# Shock Effects in Meteorites I: Basic Shock Physics

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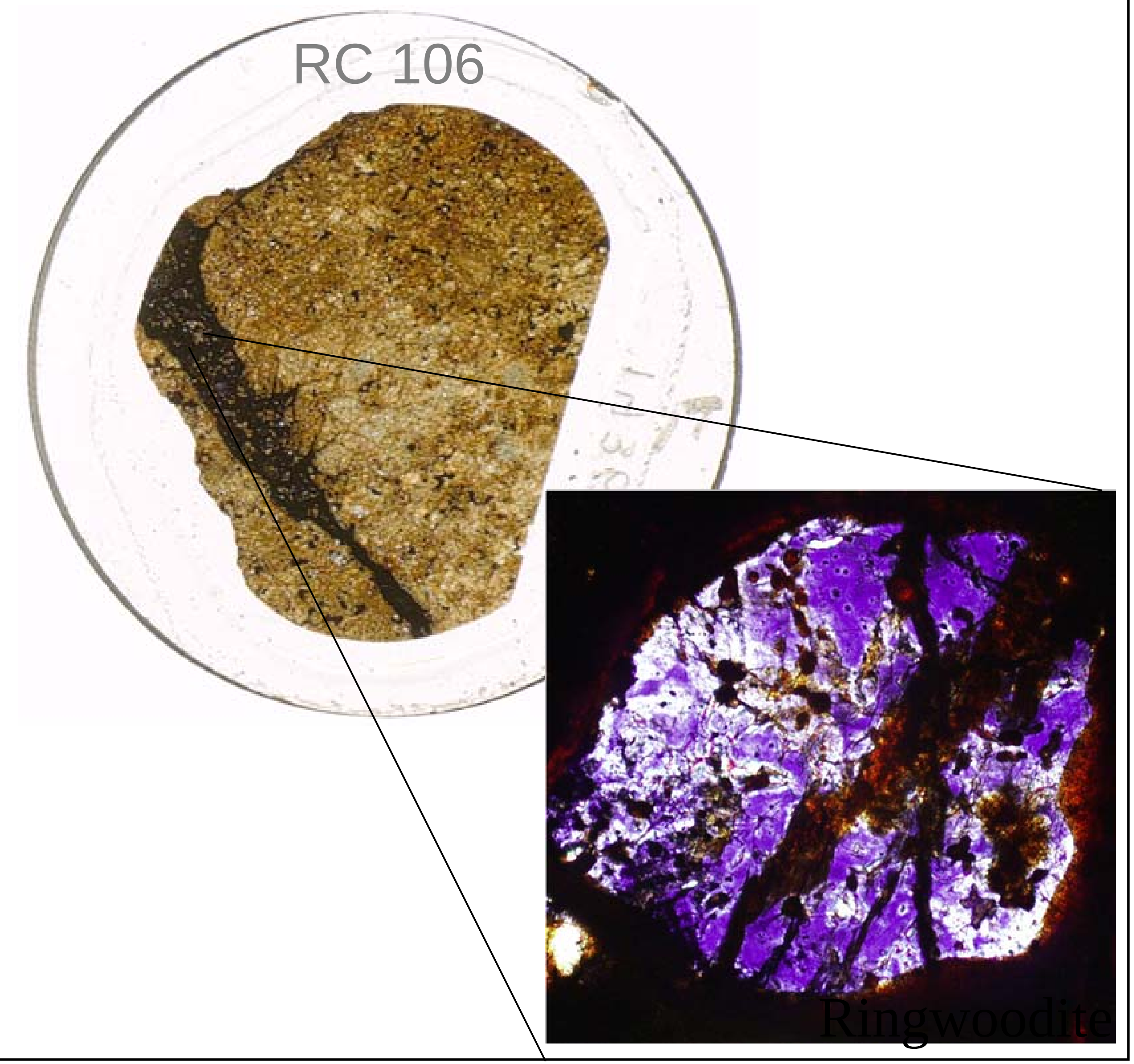
# Outline

- Introduction
- The Rankine Hugoniot Equations
- Shock loading, release and waste heat
- The effect of porosity
- Phase transitions
- Shock reflections and loading path
- Shock collisions
- Shock heterogeneity and local P-T excursions.
- Some conclusions
- Working with and synthesizing Hugoniots
- 3-D Hydrocode calculations

# Shocked Chondrites

- Most chondrites are shocked
  - Shock-induced deformation and transformation
  - Shock-induced melting causes black shock veins
- Impact shock is an important part of parent body processing.
  - It may be an important heat source for metamorphism (Rubin, 2004).



# Impact history of the Solar System

- Collisions between meteorite parent bodies cause shock.
  - Transient high pressure and temperature state
- Shock features record the impact history
  - How big were impacts?
    - Shock pressure is related to relative velocities.
    - Shock duration is related to impactor size.

# The Big Questions

- How big were the collisions that caused the shock effects that we see in meteorites?
  - Shock pressure provides constraints on minimum relative velocity of the impact.
  - Shock pulse-duration provides constraints on minimum size of the impacting body.
- When did these impacts occur?
- The answers come from the samples.

“If you knew anything about shock, you’d know you were wrong.”

Knowledge of shock physics is needed to understand shock effects

– Most shock physics texts are hard for geologists and mineralogists.

Purpose: Present basic concepts of shock physics so that we can interpret shock effects in meteorites and constrain shock pressure and temperature conditions.

# Background

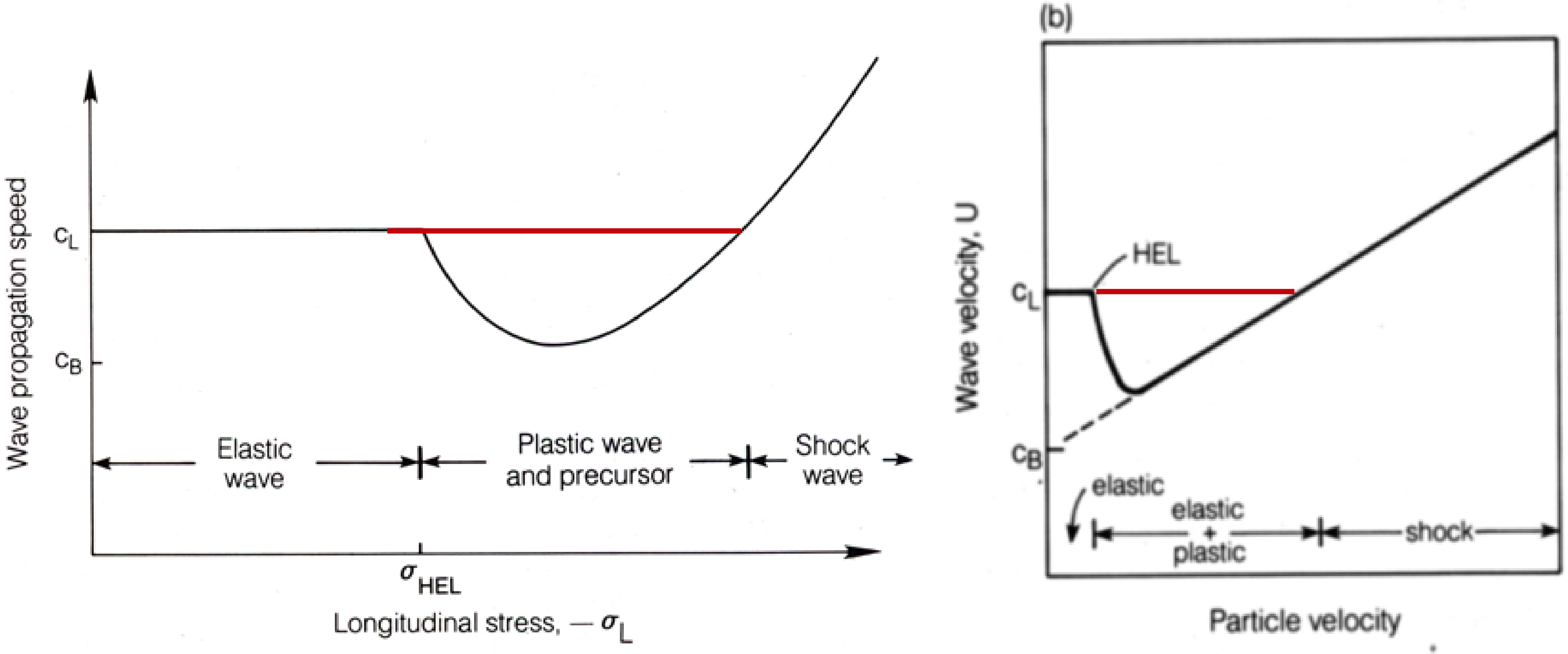
- Interest in shock since the invention of the cannon.
  - Military engineers need to understand shock in designing weapons and armor.
  - Nuclear weapons are shock devices.
- Physicists have been interested in understanding materials under extreme conditions.
  - Determine Equations of State at very high P
- Geologists and planetary scientists became interested in shock metamorphism in the 1960s.
  - Stishovite and coesite found at Meteor Crater

# Complex problems

- Shock effects in heterogeneous materials are very complex at the μm to sub-μm to scale
  - P-T conditions at the shock shock front are heterogeneous
  - Heterogenious metamorphism in shocked Coconino Sandstone (Kieffer, 1971, 1976)
  - Heterogeneous shock effects in meteorites: “local P-T excursions”
- 3-D calculations at meso-scales are possible (Baer and Trott, 2002, 2004)
- Simplify the problem by assuming that the material is homogeneous.
  - Average over larger scales and longer times.

# What is Shock?

- A compression wave with a velocity greater than the sound velocity for the material
  - Example: The bow shock of a supersonic aircraft
    - Sonic boom is the shock wave
  - Instantaneous increase in pressure, density, energy and velocity
    - Material behind the shock wave is accelerated to a characteristic particle velocity.




Melosch 1989

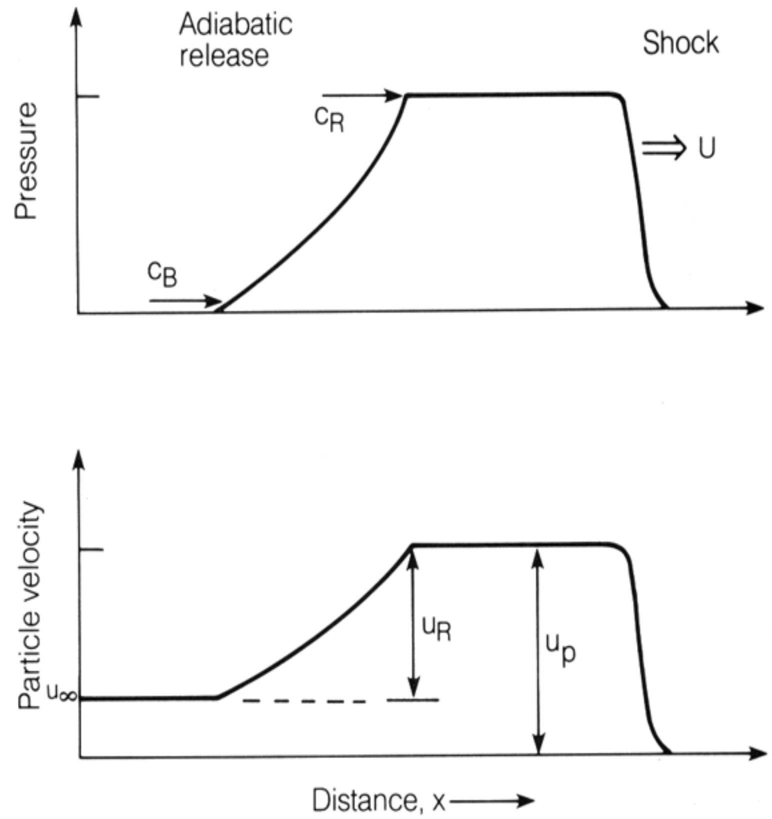
Elastic waves have a constant velocity

Plastic deformation occurs once the Hugoniot Elastic Limit (HEL) is exceeded.

Wave velocity decreases and then increases to shock.

