ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 8: Craters

Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I’ll let you know in advance if we’ll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 2 is due TONIGHT, 11:59pm

Review of the last class

- What type of crater is this?
  - (A) — Simple Crater
  - (B) — Complex Crater
  - (C) — Multiring Basin

Review of the last class

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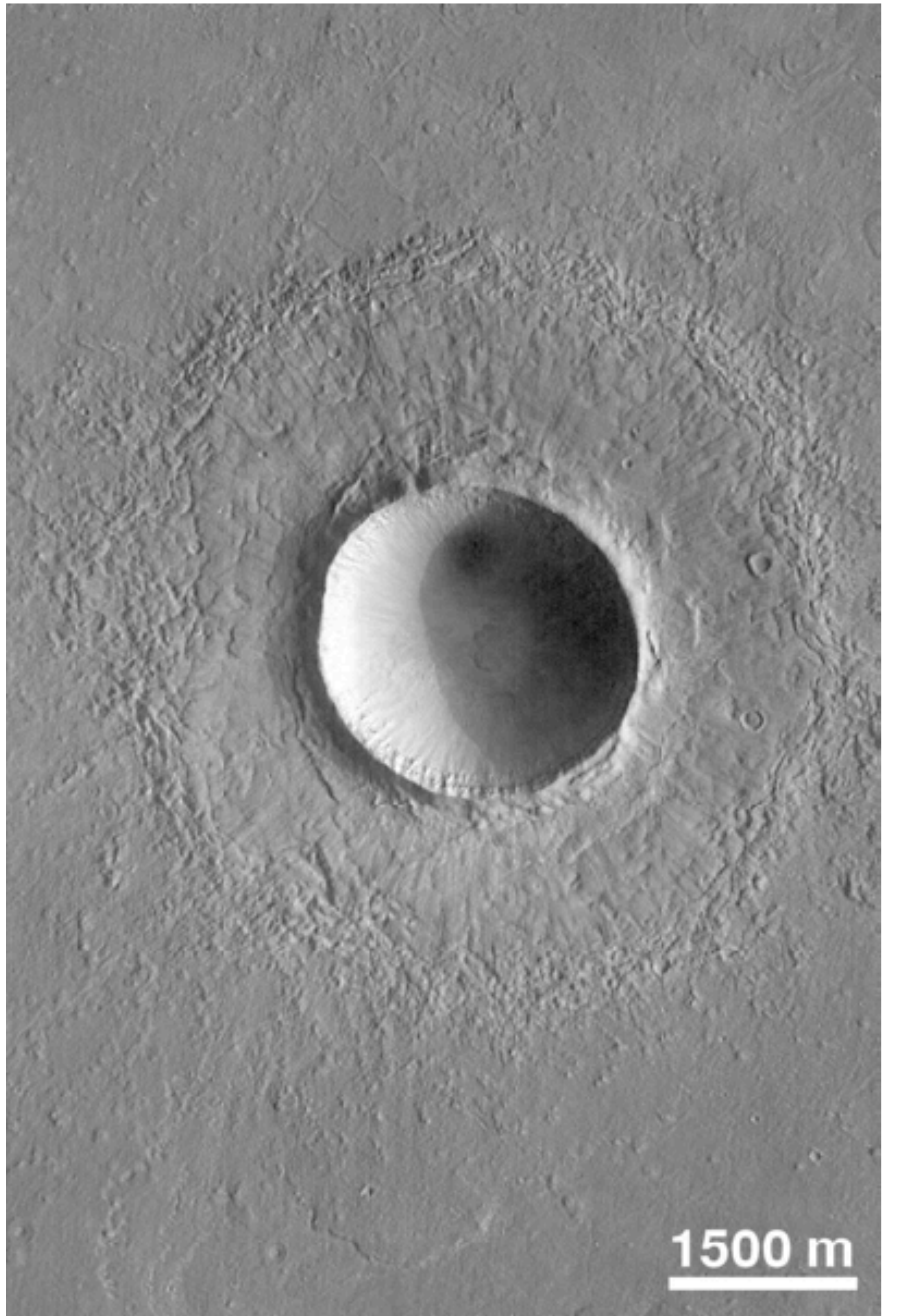


Review of the last class

- Three asteroids hit the same body, asteroid 1 makes a multi-ring basin, asteroid 2 makes a simple crater, asteroid 3 makes a complex crater. Which of these correctly ranks their impact energies from lowest to highest?
  - (A) — (lowest) asteroid 1, asteroid 2, asteroid 3 (highest)
  - (B) — (lowest) asteroid 1, asteroid 3, asteroid 2 (highest)
  - (C) — (lowest) asteroid 2, asteroid 1, asteroid 3 (highest)
  - (D) — (lowest) asteroid 2, asteroid 3, asteroid 1 (highest)
  - (E) — (lowest) asteroid 3, asteroid 1, asteroid 2 (highest)

