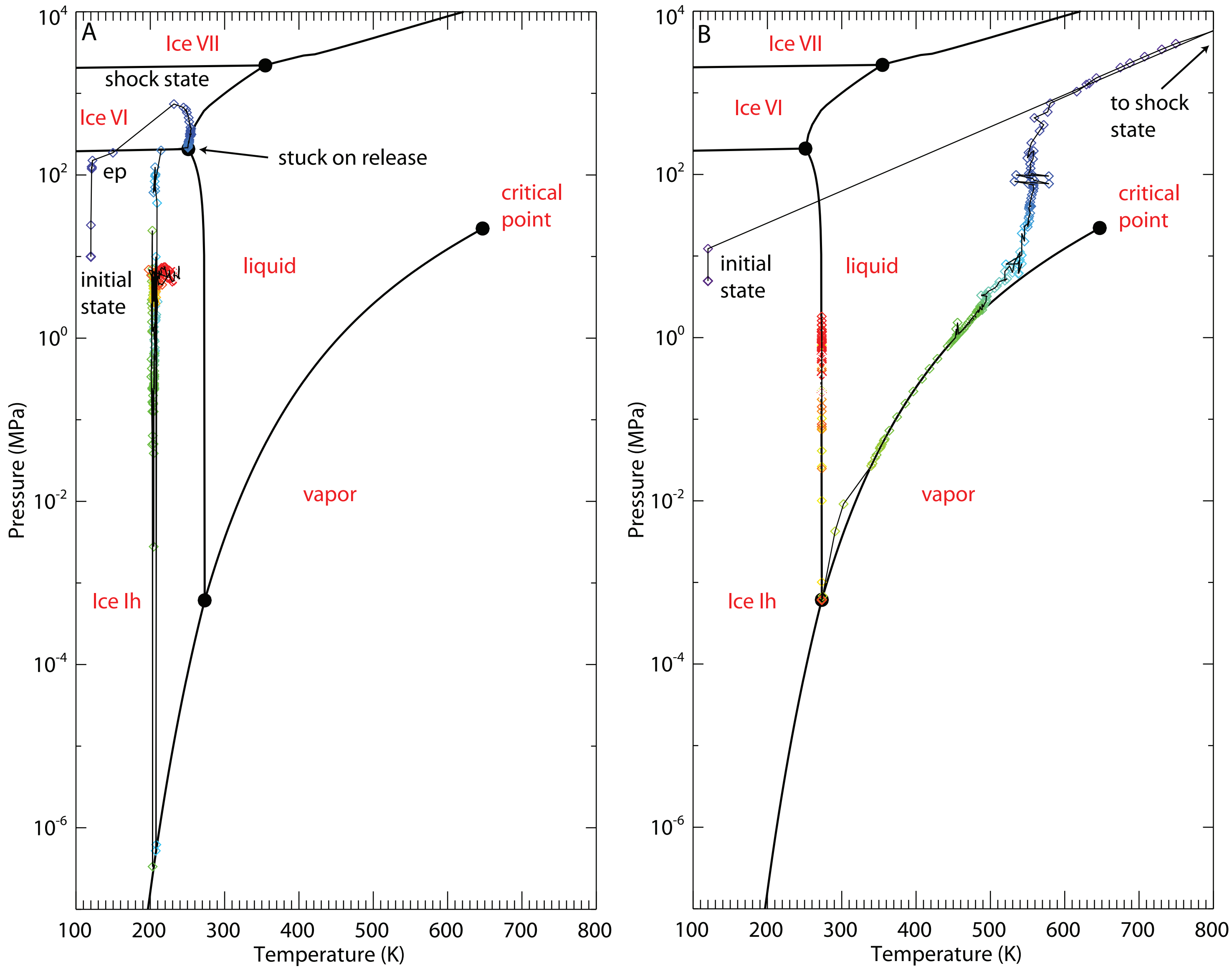


Central feature is a product of phase changes

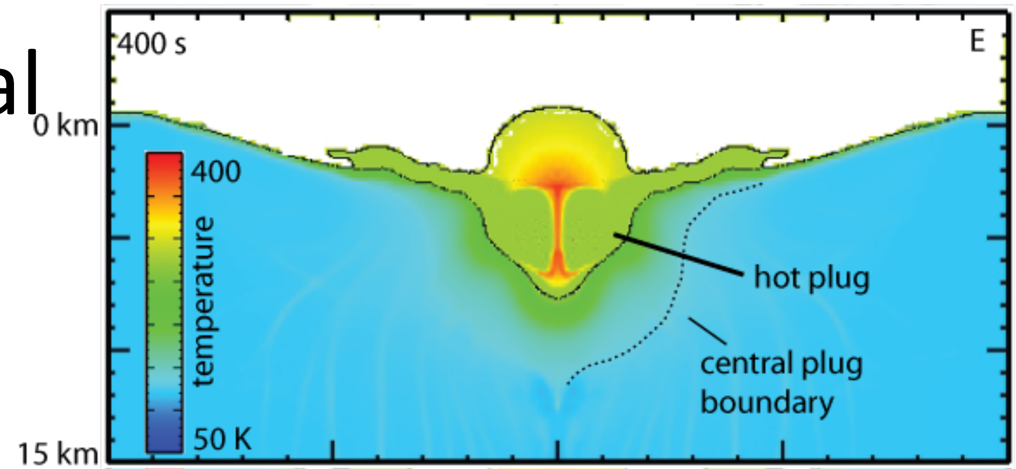
Ice at the melting point is concentrated in crater floor