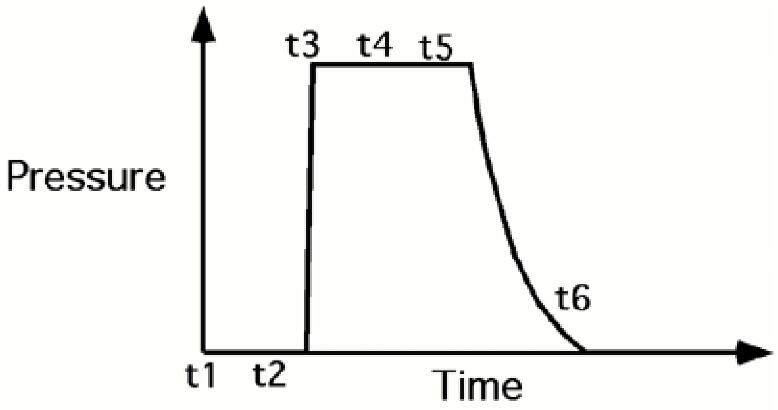
# Shock Pulse

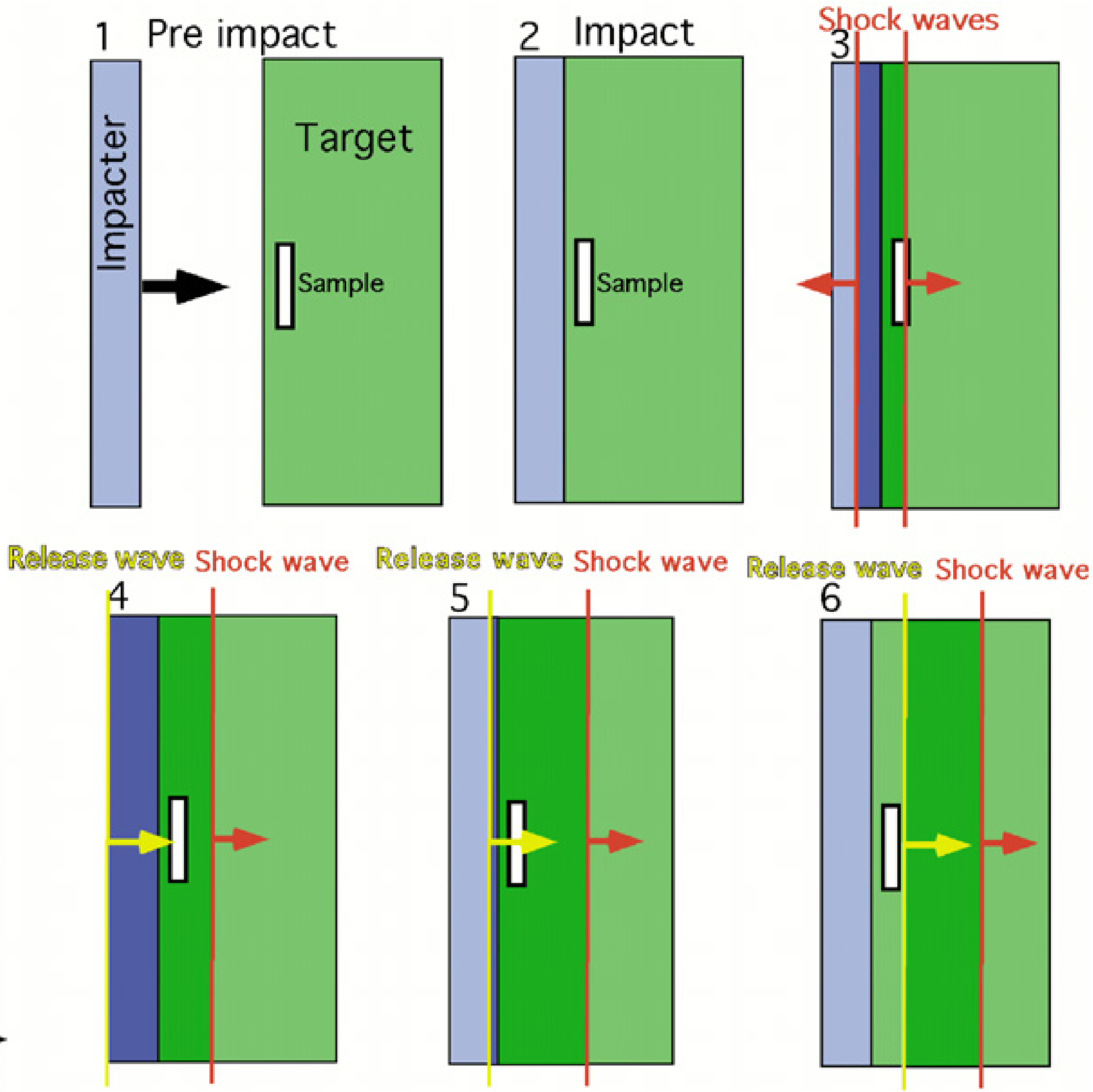
- Since wave speed increases with pressure, shock waves are abrupt.
- The shock pulse is the time between passage of the shock wave and the rarefaction (release) wave.
  - The release wave travels in compressed material and is faster than the shock wave.
  - The release spreads out with distance.



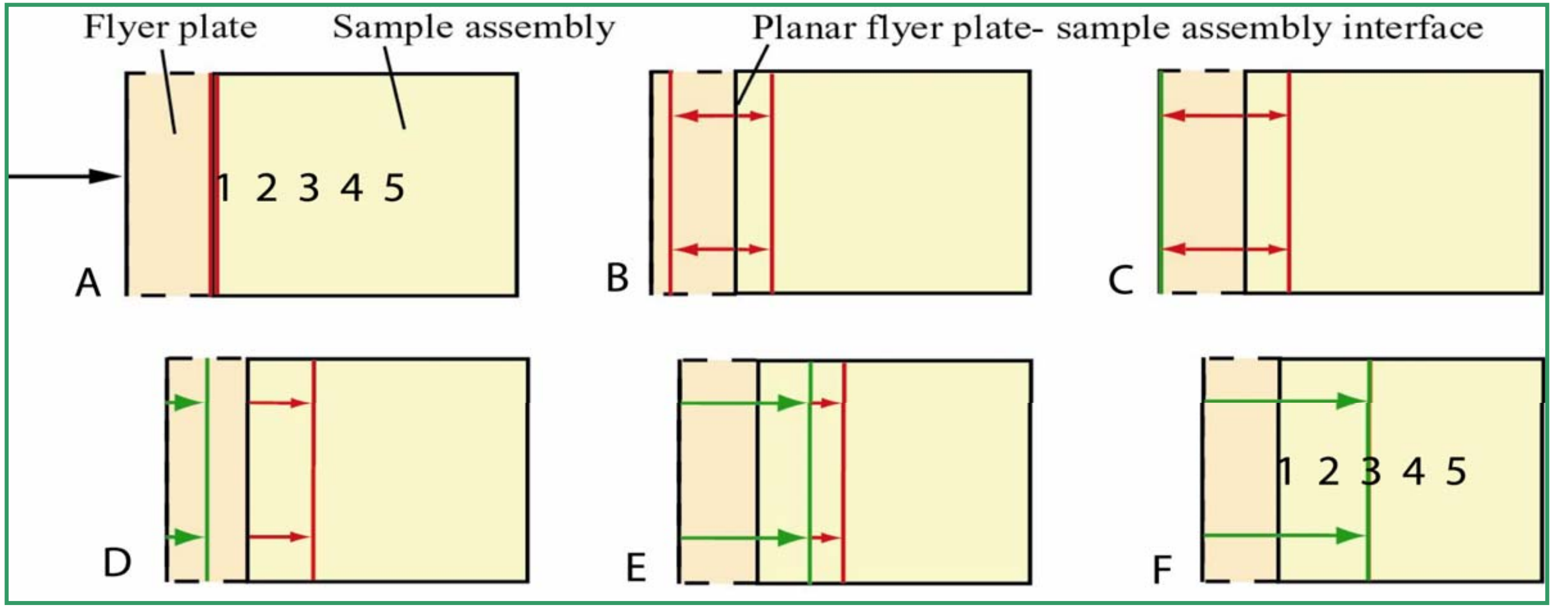
# Pressure-Time History

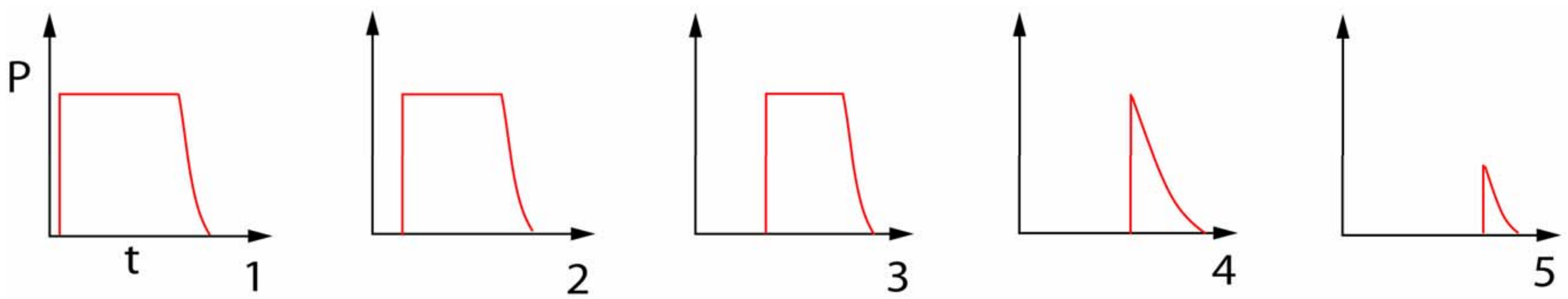
- Planar-shock wave approximation
- Sample behaves like the surrounding target.
  - Instantaneous pressure jump to the Peak shock pressure
  - Adiabatic pressure release



# Pressure vs. Distance



# The Rankine Hugoniot Equations

- From conservation of mass

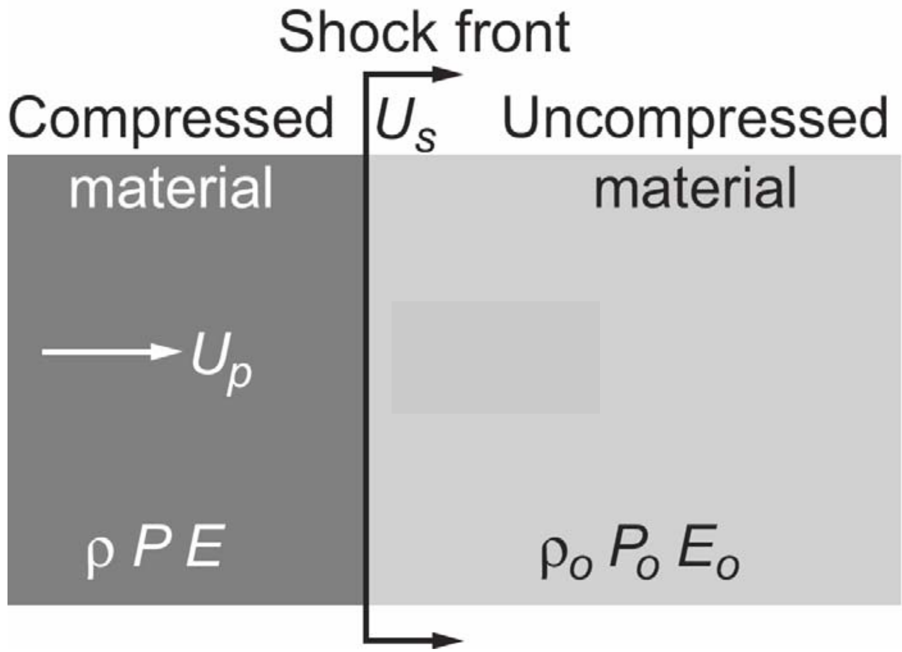
1) $\rho(Us-Up) = \rho_0 Us$

- momentum

2) $P-P_0 = \rho_0 UsUp$

- energy

3) $PUp = \rho Us(E-E_0) + (1/2)\rho_0 Up^2 Us$




Up = particle velocity, Us = shock velocity
P = pressure, E = internal energy
$\rho$ = density

# The Rankine Hugoniot Equations

3) $Up^2 = (P-P_0)(V_0-V)$

4) $Us^2 = V_0(P-P_0)/(V_0-V)$

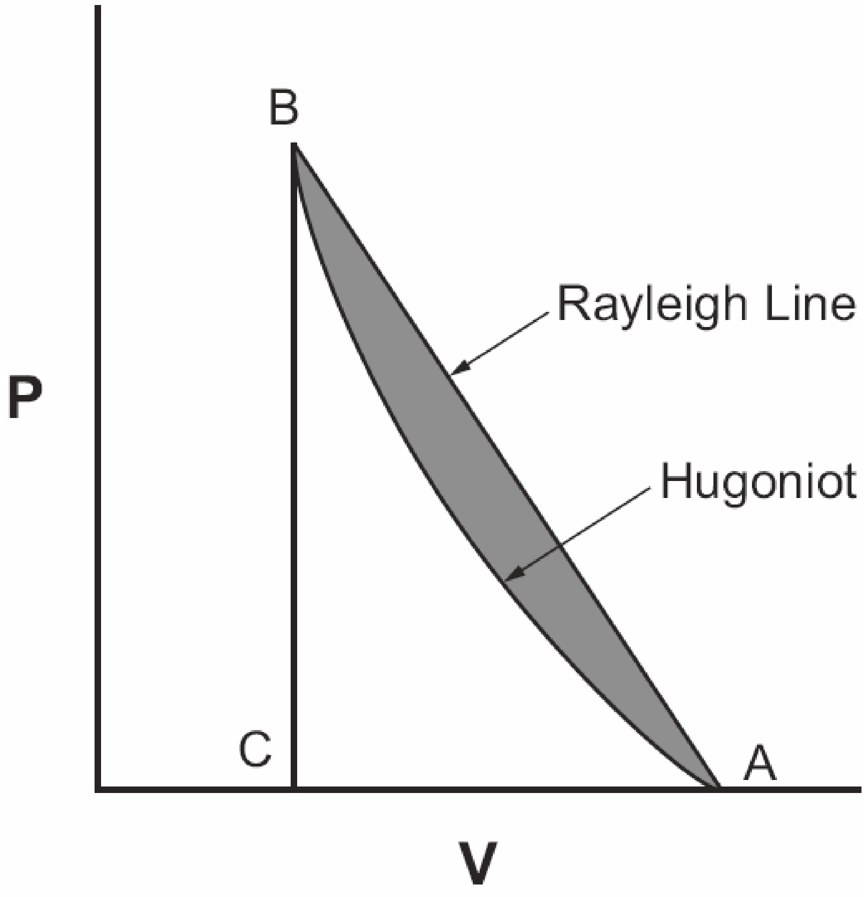
5) $E-E_0 = 1/2(P+P_0)(V_0-V)$

- V = specific volume = $1/\rho$

- Need one more relationship: a shock equation of state
- Examples
  - P-V
  - P-Us
  - P-Up
  - Us-Up

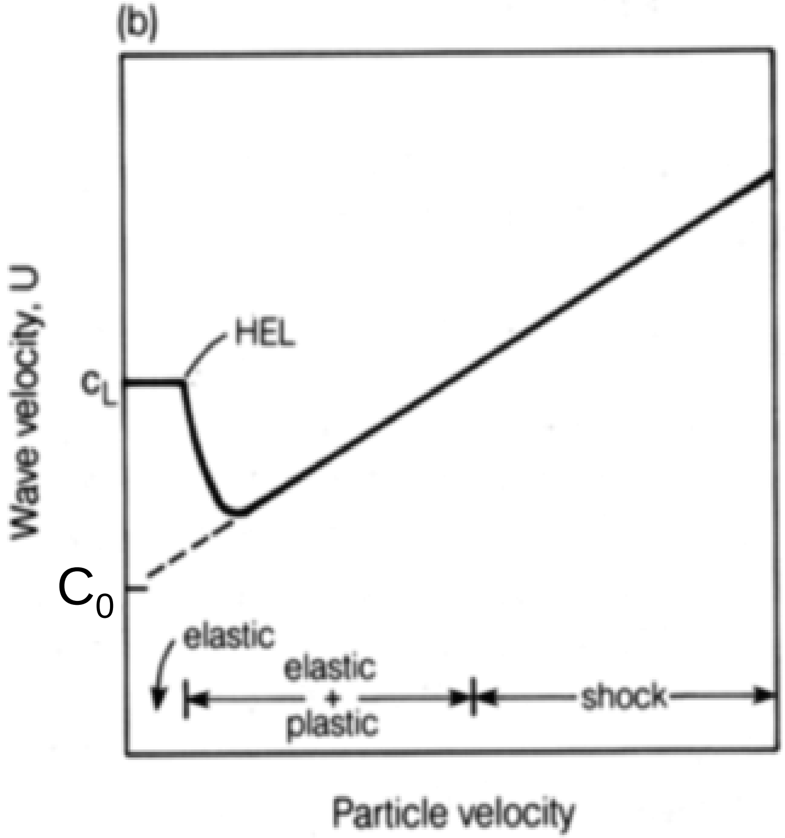
# The Hugoniot: Shock Wave Equations of State

- P-V plane
  - The Hugoniot is a locus of shock states , but not a thermodynamic path
  - For a single shock front, the loading path is the Rayleigh Line.
  - Useful for calculating energy changes and temperatures.