Review of the last class

- The Vis-viva equation, $v = \sqrt{GM_{\odot}\left(\frac{2}{r} - \frac{1}{a}\right)}$, in the limit of e=0, reduces to:
  - (A) — Escape velocity (from the Earth)
  - (B) — Escape velocity (from the Sun)
  - (C) — Circular orbital velocity of the Earth
  - (D) — Rotational orbital velocity of the Earth
  - (E) — 0 m/s

Review of the last class

- The Vis-viva equation, $v = \sqrt{GM_{\odot}\left(\frac{2}{r} - \frac{1}{a}\right)}$, in the limit of eccentricity very close to 1, and the body being at perihelion, reduces to:
  - (A) — Escape velocity (from the Earth)
  - (B) — Escape velocity (from the Sun)
  - (C) — Circular orbital velocity of the Earth
  - (D) — Rotational orbital velocity of the Earth
  - (E) — 0 m/s

Review of the last class

- Escape velocity (from the Sun) at 1 AU is about 40 km/s. If Earth hits a long-period comet head-on, the impact velocity will be about:
  - (A) — 10 km/s
  - (B) — 30 km/s
  - (C) — 40 km/s
  - (D) — 70 km/s
  - (E) — 80 km/s

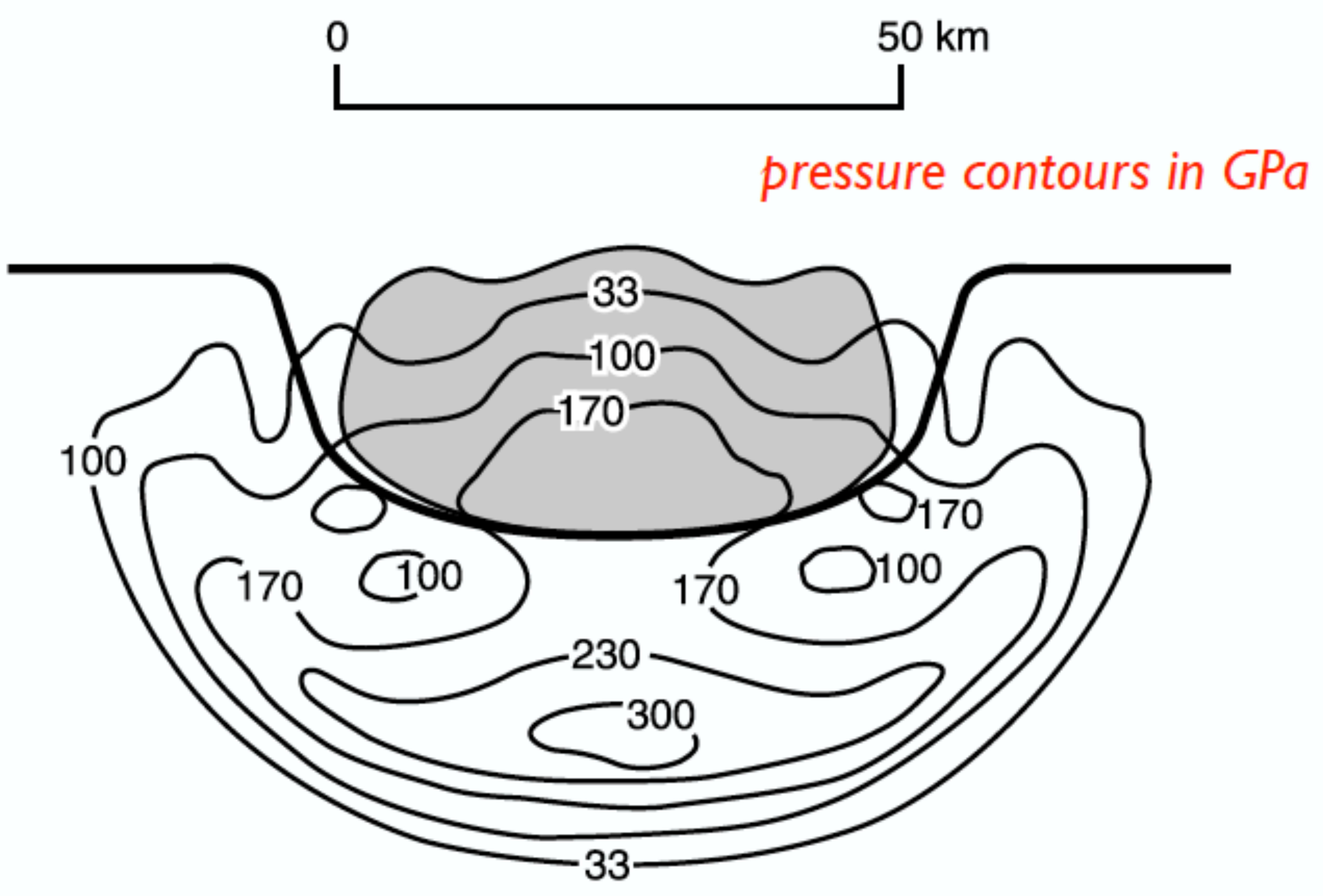
Stages of Crater Formation

- 1) Contact and compression
- 2) Excavation
- 3) Modification
- Timescale is the time required for impactor to penetrate its own diameter into the target:

$$\tau = \frac{D_{impactor}}{v_{impactor}}$$

Contact and Compression

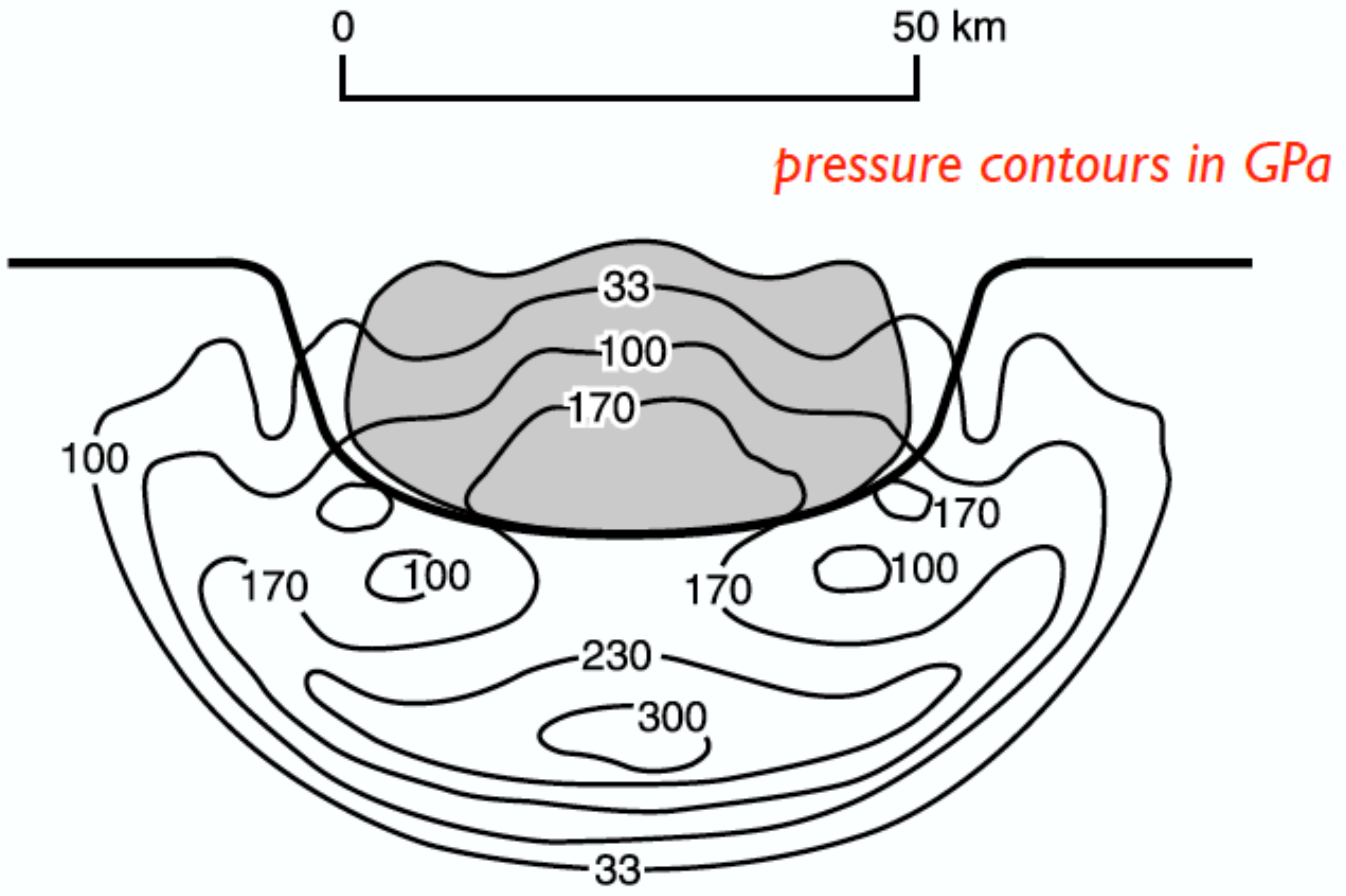
- Jetting: highest speed ejecta thrown out as impactor edge penetrates into target
- short-lived: persists for $\sim\frac{\tau}{2}$
    - jetted material can continue in flight for long time after that
- Jetting can eject up to 80% of impactor mass, and pressures that drive this jetting can reach hundreds of GPa