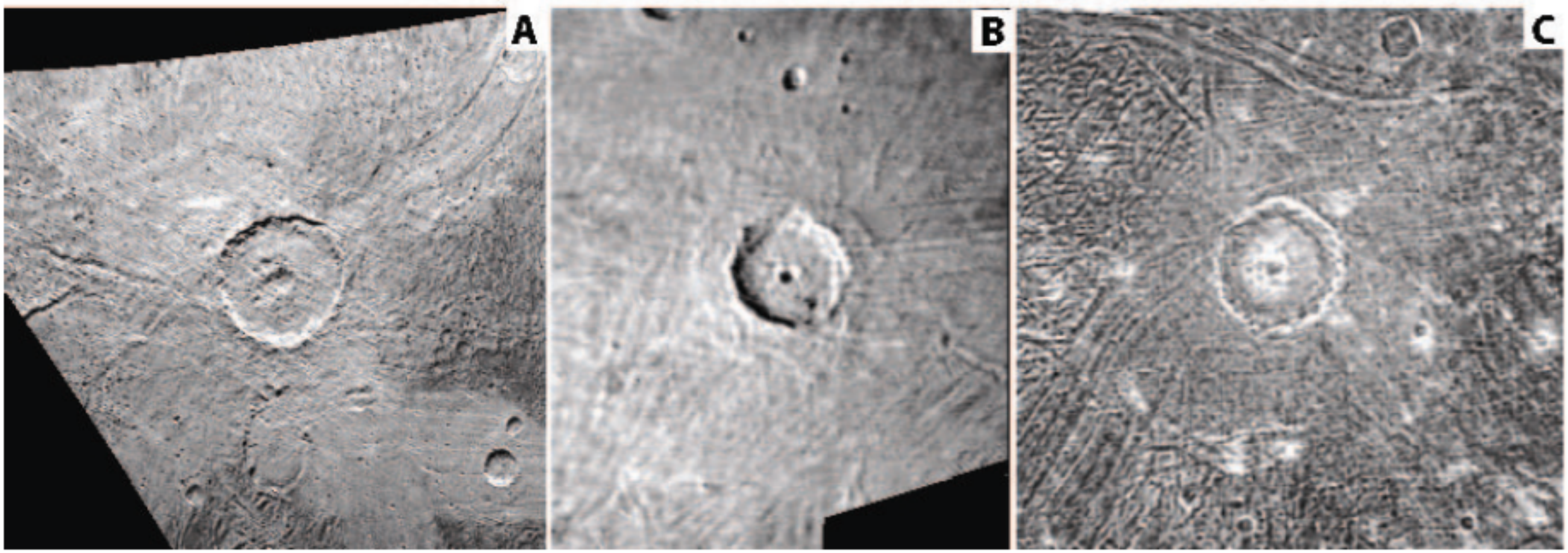


Thermodynamic Paths



Is there observational support for discontinuous excavation?