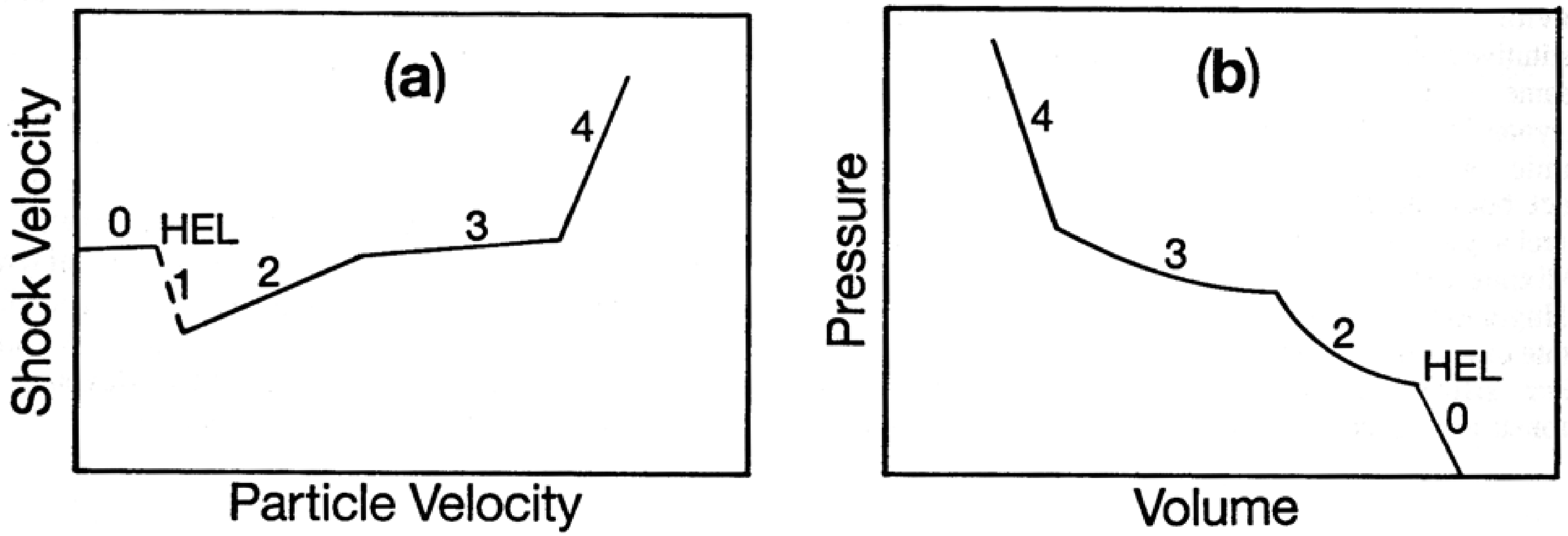
# Us-Up Hugoniot

- Most published shock data is in Us-Up
  - Us is measured directly and Up from the free surface velocity Up ~ Ufs/2
- Linear relationship for simple shock compression
  - Us = $C_0$ + sUp




Melosch, 1989

- Real shock data have many segments
  - In Us-Up, Hugoniot consists of linear segments
    - 0 Compression up to the Hugoniot Elastic Limit (HEL)
    - 1 dynamic yielding to quasi-hydrostatic state
    - 2 low pressure state Hugoniot
    - 3 mixed phase region
    - 4 high-pressure phase




Ahrens and Johnson (1995)

# Applications

- Tabulated rock and mineral Hugoniot data allow one to generate mineral and rock Hugoniots

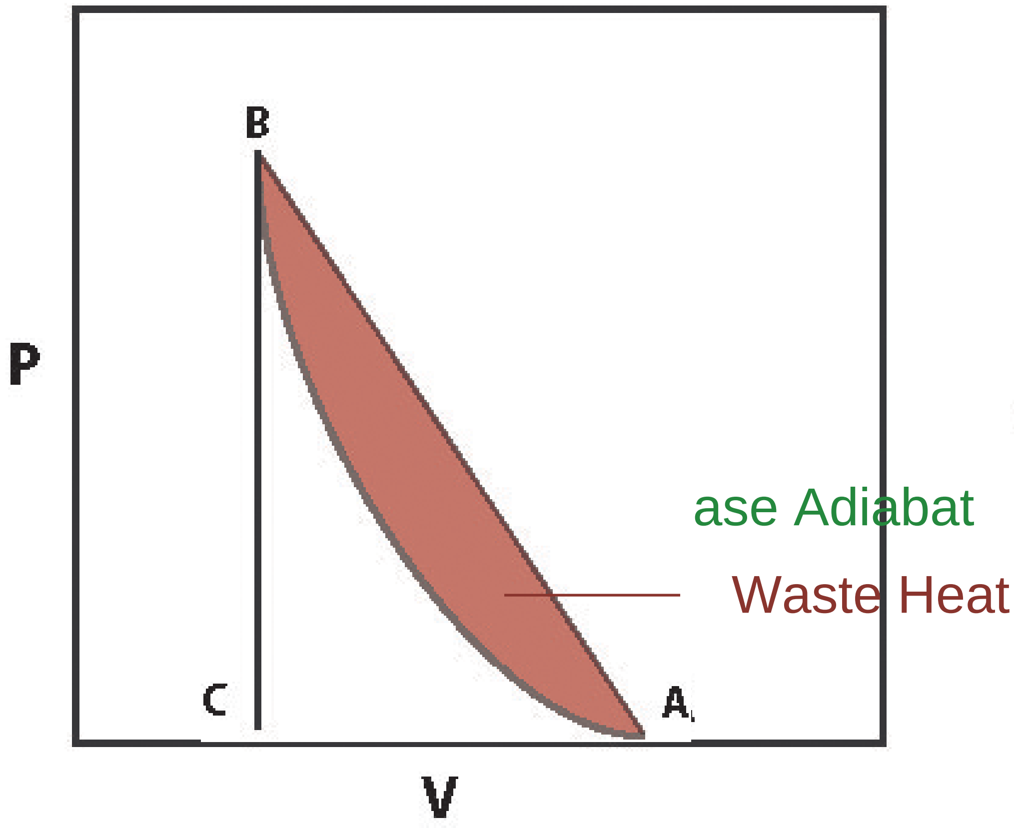
  (Ahrens and Johnson, 1995a, 1995b, AGU reference books)

  - Allows one to calculate energetics of shock as well as post-shock and shock temperatures
  - A simple spread-sheet method of Hugoniot calculation will be discussed later.

# Energy and Waste Heat

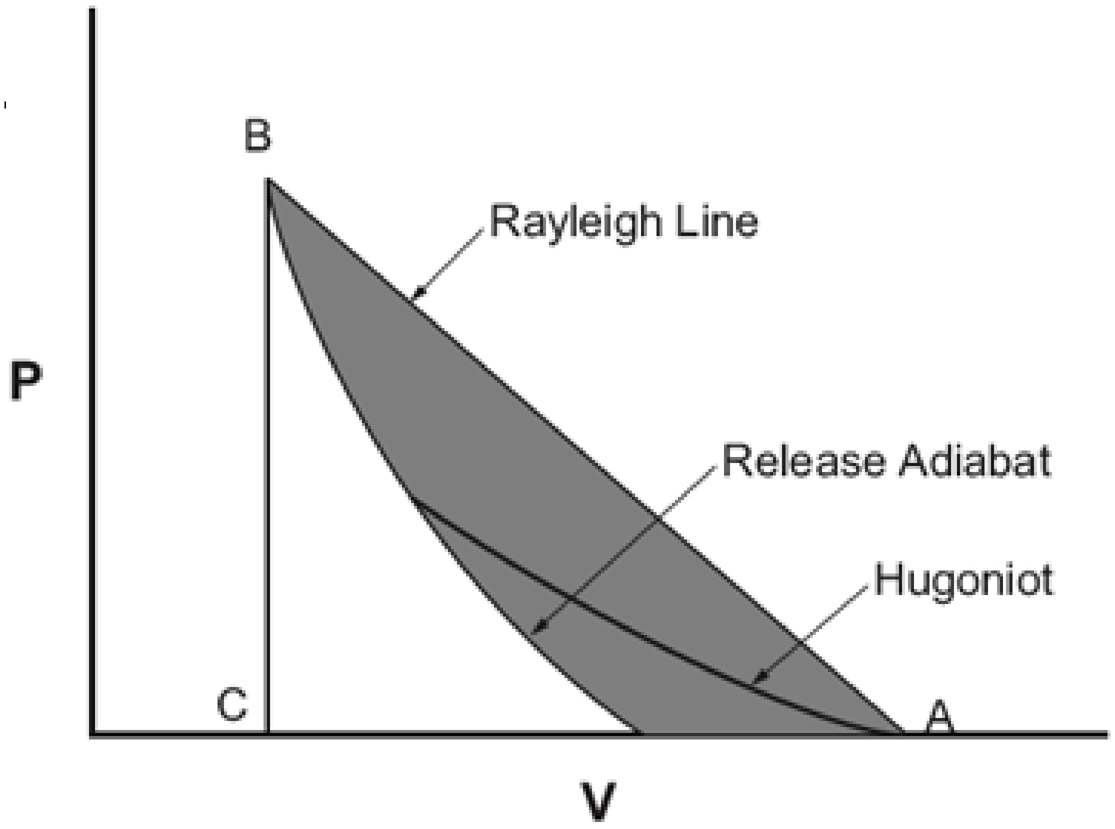
- Loading path = Rayleigh Line
- Energy added ($\Delta E$) = area of the A-B-C triangle.

  $= (1/2)P(V_0\text{-}V)$
- Recovered mechanical energy on release = area under release adiabat
- Non-recovered energy is termed waste .



# Effect of Porosity

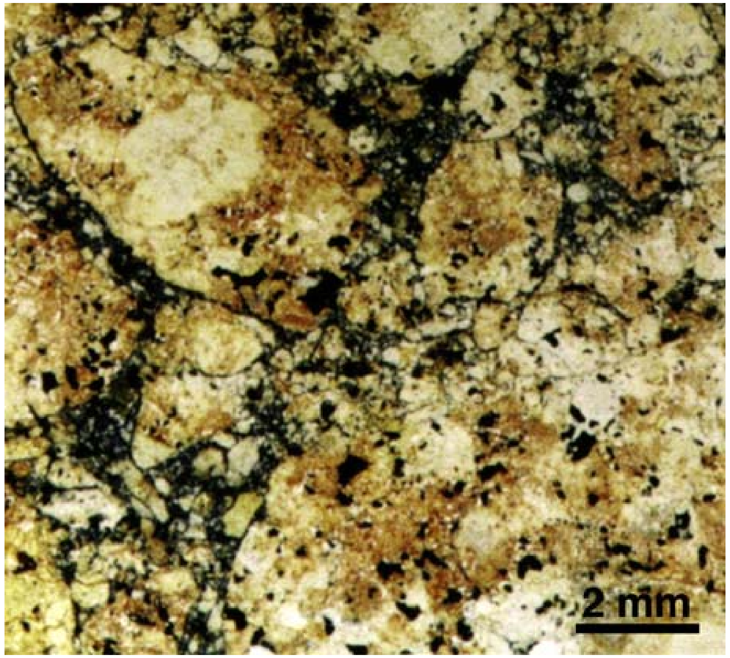
- A porous sample has a larger initial volume.
- The Hugoniot includes a shallow slope region where the porosity is crushed out.
- Above this pressure, the Hugoniot is the same as for the non-porous mineral.
- How does the $E-E_0$ and waste heat change with porosity?




It increases!

# Implications

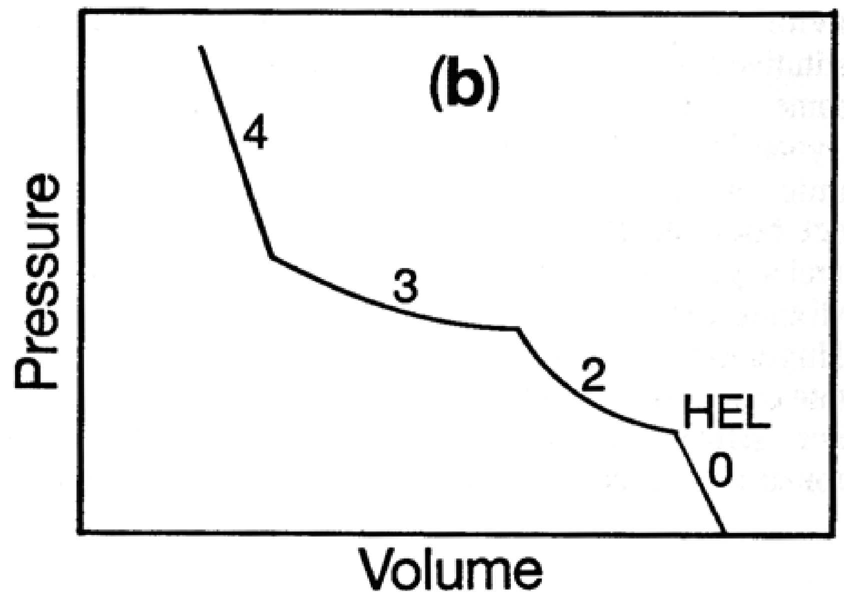
- Porous rocks are heated much more than non porous rocks.
  - Heat provides the energy to drive kinetic processes.
    - Ex. Diamond synthesis from disordered graphite
- Collapsed pores and fractures produce thermal heterogeneities.
  - A major cause of local shock melting.
- Collisions of porous material during planetary accretion would make shock heating important in the early solar system.