Compression and Shock

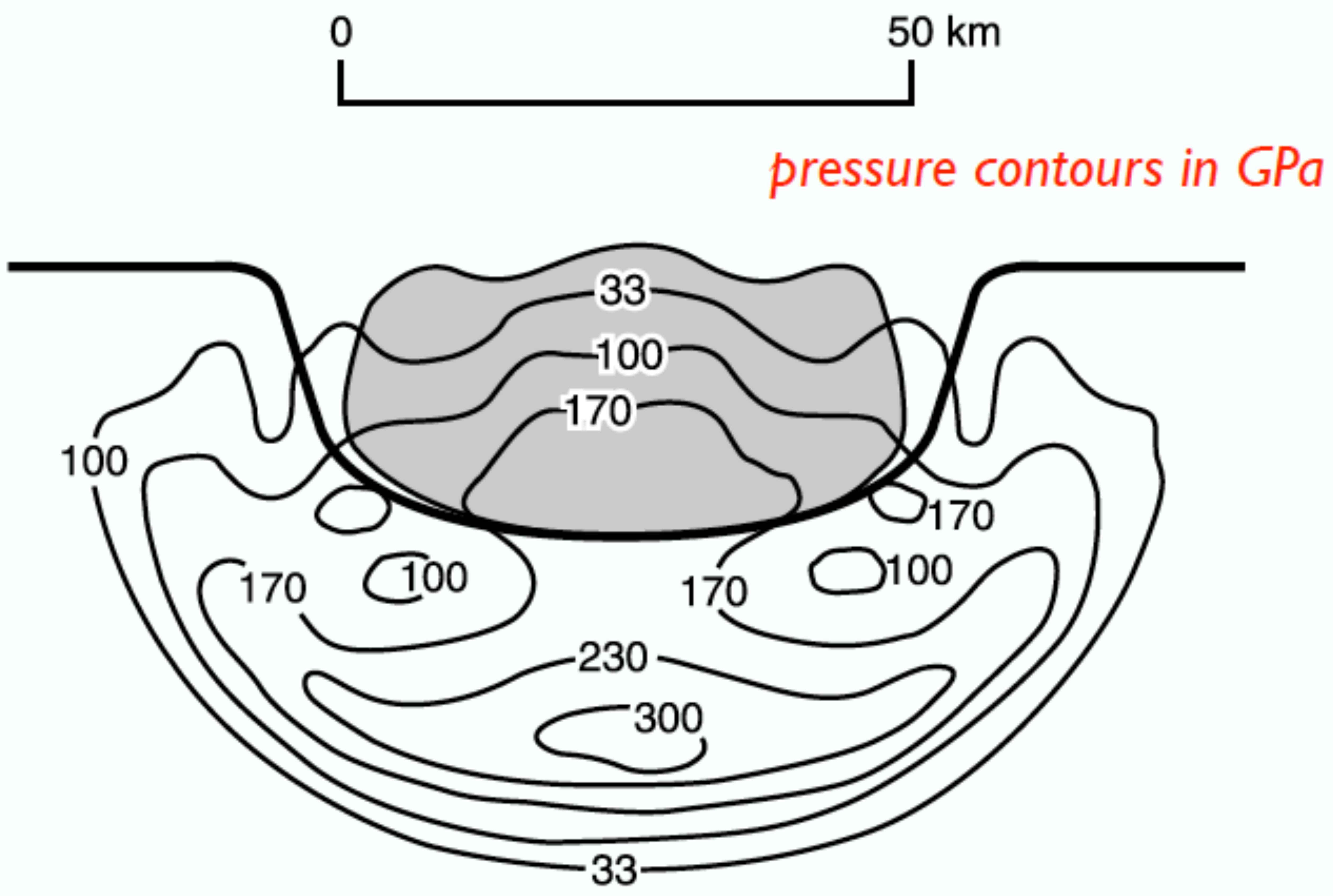
- Extreme pressures from impact produces shock waves that travel through both impactor and target