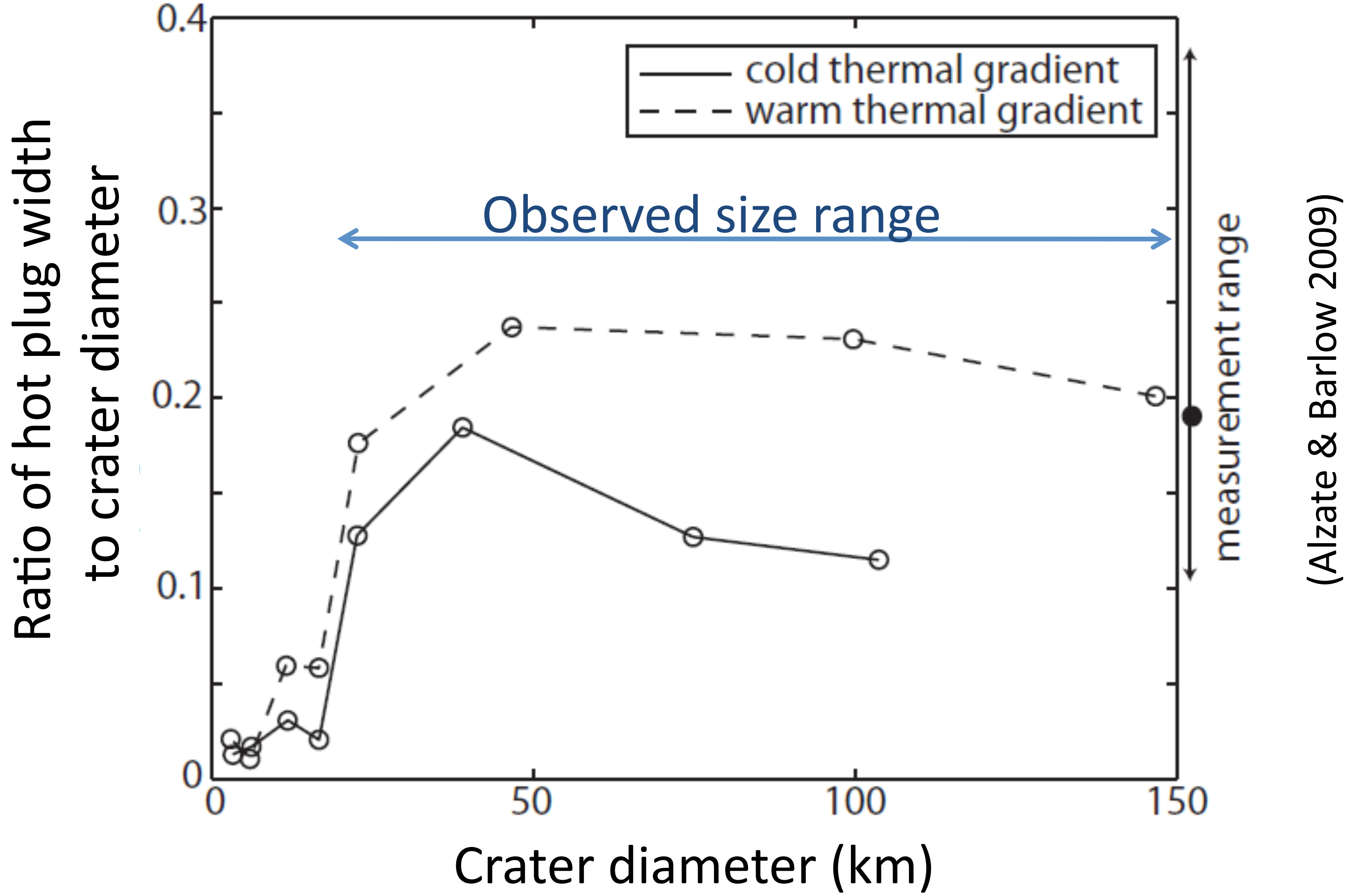




D=73 km D=64 km D=62 km

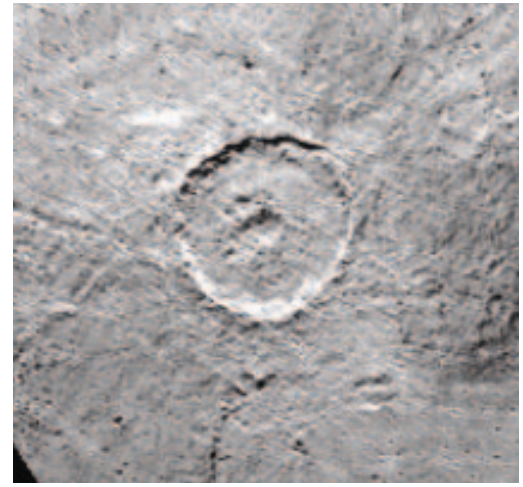
Central pit craters on Ganymede and Callisto

Hot plug diameter and size range agree with central pit crater observations



Discontinuous excavation not significant in small craters (small volume shocked to high pressure solid phases).

Discontinuous excavation and the origin of central pit/dome craters?



Width of hot plug is same as central pits

Size range of craters with hot plugs same as central pits
(about 25-150 km diameter)

Pits observed on Callisto & Ganymede but not other icy
satellites (resurfacing or not enough melted material)

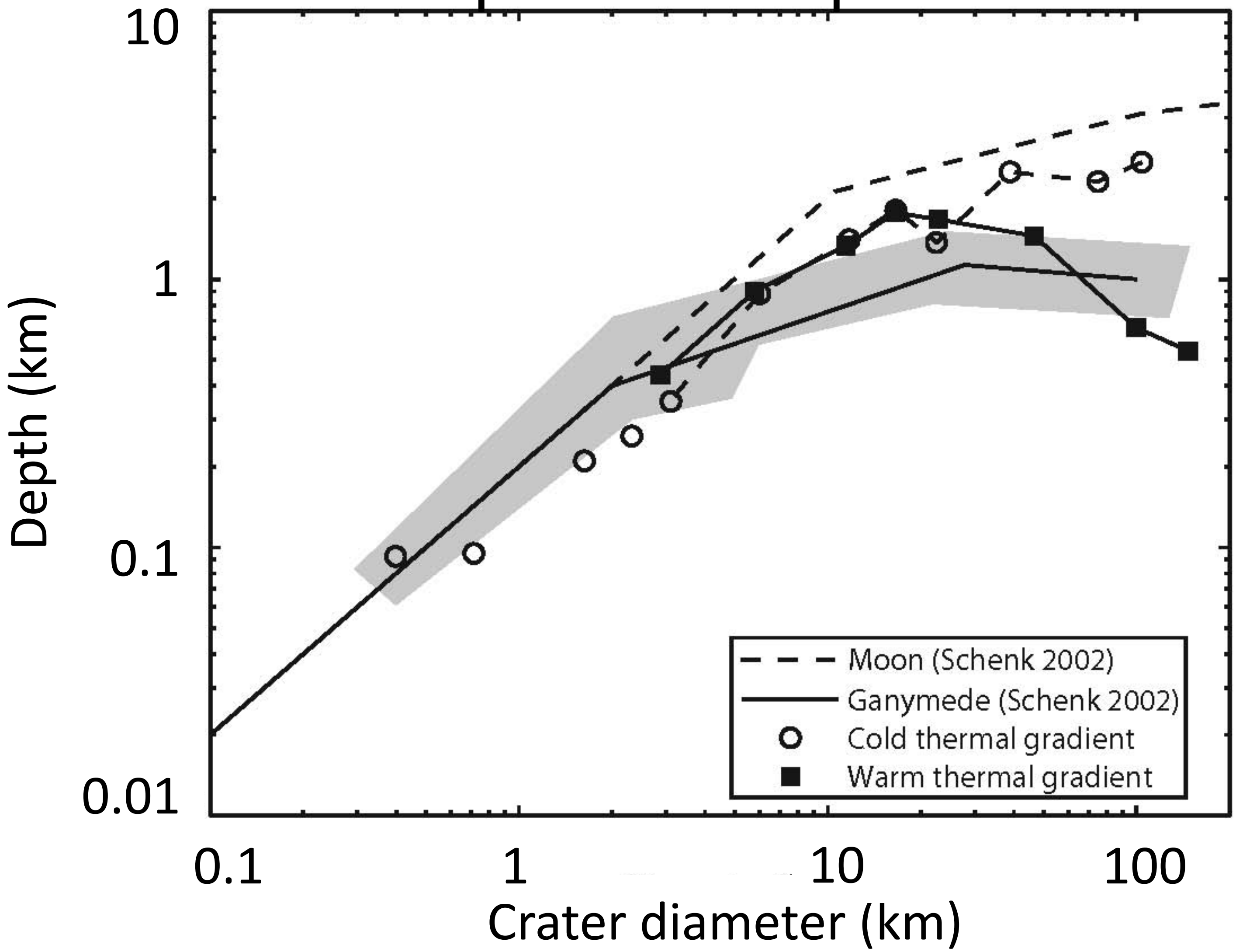
Expect variations with impact velocity
Less melt at very low and very high impact velocities