Melt veins and pockets in Acfer 040

# Phase transitions

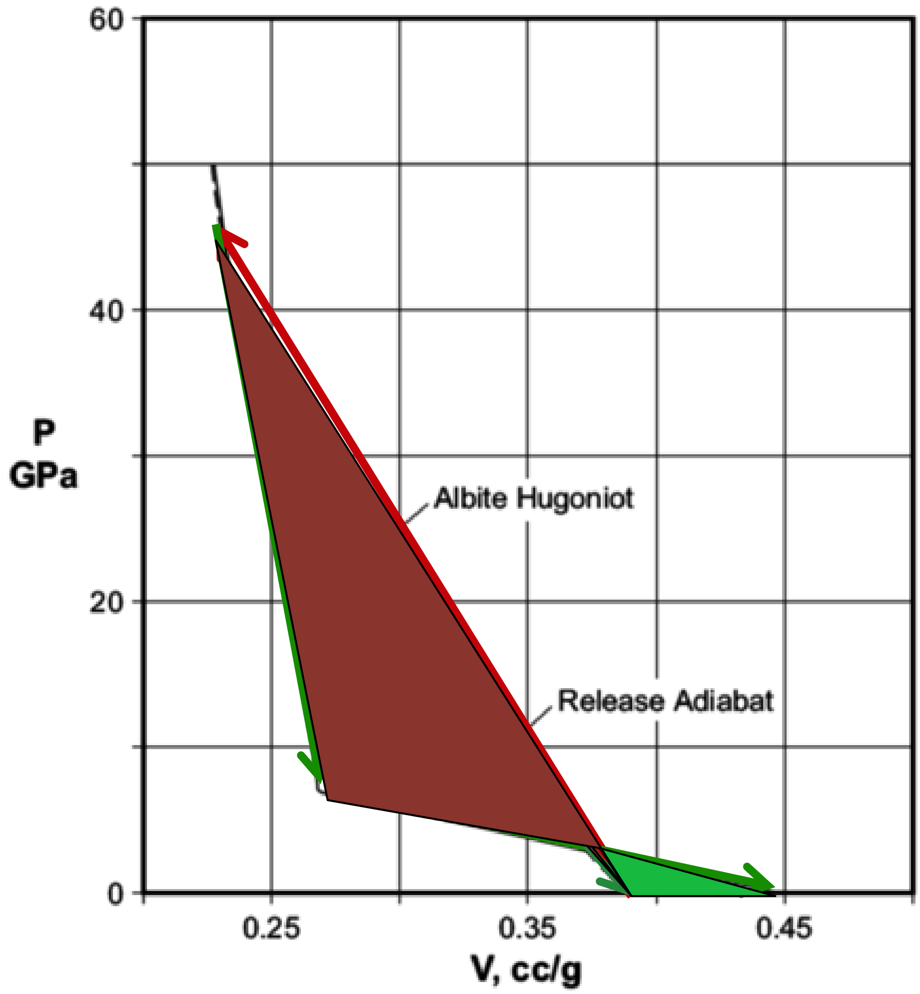
- Shock data provide evidence for phase transitions.
  - Different Hugoniot segments
- Tectosilicates
  - Clear evidence of transformation in Hugoniot data and shock-recovery experiments.
- Olivine and pyroxene
  - No evidence that they transform during shock experiments
- How do transitions occur under such short time scales?
  - Nucleation and growth?
  - High temperatures are needed.




Ahrens and Johnson (1995)

# Transitions in Albite

- Above ~ 30 GPa Hugoniot is like that of $CN_{Si}$=6 structures (like stishovite of hollandite)
- Release adiabat follows that of high-ρ $CN_{Si}$ = 6 phases to about 7GPa
- Below 7 GPa, rapid expansion of release adiabat
- Recovered sample is diaplectic glass
  - Glass formed by structural collapse, without melting
- For shock to < 30 GPa, release adiabat is approximately the Hugoniot for the low-P phase
  - No change to CN=6 structures.




Albite data (Ahrens and Rosenburg, 1968)

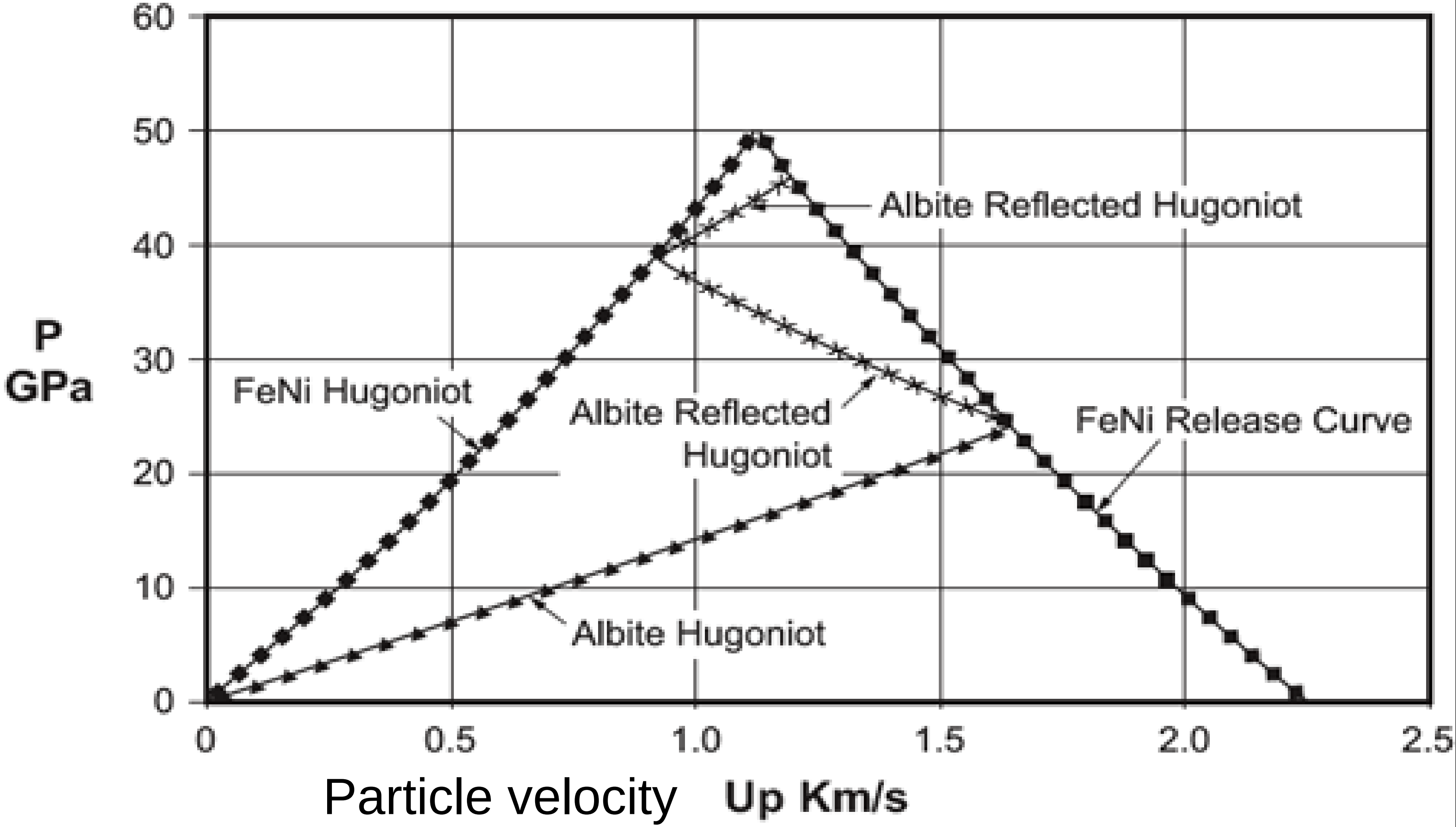
# Implications

- Shock-induced phase transformations occur readily in open structures such as tectosilicates
  - Plagioclase is transformed to maskelynite throughout highly shocked meteorites.
  - Less dependence on temperature.
- Dense structures don’t transform in shock experiments
  - No evidence of olivine transformation in shock experiments (Jeanloz, 1980)
  - Olivine and pyroxene only transform in “hot” melted regions of shocked meteorites (Chen et al. 1996, and many others)
  - Poorly ordered graphite only transforms to diamond if the starting material is porous and shock temperatures exceed 3000 K. DeCarli and Jamison (1961)

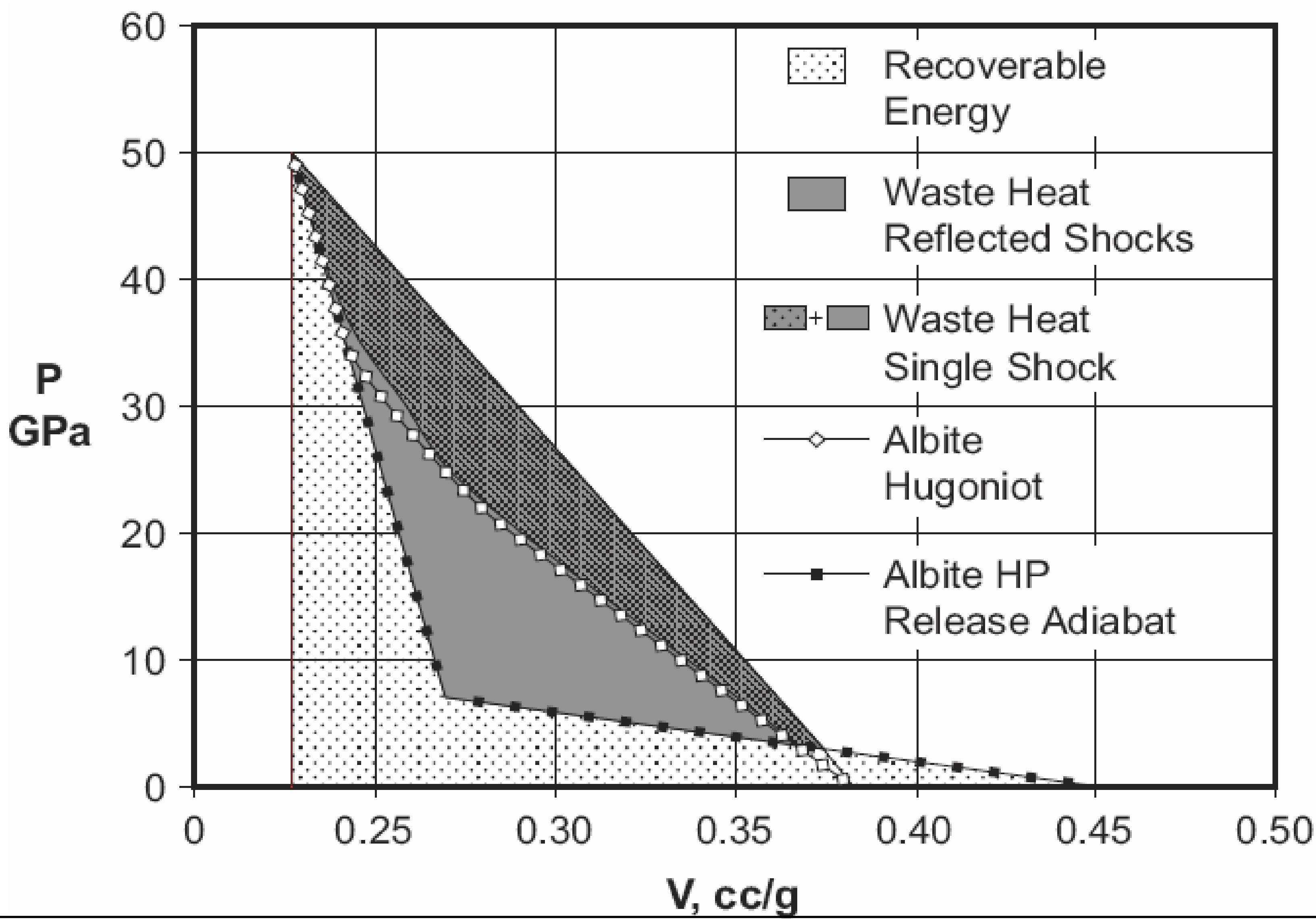
# Shock reflections and loading

- Variations in shock impedance ($\rho$Us) result in different pressures in different materials.
  - Most shock-recovery experiments use a reverberation method to reach higher pressures.
  - Simulate this with an infinite layer of albite in Fe
- Assume initial shock pressure in Fe is 50 GPa.
  - Shock pressure in albite will be less.
  - Albite pressure will "ring up" by reverberation.

# Reflections in P-Up



# Loading Path and Energy



# Energy Consequences

- Total energy increase in albite
  - For reflected shock to 50 GPa
    - Total energy added ~ 1040 J/g
    - Assuming 300K initial T, post-shock T = 1220 K
  - For a single shock to 50 GPa
    - Total energy added ~ 2060 J/g
    - Post-shock T = 1770 K
- Shock reverberation experiments do not model nature very well.
  - Shock and post shock temperatures are low.
  - Many shock effects are are thermally activated kinetic processes where temperature is a very important variable.

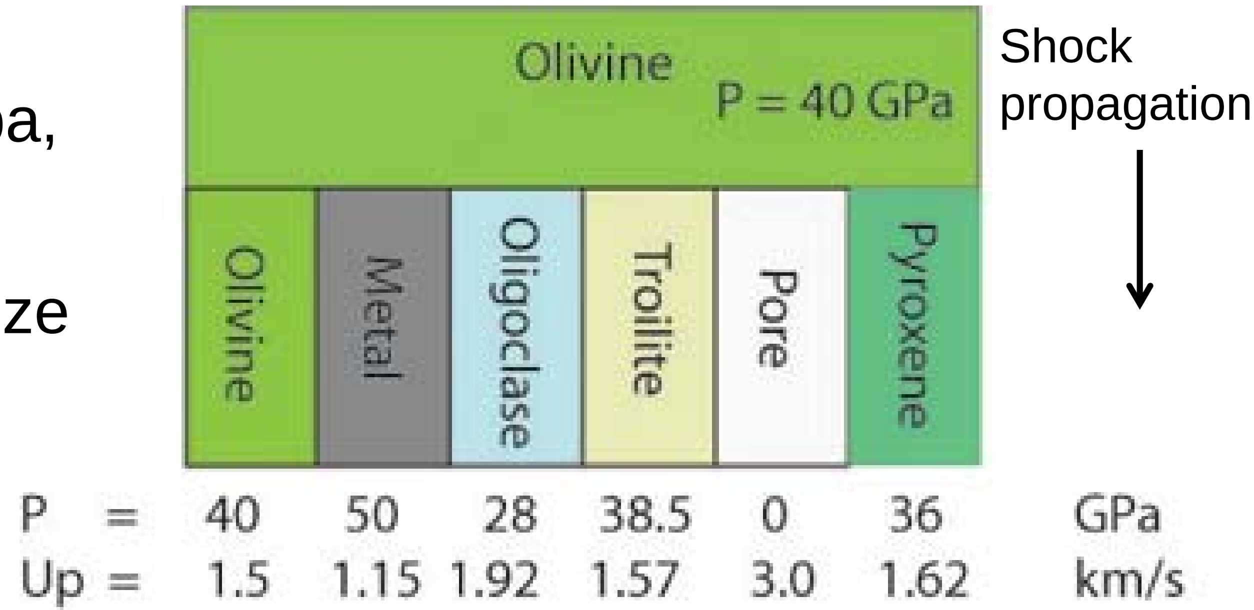
# Pressure Equilibration

- The initial shock front creates a range of pressures, particle velocities and temperatures
  - Causes deformation and sheer heating
  - Pressure must equilibrate by shock reverberation
  - Equilibration time scale = several reverberations
    - ~ (grain size)/Us      Us= 7.1 km/s

For olivine at 40 Gpa, Us = 7.1 km/s

For a 1-mm grain size

Equilibration in less than a μs.