(Do not expect central pits on Pluto)

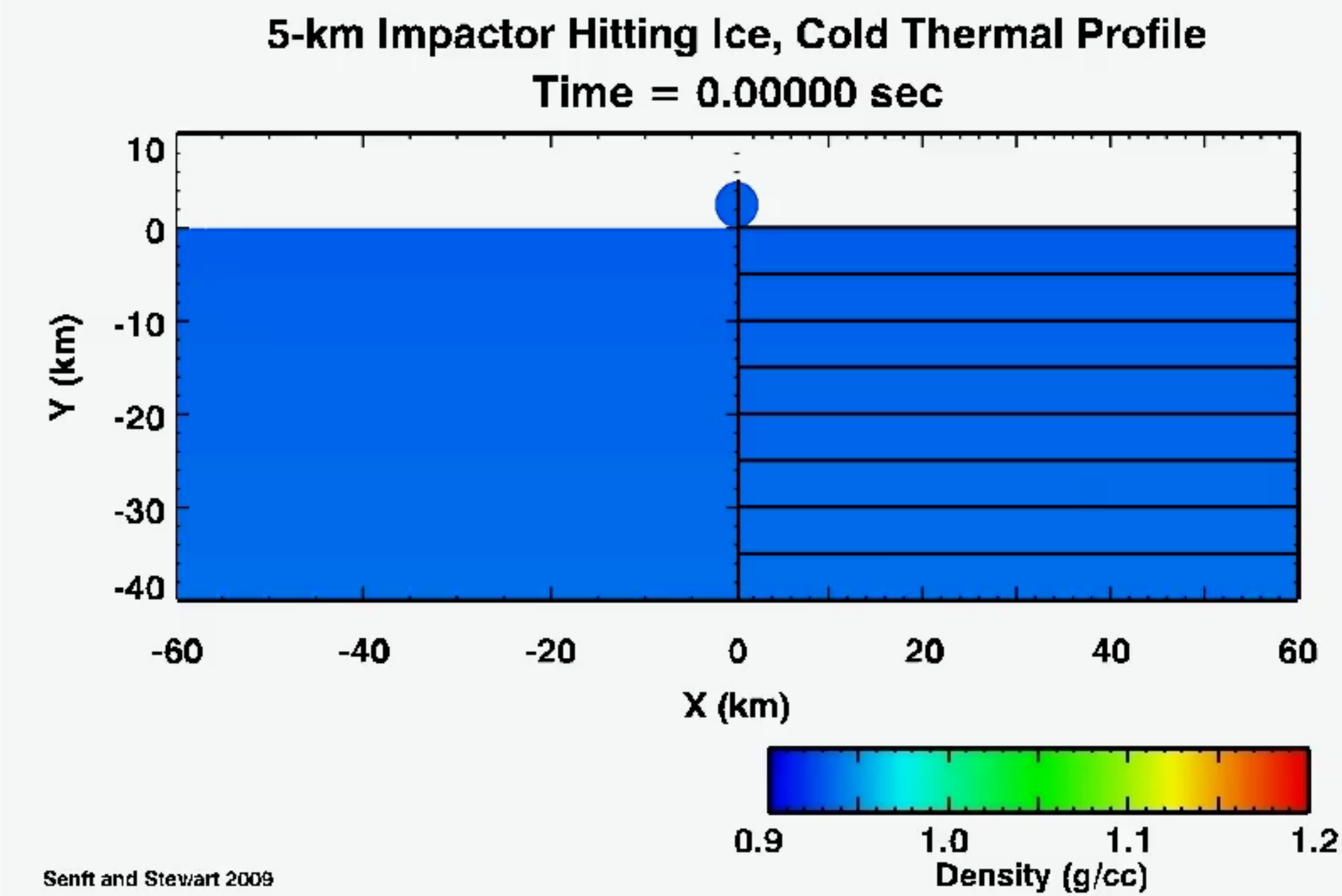
Hot plug evolution into a pit/dome is TBD

Ganymede & Callisto depth vs. diameter

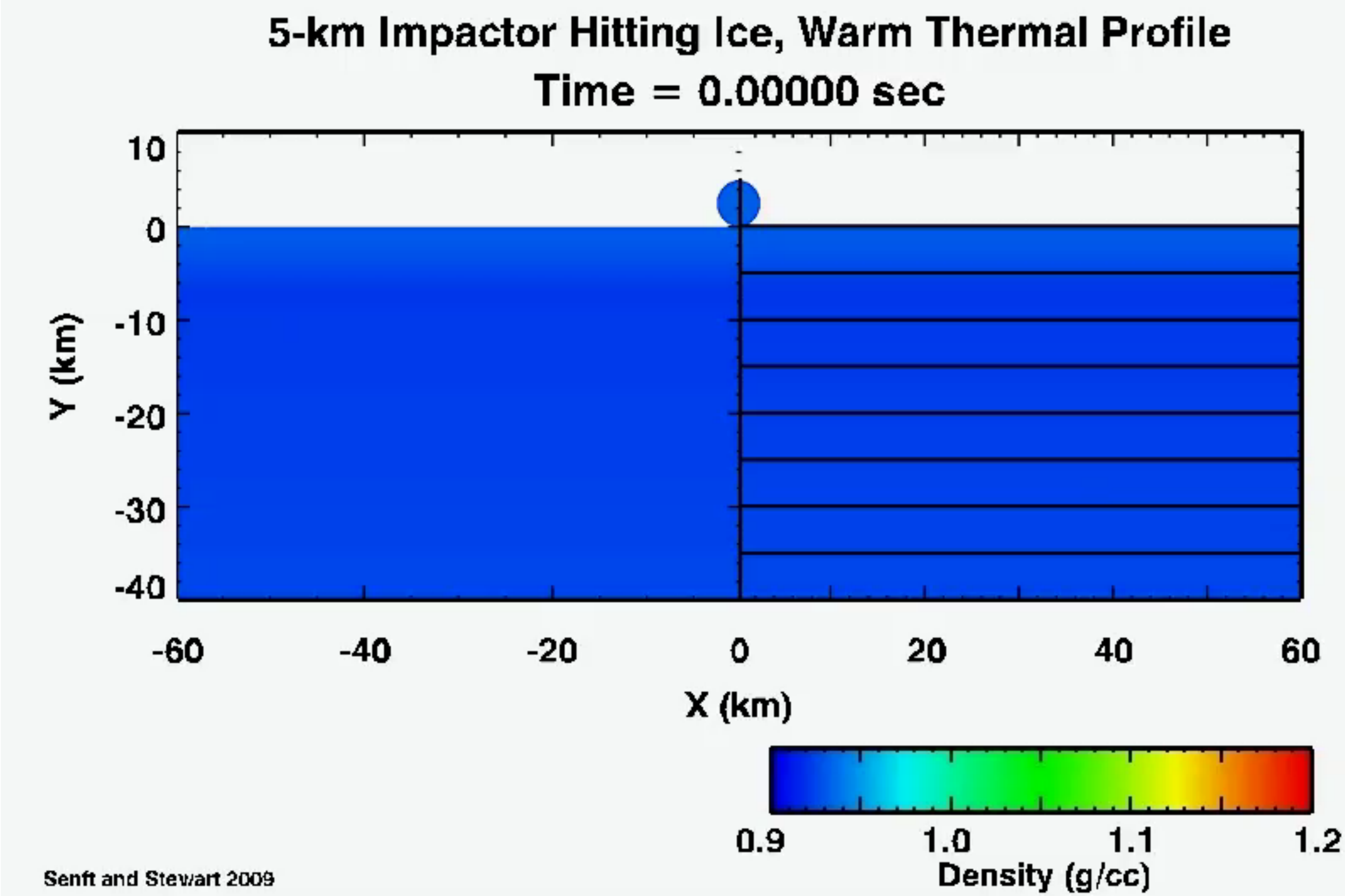
Warm thermal profile leads to negative slope because of temperature dependent strength