# Implications

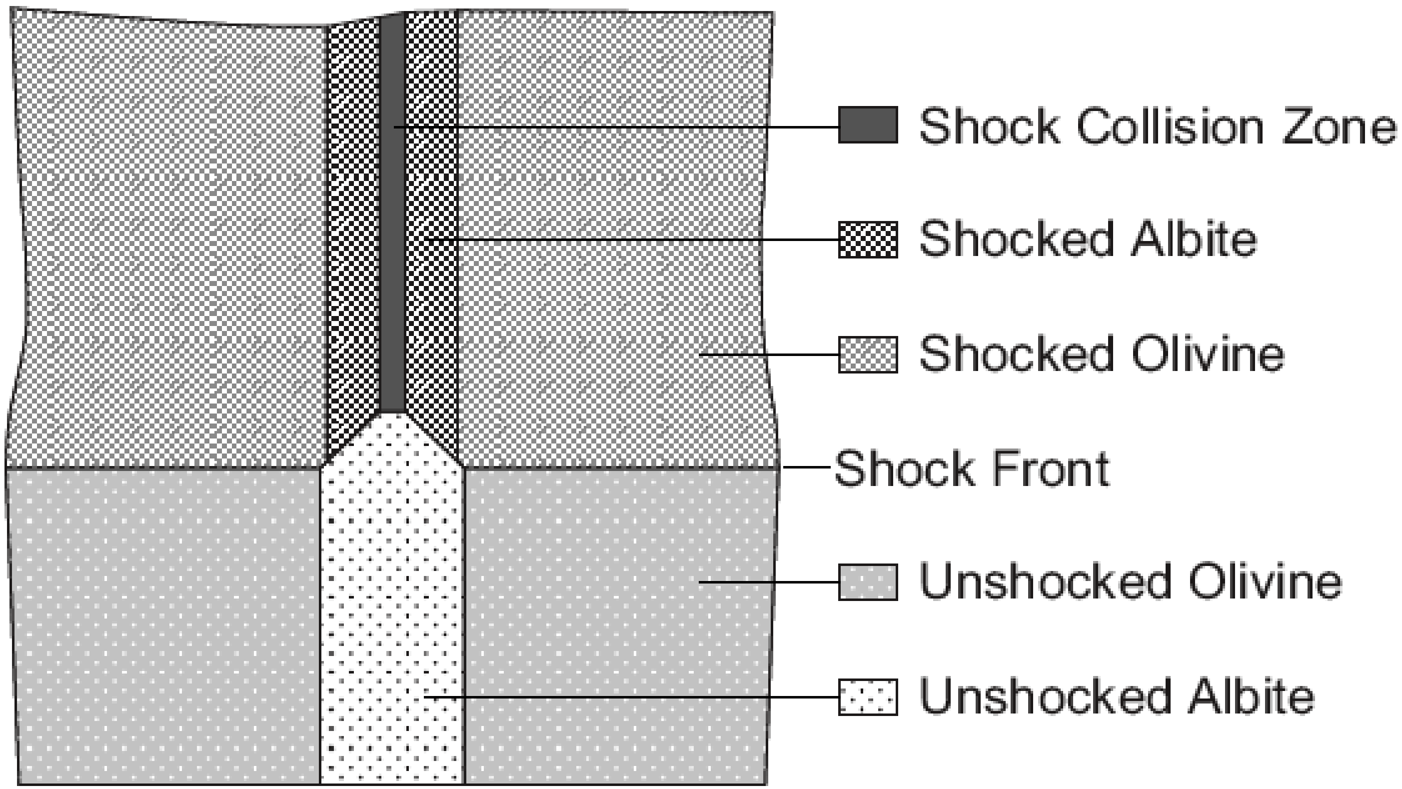
- Pressure equilibration occurs very fast.
- Temperature equilibration, by conduction, is slow.
- If the pressure pulse is long (large impacting body), temperature heterogeneities will predominate

# Pressure terminology

- Peak Shock Pressure
  - equilibrated shock pressure after the passage of the initial shock wave front has passed.
- Pressure spike
  - Transient pressure variations before equilibration
- Ringing down
  - Decrease from high pressure by reverberation
- Ringing up
  - Increase from low pressure by reverberation

# Shock Collisions

- High pressure and temperature can be generated by shock collisions.
  - Albite layer in olivine, parallel to shock direction



# Some Conclusions

- Complexities of shock can be simplified by using simplifying assumptions and continuum approach.
  - Hugoniot data and calculations are easy.
- P-V Hogoniot provides $\Delta$E and waste heat values that can be used to calculate shock and post-shock temperatures.
  - More compressible materials get hotter
  - Porous samples get much hotter than non porous samples.

- P-Up Hugoniots allow one to calculate loading path for shock experiments
  – Can calculate thermal effects of reverberation
  – Can adjust sample container materials.
- These simple calculations allow us to better understand shock heterogeneities.

# Hugoniot Calculations

- Simple spreadsheet calculations can provide Hugoniot data for many minerals and rocks.
  - Example Stillwater Bronzite
  - EoS data from Ahrens and Johnson (1995)
  - Set up spreadsheet with the following columns
  - Fill column A with Particle Velocity values from 0 to 5 km/s in 0.01 increments

| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| **Stillwater Bronzite** | | **$\rho 0$ = 3.277** | **Specific** | **Internal Energy** | **Recoverable** | **Waste He** |
| **Part. Vel.** | **Shock Vel** | **Pressure** | **Volume** | **Increase** | **Energy** | |
| **Up, km/s** | **Us, Km/s** | **Gpa** | **cc/g** | **E-E0, kJ/g** | **kJ/g** | **kJ/g** |

# Column B: Shock Velocity

- Us = $C_0$ + sUp
  - Us = $C_0$ + s*Ax
- From Ahrens and Johnson (1995a)
  - Us = 5.99 + 1.56*Up (Up up to 0.483)
  - Us = 6.47 + 0.6*Up (for 0.483 km/s <Up< 2.131 km/s)
  - Us = 5.16 + 0.6*Up (for 2.043 km/s <Up< 3.481 km/s)
- Start by inputting all equations in columns B, C and D and find crossover values of Up.
- Complete column B with appropriate formulas for the Up values

# Column C: Pressure

- $P - P_0 = \rho_0 UsUp$
  - Assume $P_0 = 0$

  Column C: = $\rho_0$*Ax*Bx

# Column D: Specific Volume

- Specific Volume $V = 1/\rho$
- $Up^2 = (P-P_0)(V-V_0)$
  - Assume $P_0 = 0$ and solve for V
- $V = V_0 - Up^2/P$
- $V = 1/\rho_0 - Up^2/P$
- Column D = $1/\rho_0$ - Ax^2/Cx

# Column E: Internal Energy Increase

- Area under the Raleigh Line
- $E-E_0 = (1/2)(P-P_0)(V_0-V)$
- Column E: $= 0.5*Cx*(1/\rho_0-Dx)$

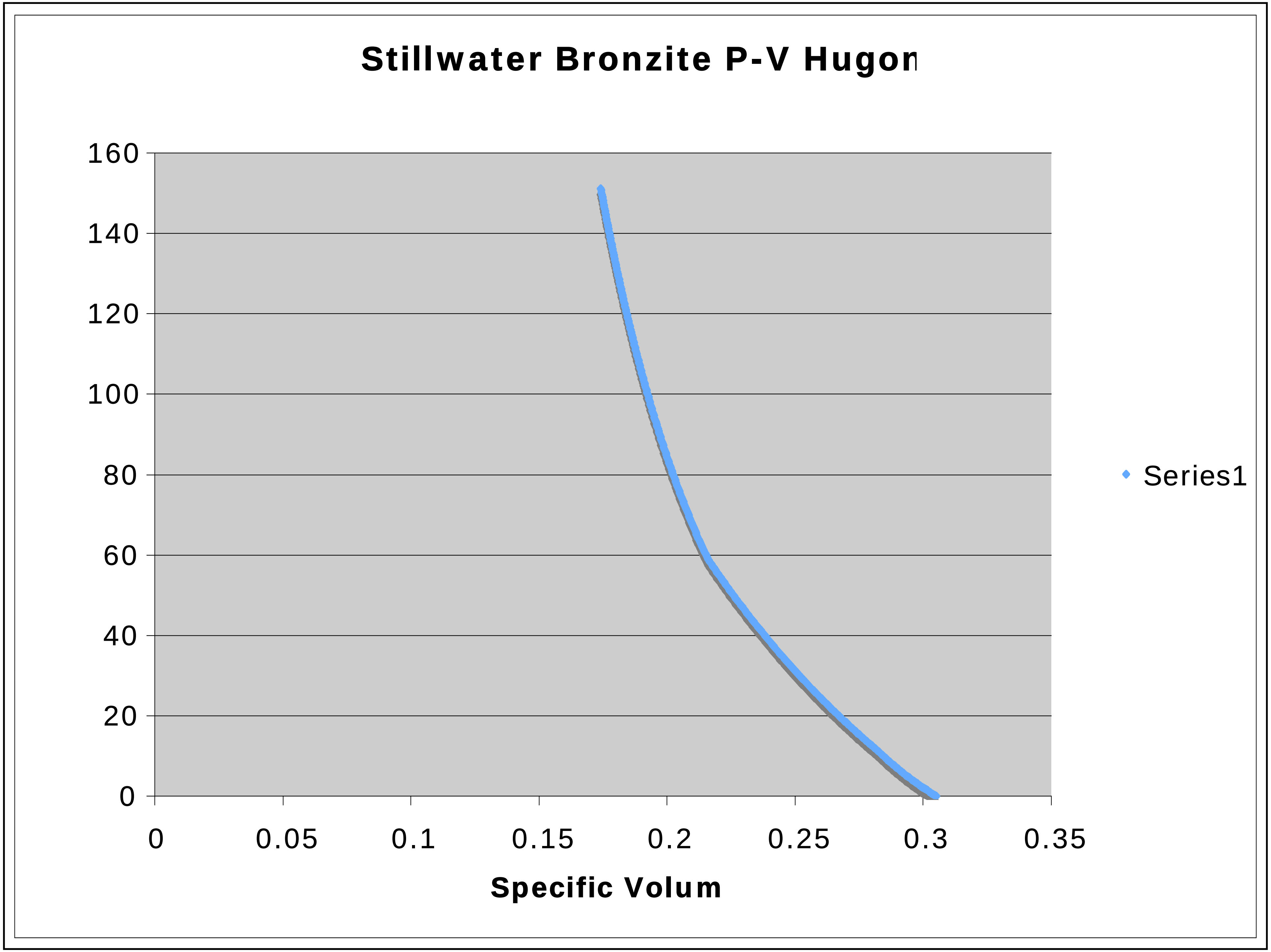
# Column F: Recoverable Energy

- Area under the release adiabat
  - (Approximated by the Hugoniot)
- $E\text{-}E0 = (1/2)(P+P_0)(V_0\text{-}V)$
  - We can use a Simpson's rule integration, which is a cumulative sum of $E\text{-}E_0$
- Column F:

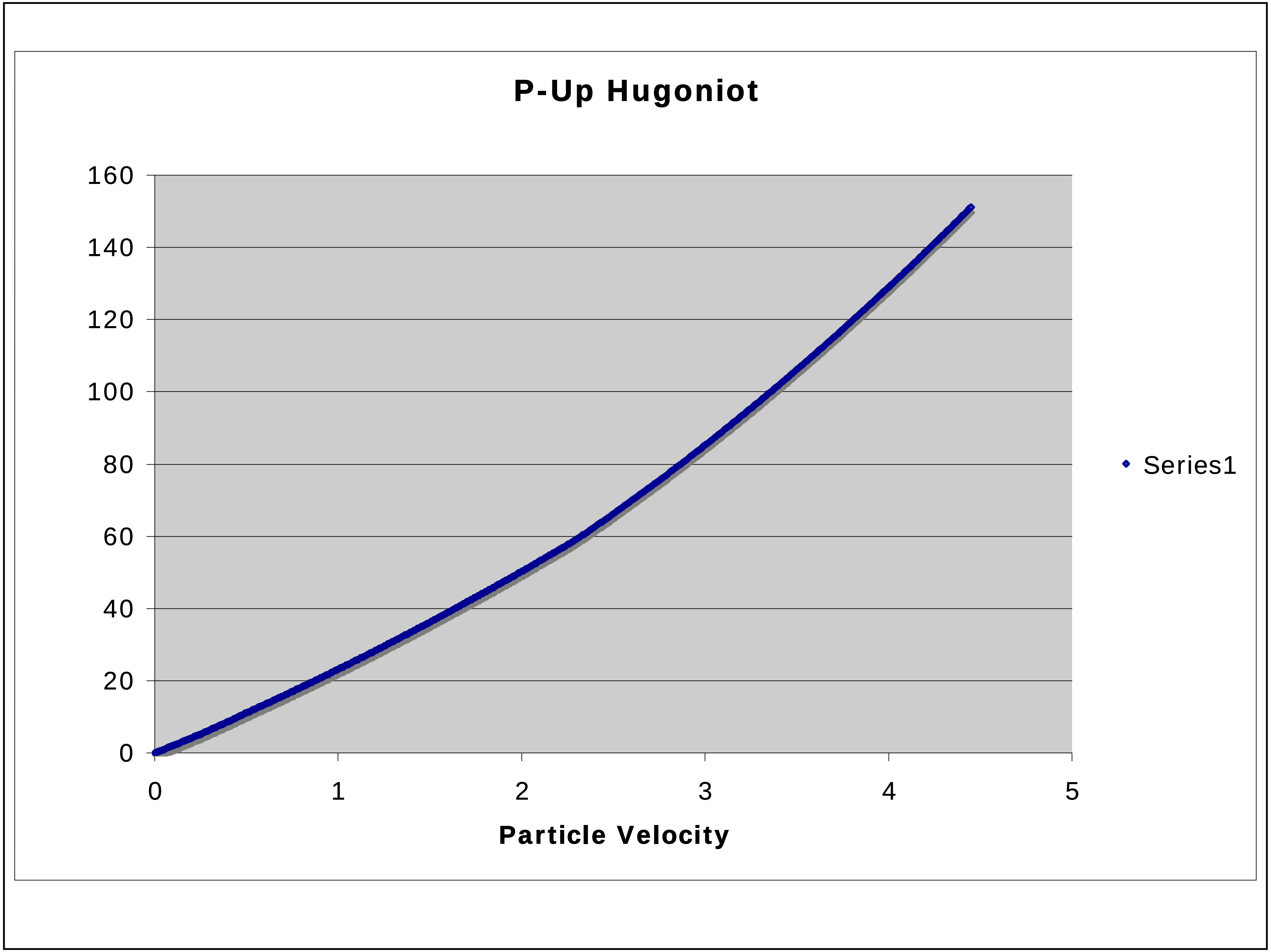
= 0.5*(Cx + Cx-1)*(Dx-1 - Dx) + Fx-1

# Column G: Waste Heat

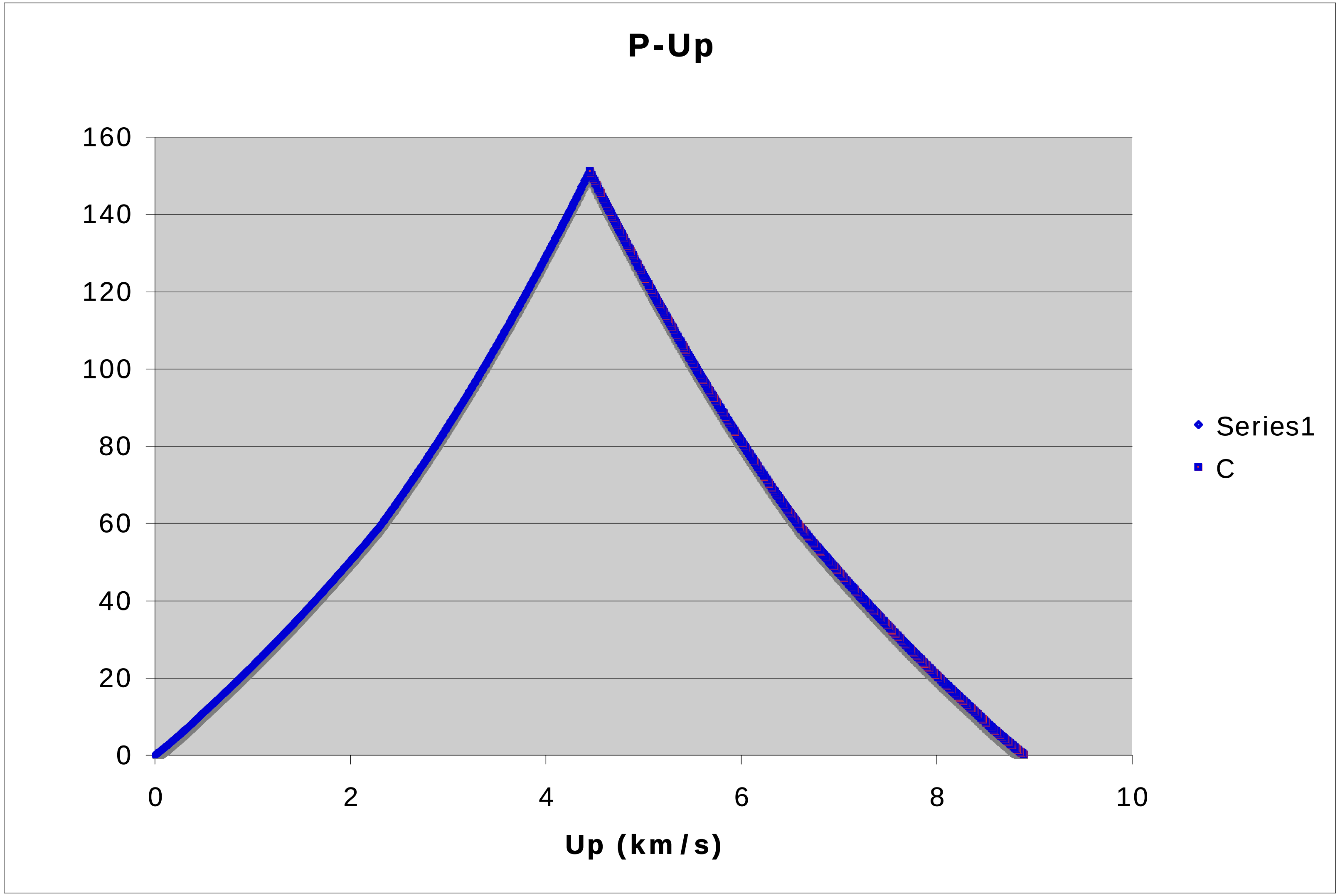
- Waste Heat = Difference between Internal Energy Increase and Recoverable Energy
- Column G: = Ex - Fx



Stillwater Bronzite P-V Hugon
160
140
120
100
80
60
40
20
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Specific Volum
Series1



P-Up Hugoniot
160
140
120
100
80
60
40
20
0
0
1
2
3
4
5
Particle Velocity
Series1



P-Up
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
Up (km/s)
Series1
C

# Post Shock Temperature

- What would be the post-shock temperature of bronzite shocked to 50 GPa?
  - From Column G: waste heat = 223 J/g.
  - Assume a specific heat of  1 J.gK and an initial temperature of 300 K
  - Post shock T ~ 300 + 223 = 523 K

# Shock Temperature?

- Need to calculate adiabatic heating from 0 GPa to 50 GPa
- $T_s = T_0 e^{(\gamma(Vo\text{-}V))}$
- Grueneisen Parameter $\gamma$ = 0.5 top 2 for most rocks and minerals.
  - Assuming a value of $\gamma = 1$, $T_s = 565$ K
  - Assuming a value of $\gamma = 2$, $T_s = 615$ K
  - Adiabatic cooling is only ~ 42 - 92 $^\circ$
- Adiabatic decompression does not produce large cooling!

# Rock Hugoniots

- Can be constructed from appropriate mineral Hugoniot data.
  - Hugoniot data (Ahens and Johnson, 1995) is fairly complete, but mineral compositions are limited.
  - Hugoniot data are are very similar for a given structure
    - Forsterite and fayolite are very similar
- One can also use isothermal P-V data from static high-pressure experiments to approximate Hugoniots.
  - Convert P-V data to Us-Up

# Synthetic Hugoniots

- For a polymineralic rock, sum the volumes of the constituent minerals at pressure.
  - Start with volume fraction at P = 0 GPa
  - For selected high pressure values, sum the volumes for P-V Hugoniot
  - From the P-V data, one can calculate Up and Us for the aggregate, using equations 3 and 4:

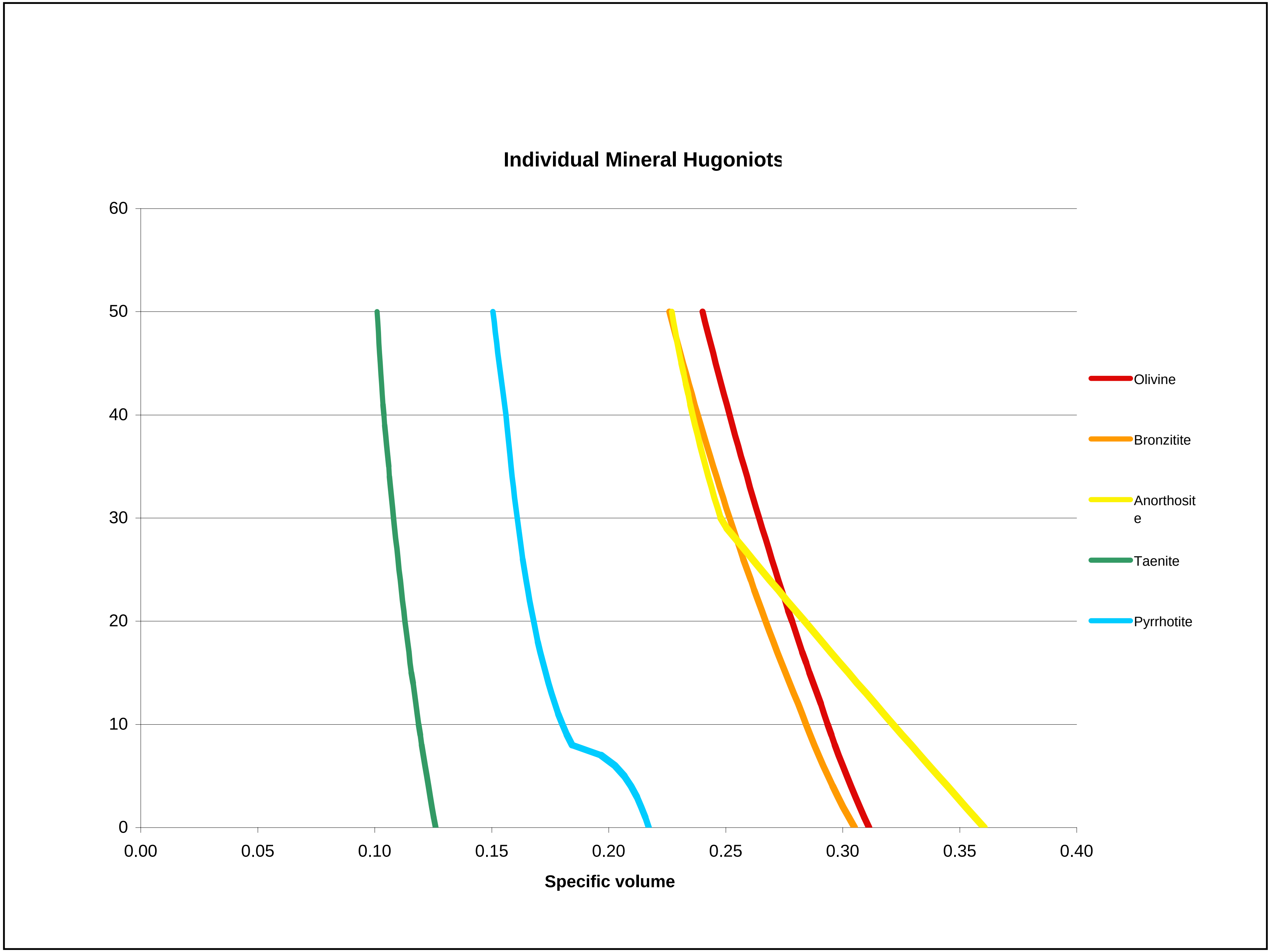
3) $Up^2 = (P-P_0)(V_0-V)$

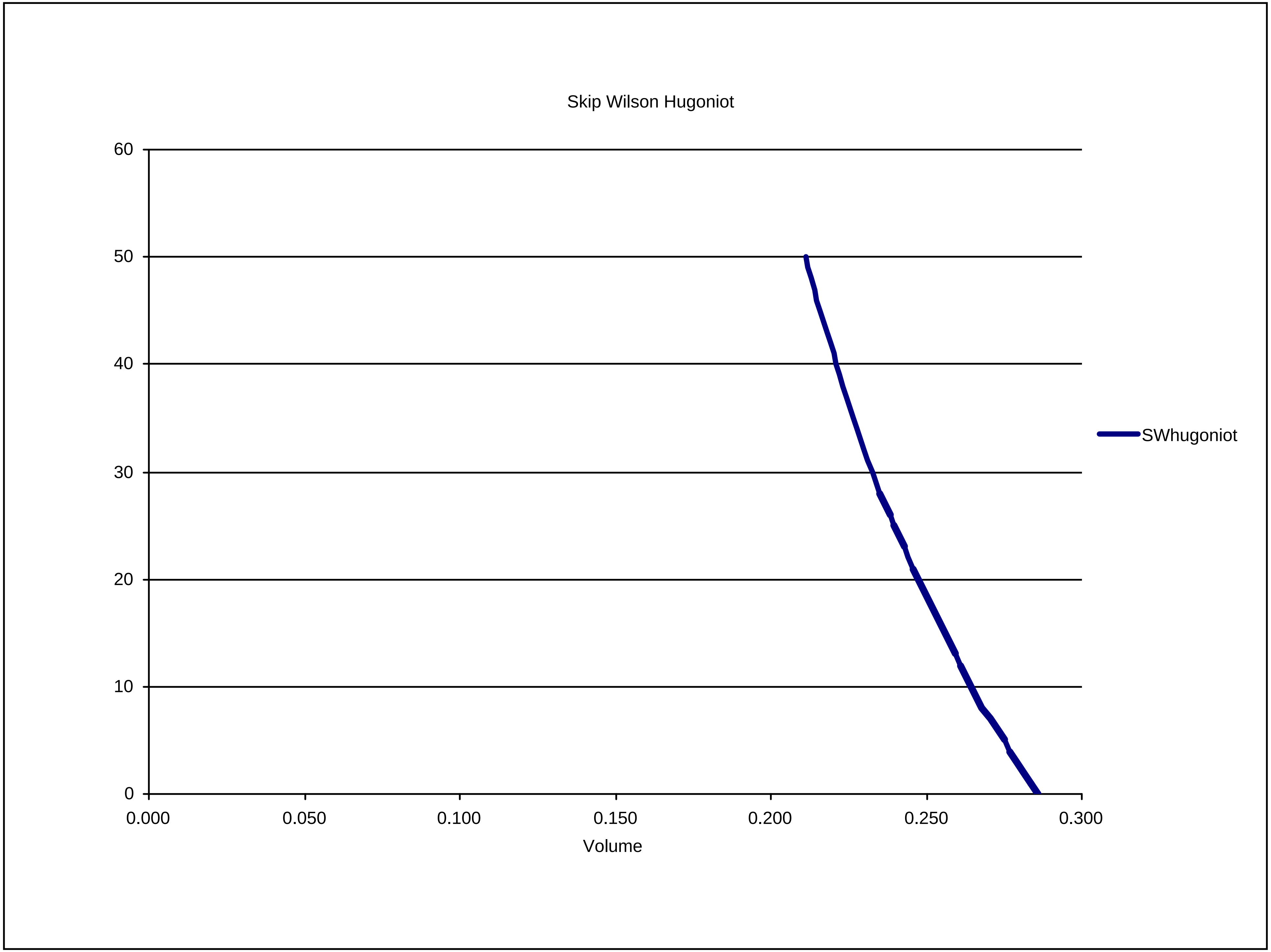
4) $Us^2 = V_0(P-P_0)/(V_0-V)$

# RC106 Hugoniot Data

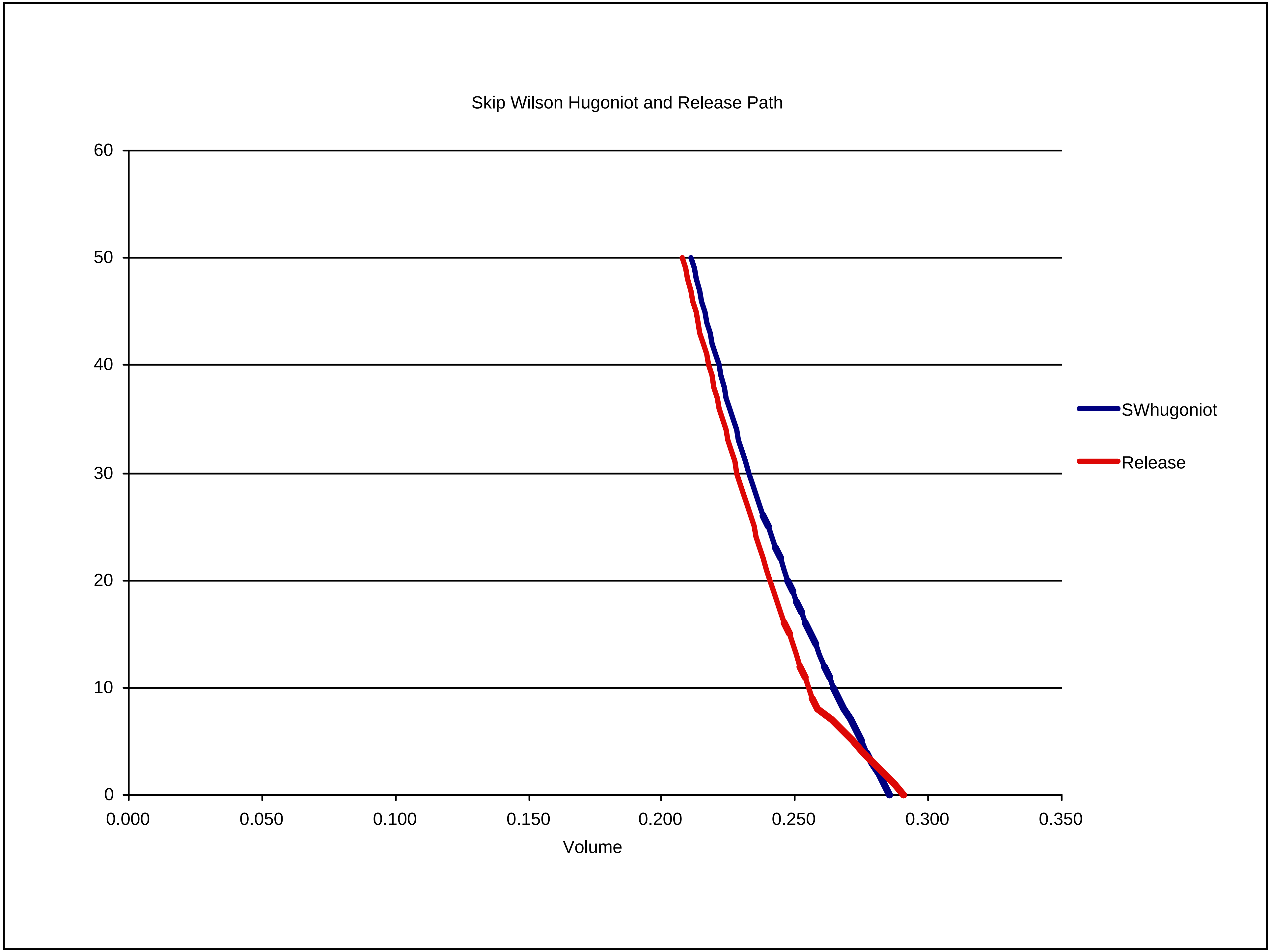
| Mineral Shock Data (1995, Ahrens and Johnson, Mineral Physics and Crystallography, AGU handbook) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mineral** | **Formula** | **Density ( _) Mg/m$^3$** | **$C_o$ (km/s)** | **$C_o$ error** | **S** | **S error** | **Lower Up** | **Upper Up** |
| **Forsterite** | $Mg_2SiO_4$ | 3.212 | 6.8 | 0.3 | 1.4 | 0.6 | 0 | 0.8 |
| | | | 7.21 | 0.1 | 0.55 | 0.06 | 0.75 | 2.45 |
| | | | 4.6 | 0.3 | 1.51 | 0.08 | 2.43 | 4.61 |
| **Bronzitite** | OPX | 3.277 | 5.99 | --- | 1.56 | --- | 0 | 0.48 |
| | | | 6.47 | 0.06 | 0.6 | 0.04 | 0.48 | 2.13 |
| | | | 5.16 | 0.07 | 1.17 | 0.03 | 2.04 | 3.48 |
| **Anorthosite** | An-Ab | 2.774 | 5.73 | 0.07 | 0.07 | 0.08 | 0 | 1.99 |
| | | | 3.2 | 0.5 | 1.46 | 0.13 | 1.99 | 4.99 |
| | | | 4.45 | 0.15 | 1.23 | 0.01 | 4.99 | 28.7 |
| **Taenite** | (Fe, Ni) | 7.933 | 4.41 | 0.05 | 1.01 | 0.05 | 0 | 1.09 |
| | | | 3.79 | 0.05 | 1.65 | 0.02 | 1.02 | 2.78 |
| | | | 4.2 | 0.17 | 1.48 | 0.05 | 2.72 | 4.59 |
| **Pyrrhotite** | $Fe_{1-x}S$ | 4.605 | 5.8 | 0.2 | -4.7 | 0.5 | 0.24 | 0.55 |
| | | | 2.31 | 0.17 | 2.08 | 0.15 | 0.49 | 1.59 |
| | | | 3.23 | 0.1 | 1.49 | 0.03 | 1.49 | 5.36 |

| Constituent Volumes (point counting results) | |
|---|---|
| **Forsterite** | **~43%** |
| **Bronzitite** | **~30%** |
| **Anorthosite** | **~10%** |
| **Taenite** | **~4.5%** |
| **Pyrrhotite** | **~8.5%** |
| **Pore space/cracks** | **~4%** |


Individual Mineral Hugoniots
60
50
40
30
20
10
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
Specific volume
Olivine
Bronzitite
Anorthosite
Taenite
Pyrrhotite



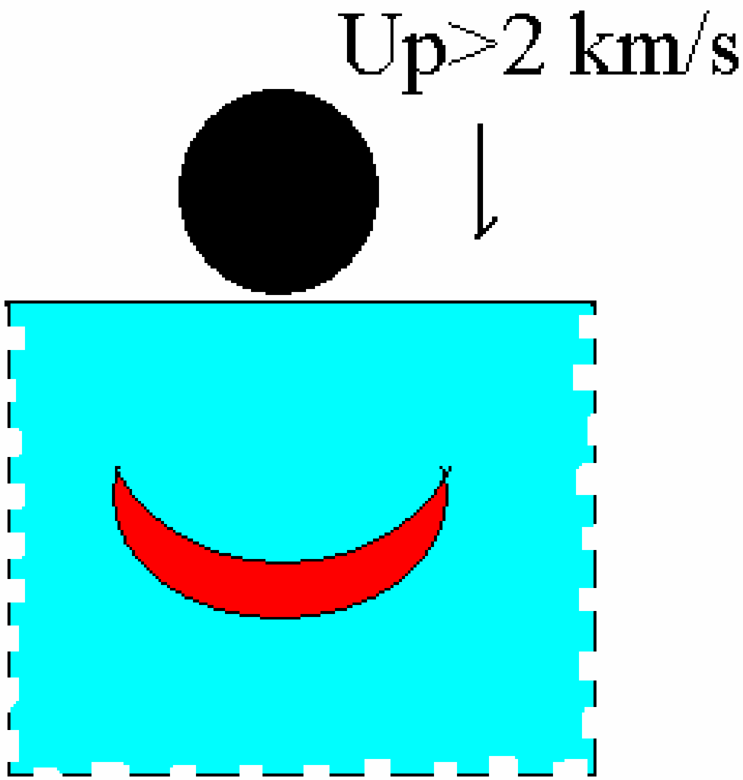
Skip Wilson Hugoniot
60
50
40
30
20
10
0
0.000
0.050
0.100
0.150
0.200
0.250
0.300
Volume
SWhugoniot



Skip Wilson Hugoniot and Release Path
60
50
40
30
20
10
0
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
Volume
SWhugoniot
Release

# 3-D Simulations

- Need 3-D numerical modeling to consider realistic geometries for impacts on parent bodies requires
  - Not 1-D planar wave
- Peak pressure at some depth will be in range 18-25 GPa
- Need hydrocode calculations of shock attenuation

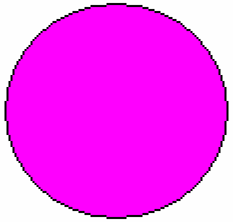


# Model Parameters

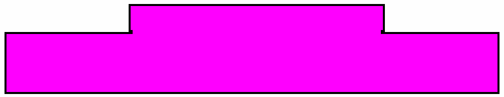
- Assume forsterite Hugoniots for parent bodies (justified by similarity with chondrite Hugoniot)
- Assume 800 m radius sphere (or equivalent) impacting larger body at velocities in range of 2-8 km/s. Note regions with pressures in 18-25 GPa range over durations ~0.1 s
- Scale as needed (8 km sphere for 1 s at 10 X depth)

Model Protoplanets

All ~ 2.2 E09 $m^3$

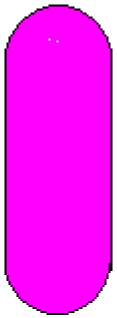


Sphere
R= 800 m



Stepped Disc
1200 m R x 400 m
+800 m R x 200 m

Quasi- Flat Plate
Impact

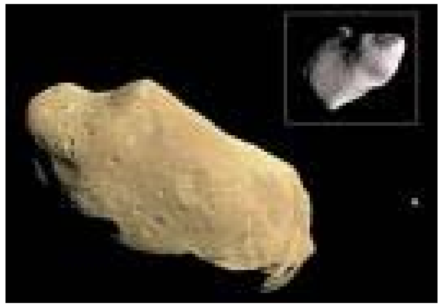


Rod
600 m R x 2400 m L

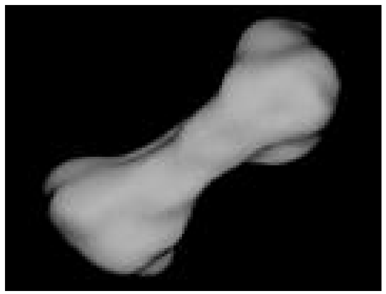
Long Rod Impact

# Real Asteroids

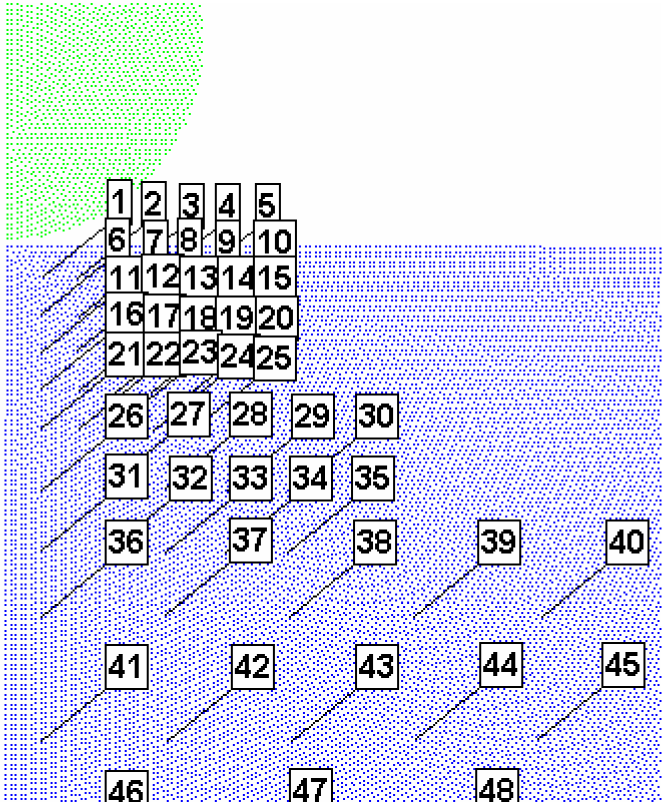
Eros



Ida and Dactyl



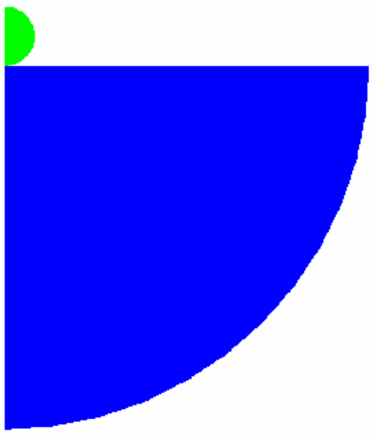
Kleopatra

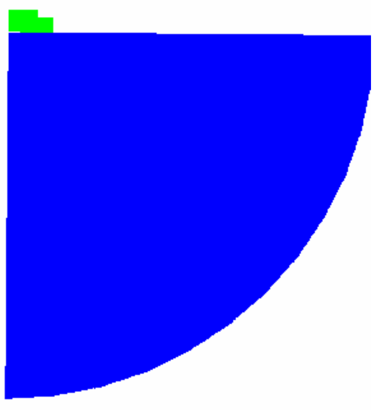


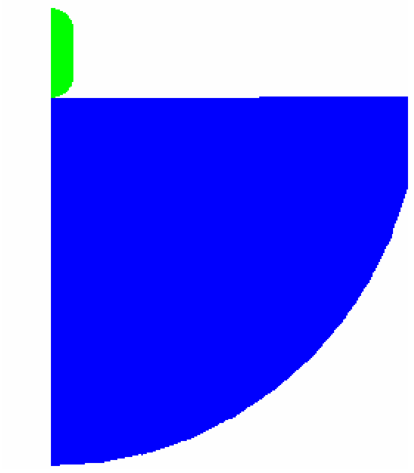

# Calculational Nuts and Bolts

Autodyn™ 2-D Axisymmetric Geometry, SPH Processor, 20 m Cell size, numerous gauge stations.

Stepped disc geometry unreal, but provides a check on the validity of the calculations via comparison of code calculation with analytic result.