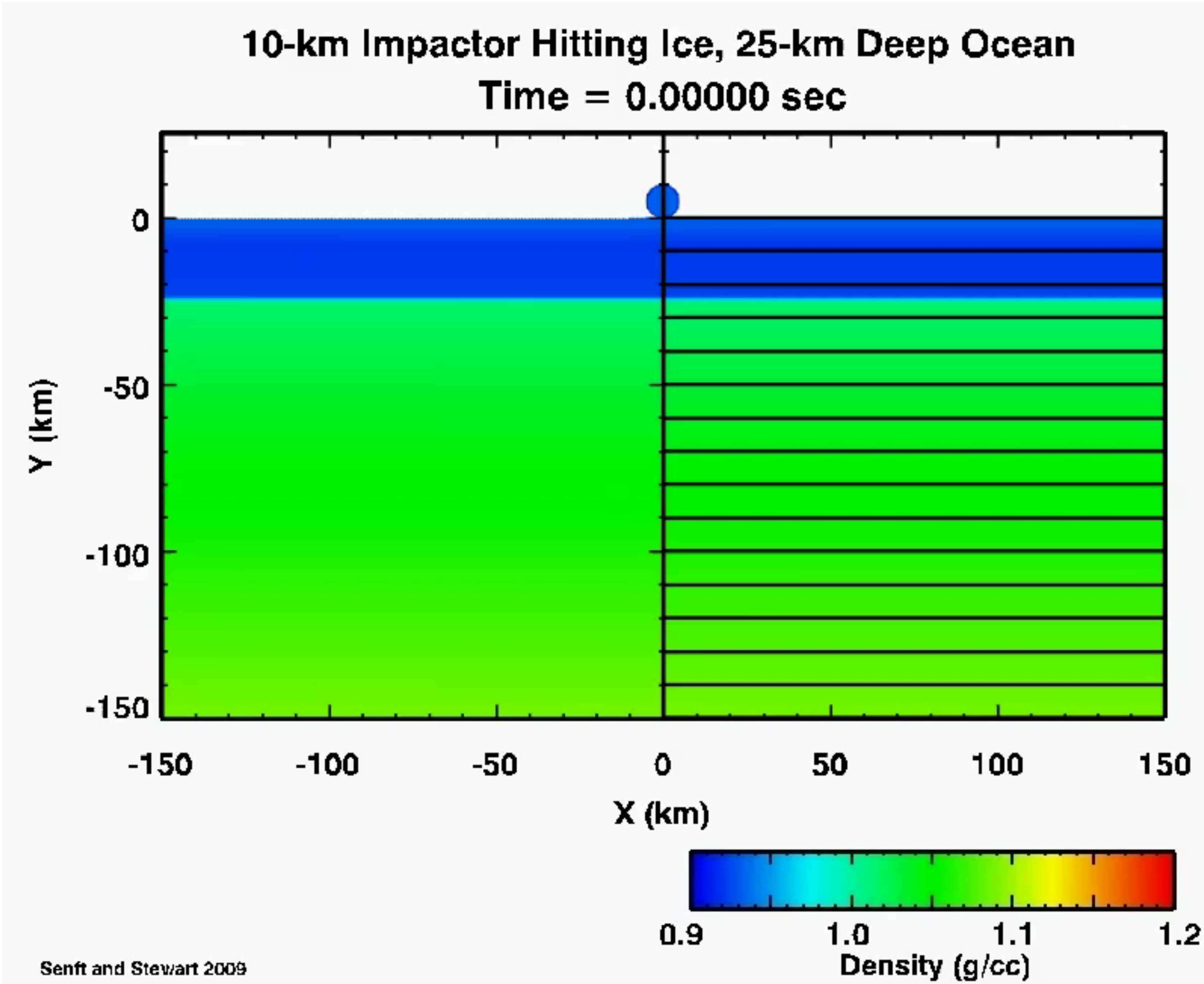


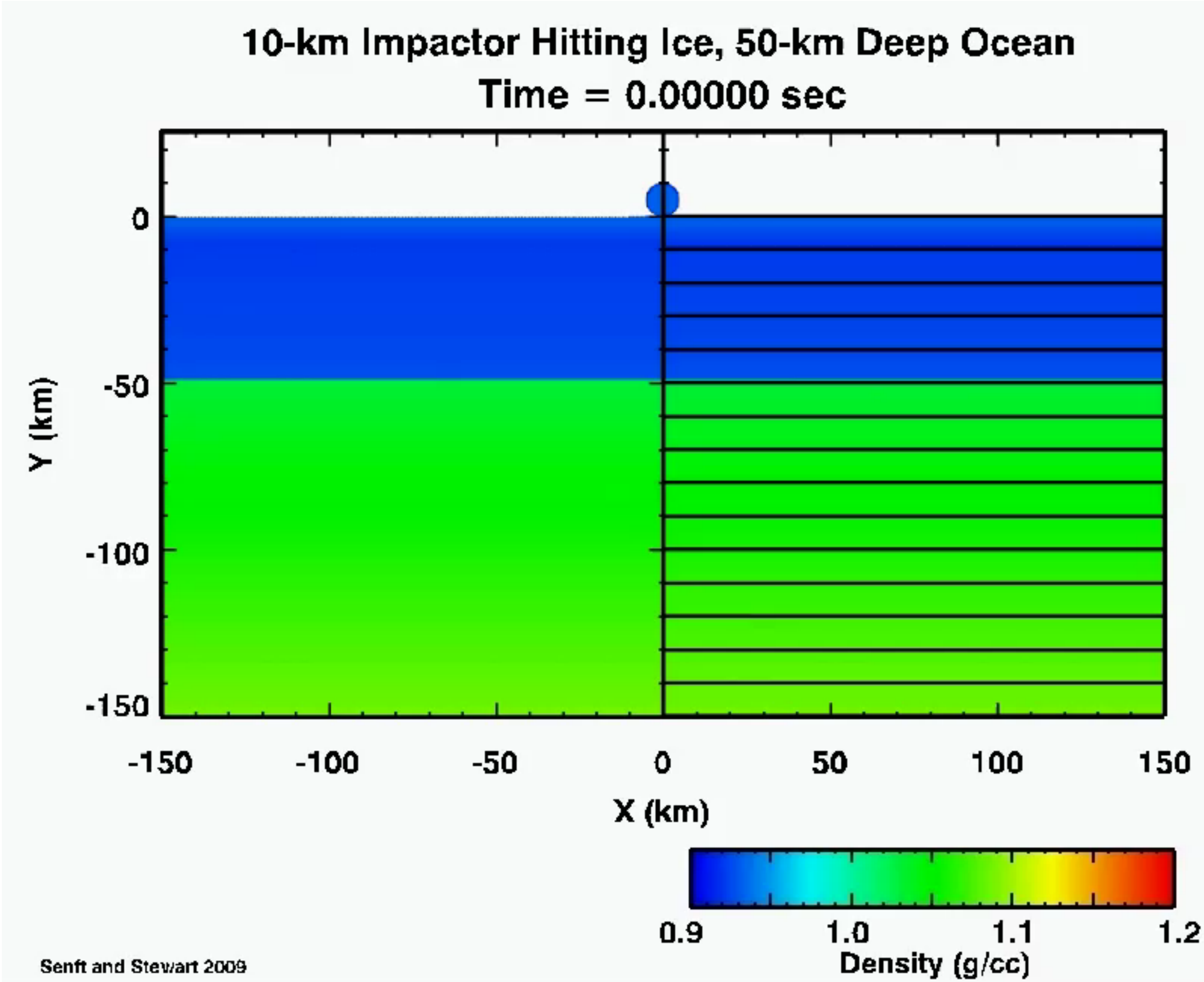
~100 km diameter crater



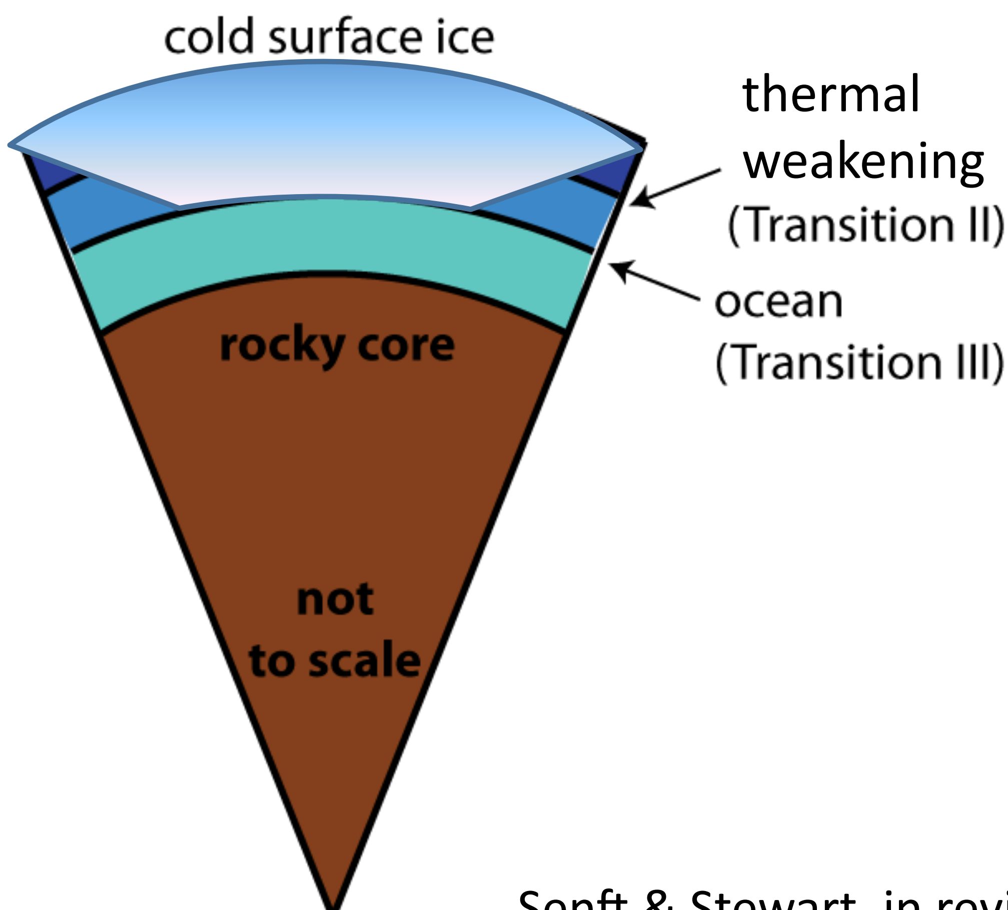
~145 km diameter crater



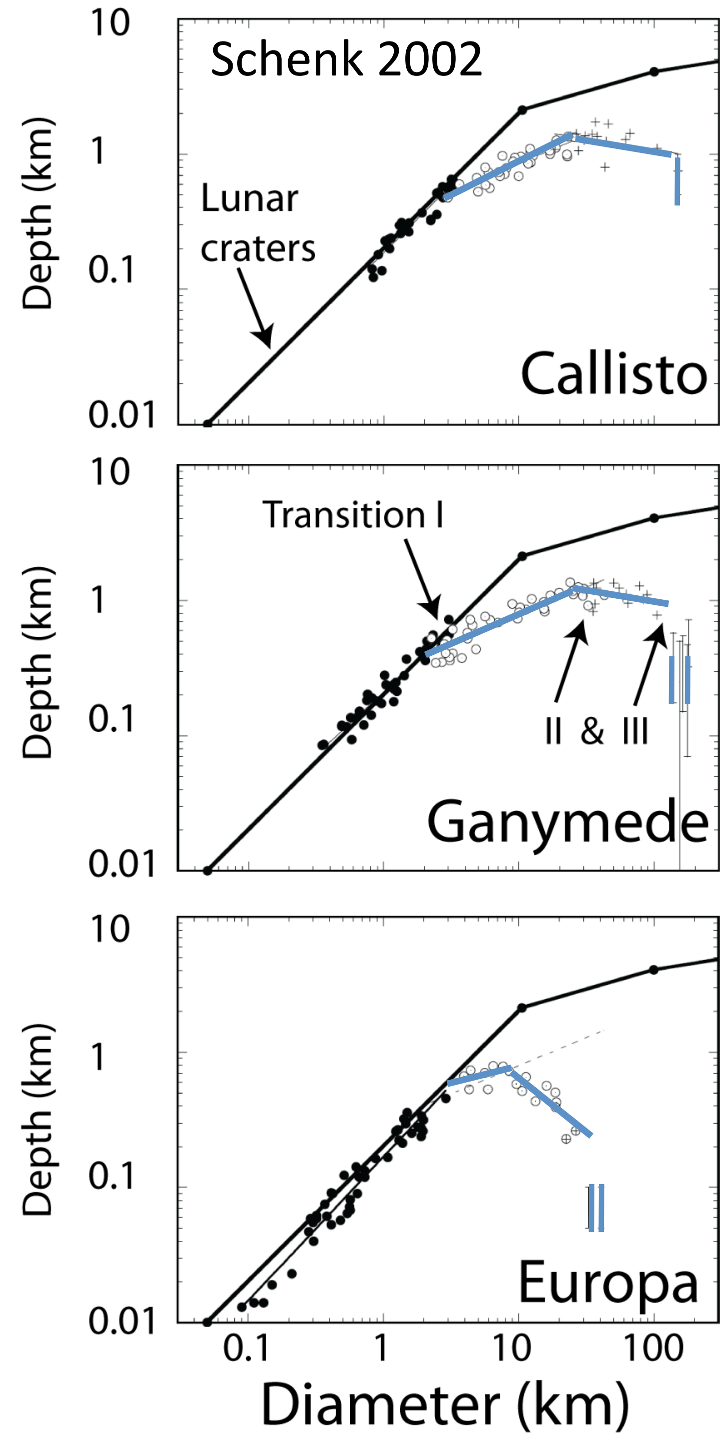

10-km Impactor Hitting Ice, 25-km Deep Ocean
Time = 0.00000 sec
0
-50
-100
-150
Y (km)
-150
-100
-50
0
50
100
150
X (km)
0.9
1.0
1.1
1.2
Density (g/cc)
Senft and Stewart 2009


10-km Impactor Hitting Ice, 50-km Deep Ocean
Time = 0.00000 sec
0
-50
-100
-150
Y (km)
-150
-100
-50
0
50
100
150
X (km)
0.9
1.0
1.1
1.2
Density (g/cc)
Senft and Stewart 2009

Explanations for the observed morphologies on icy satellites

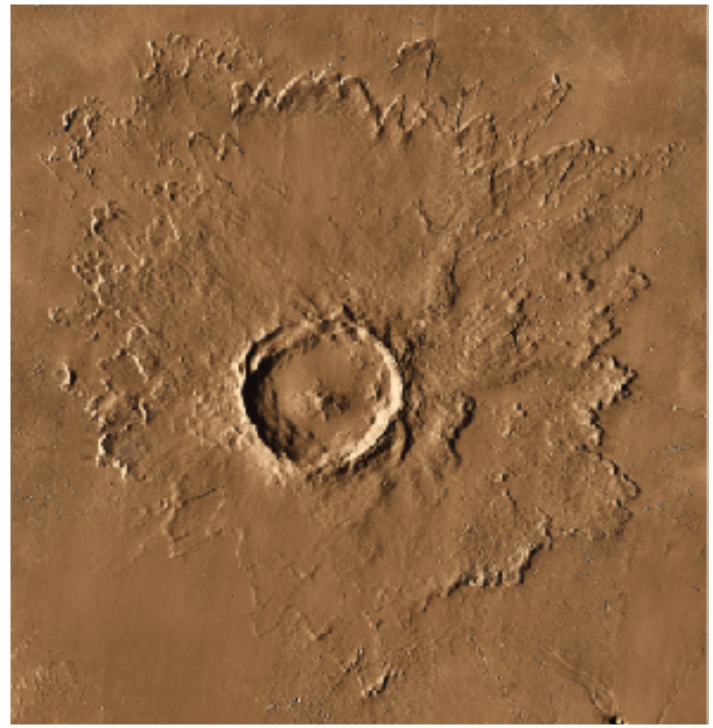


Senft & Stewart, in revision



And Mars.....

Central pit crater



Layered ejecta blanket

Layered subsurface on Mars (Senft & Stewart 2008)
Melting ice in a mixture (Rick Kraus' talk)

Conclusions

- H_2O is full of surprises!
- Laboratory data + modeling led to discovery of a new phenomena: discontinuous excavation
  - Phase transitions change the dynamics of impact cratering
- Discontinuous excavation leads to formation of a hot plug in center of crater floor
  - Hot plug characteristics similar to central pits
- Decreasing crater depth with increasing diameter
  - Thermal weakening from a thermal gradient

Icy crater morphology explained up to size range where subsurface oceans become important*