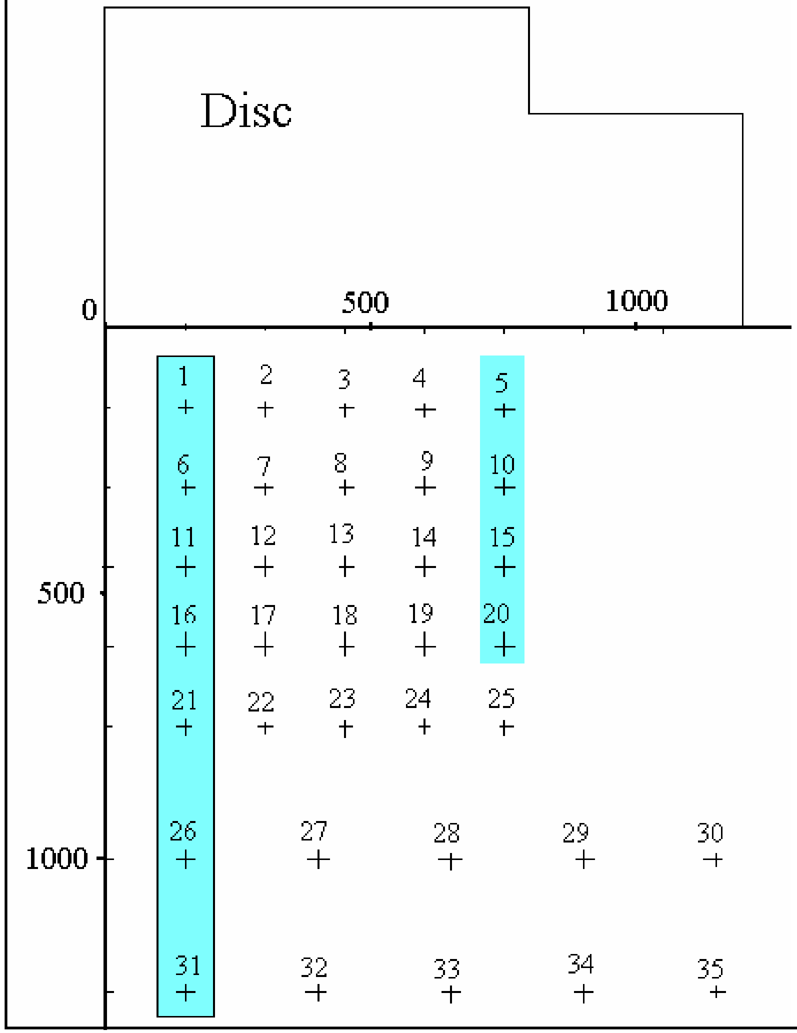


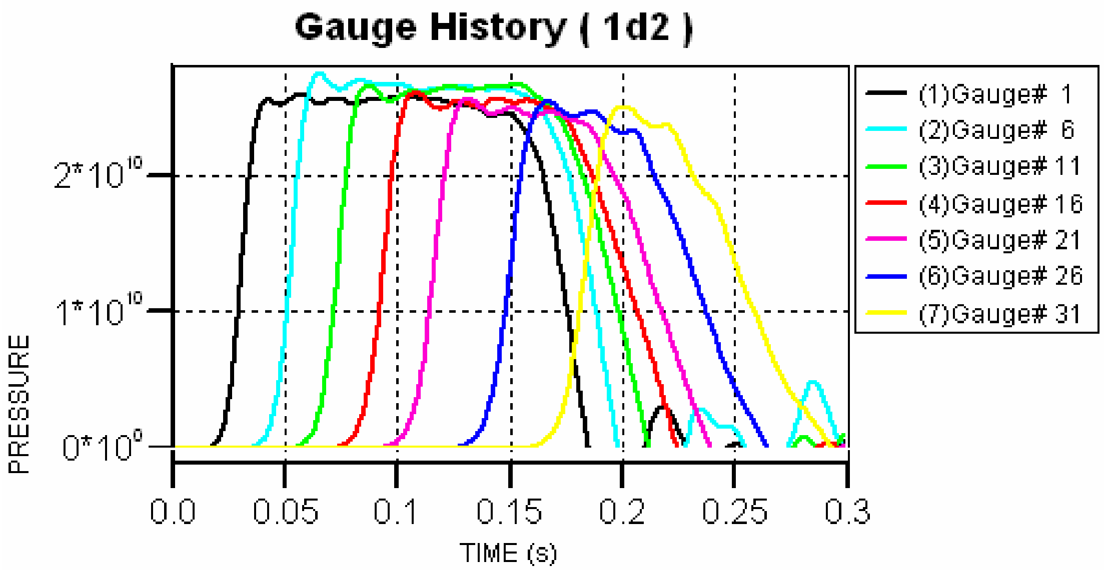


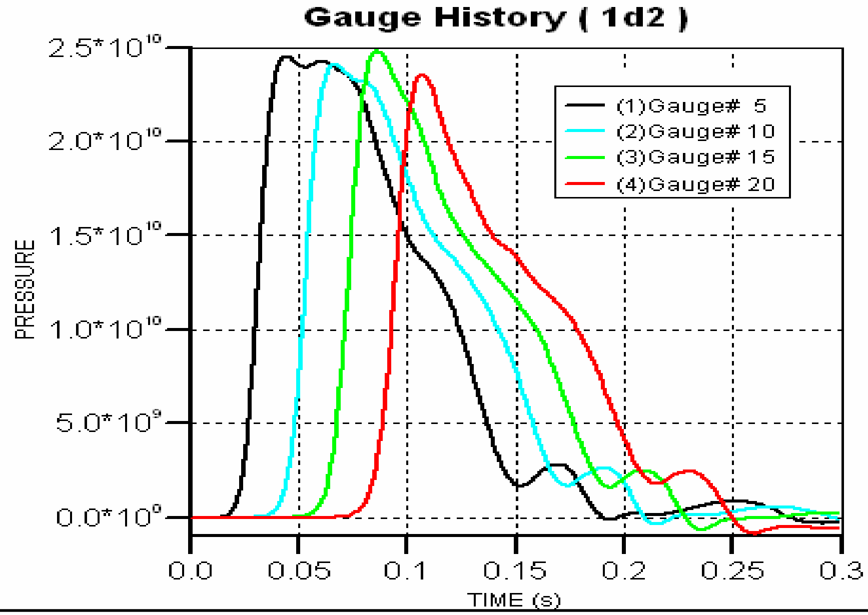


# 2 km/s Impact

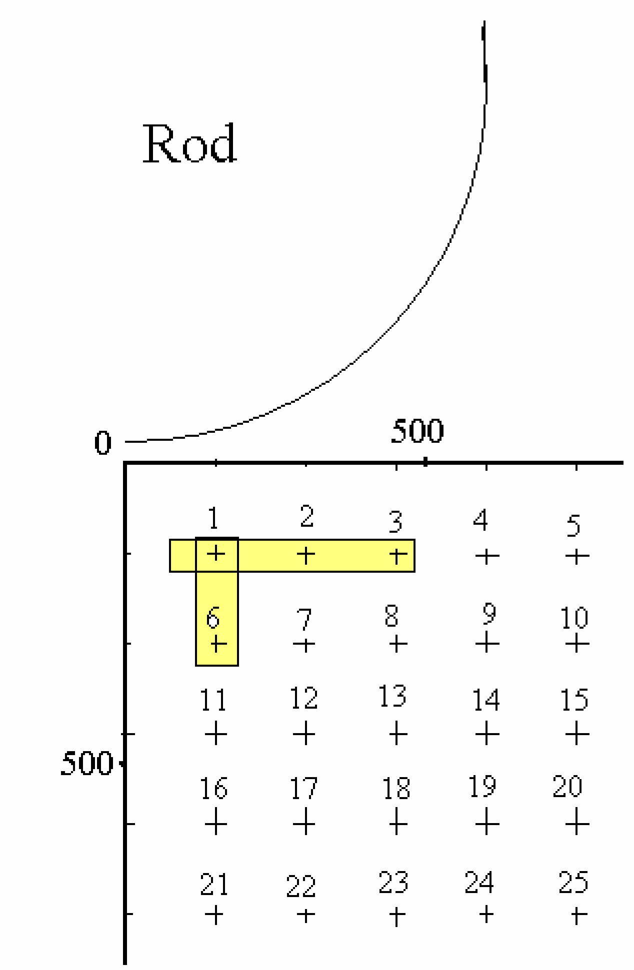
Good agreement with analytic result, except for predicted risetime distortion, implies credible Autodyn™ results.



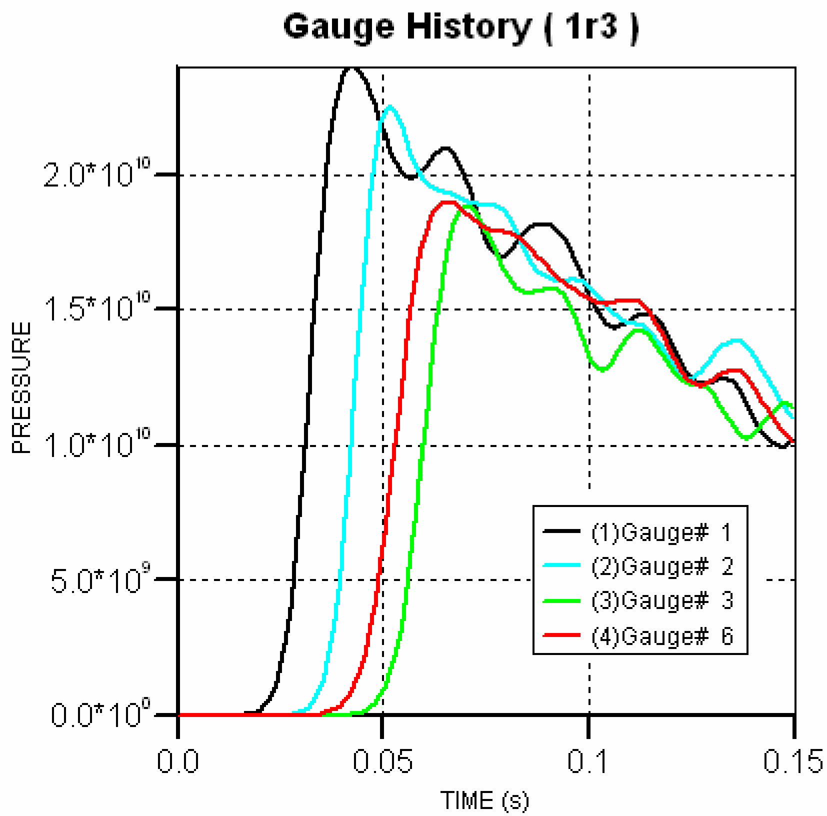



# 3 km/s Impact

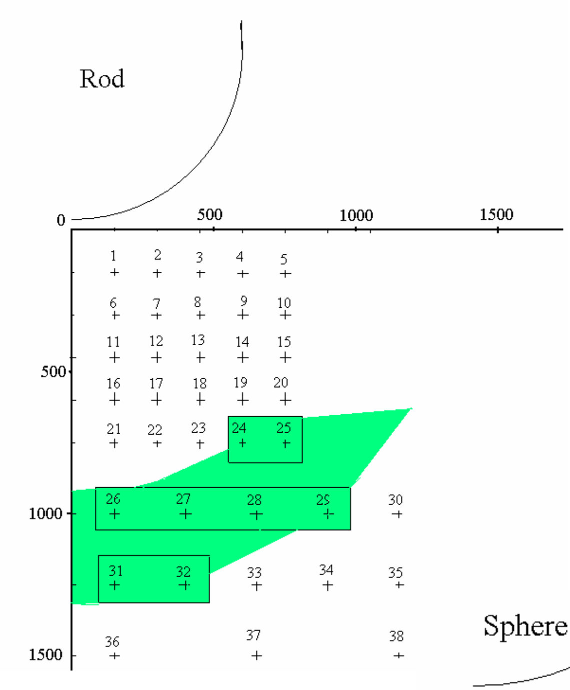


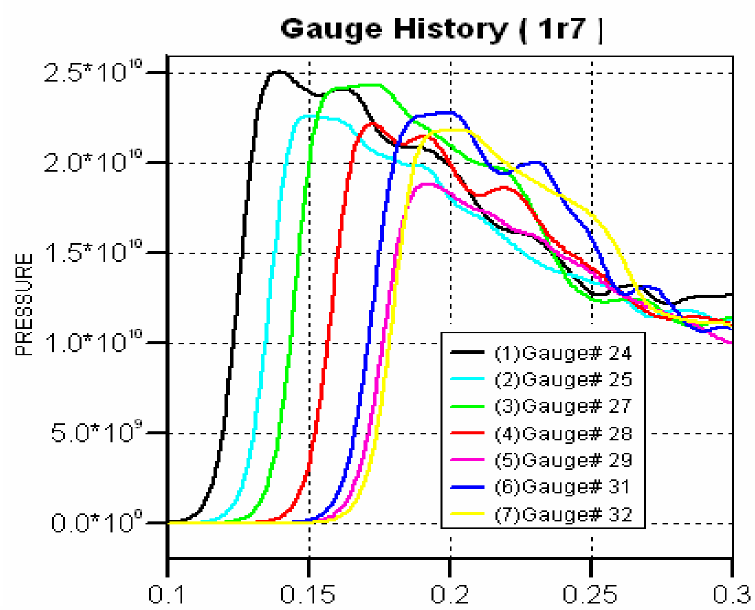
Rod
0
500
500
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

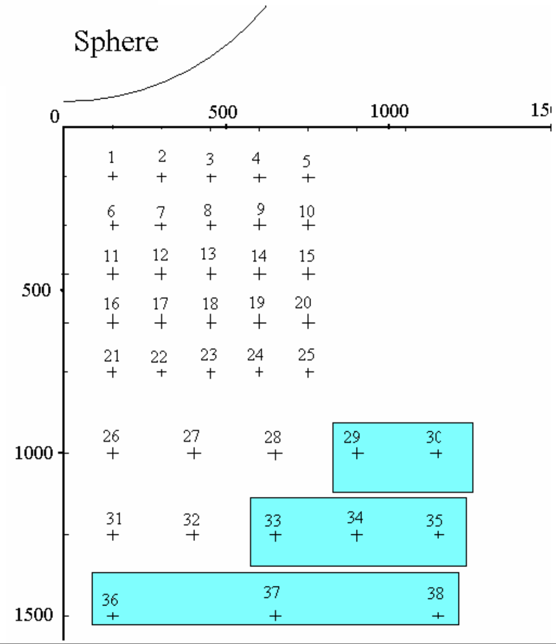



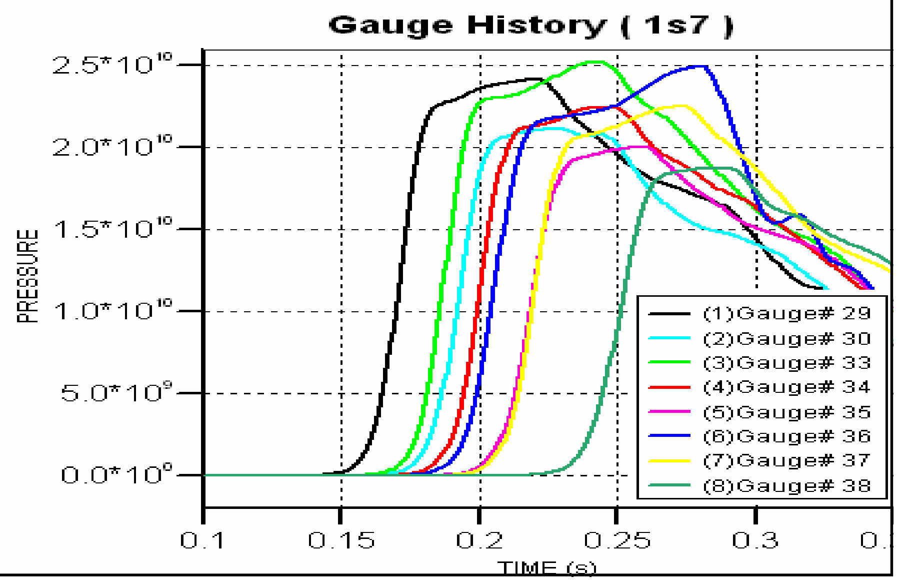
Gauge History ( 1r3 )
PRESSURE
2.0*10^10
1.5*10^10
1.0*10^10
5.0*10^9
0.0*10^0
0.0
0.05
0.1
0.15
TIME (s)
(1)Gauge# 1
(2)Gauge# 2
(3)Gauge# 3
(4)Gauge# 6

# 5.4 km/s Impacts



# Summary

- Hydrocode calculations allow us to make more realistic interpretations of shock pressure and duration.
  - Realistic shapes
- Also allow for attenation
  - Explor range of velocities and depths of shock effects.