- Physics of shock involve conserving mass, momentum, and energy across the shock, as well as equation of state of material



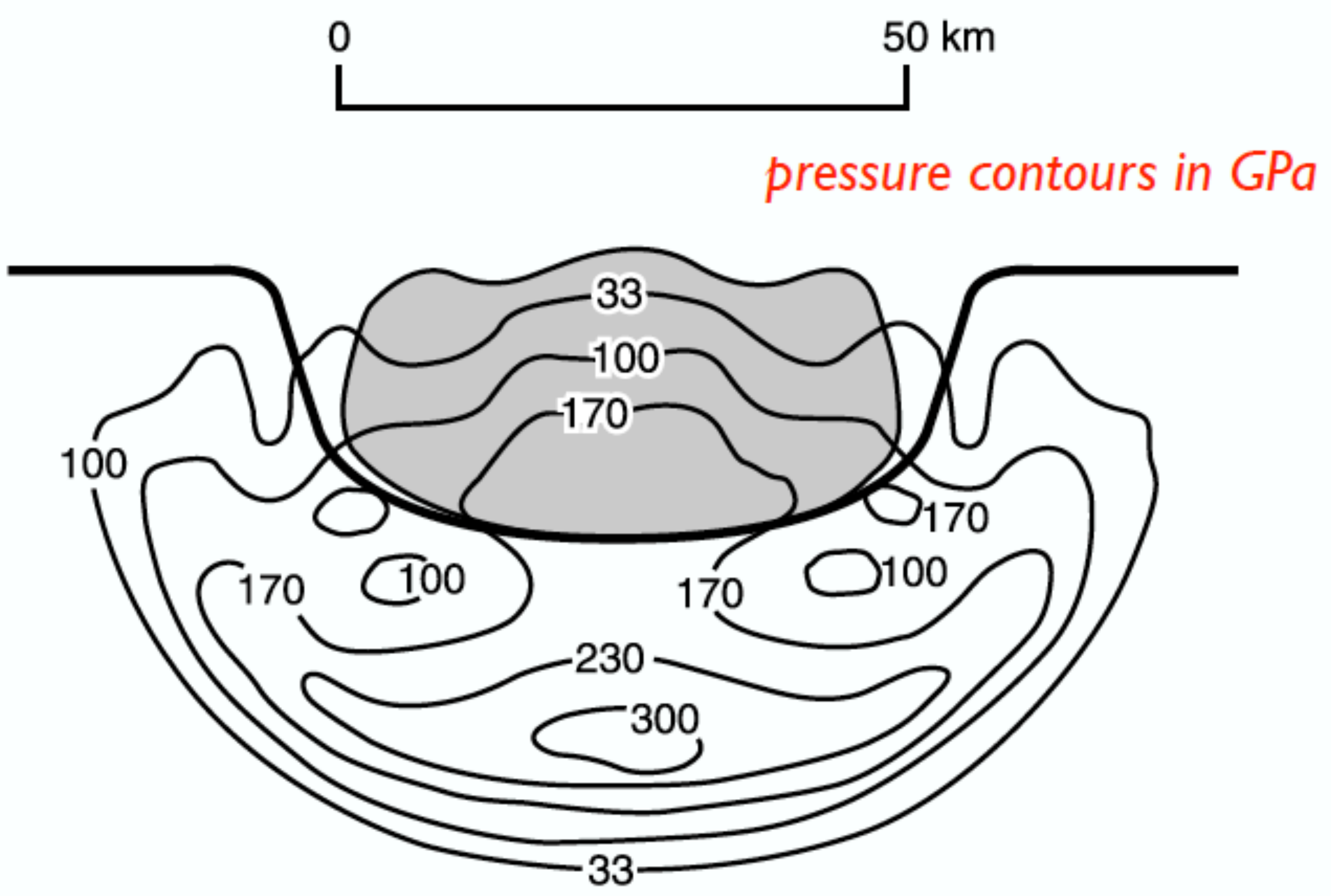
Crater Formation

- Impactors strike ground with speed much greater than sound speed of target rock
- Speed of shock is similar to speed of impactor (very fast)
- Crater produced by intense shock waves and are generated at impact point and radiate outward at velocities of ~10 km/s
- As it expands outward, shock waves set large volumes of rock into motion, excavating crater



Shock Wave

- Shock from impact location travels both down through target, and up through impactor
- When shock reaches top of impactor, pressure is released in a rarefaction wave: this is what vaporizes the impactor
- Total duration (impact, shock wave, rarefaction wave): $\sim 1.5\tau$

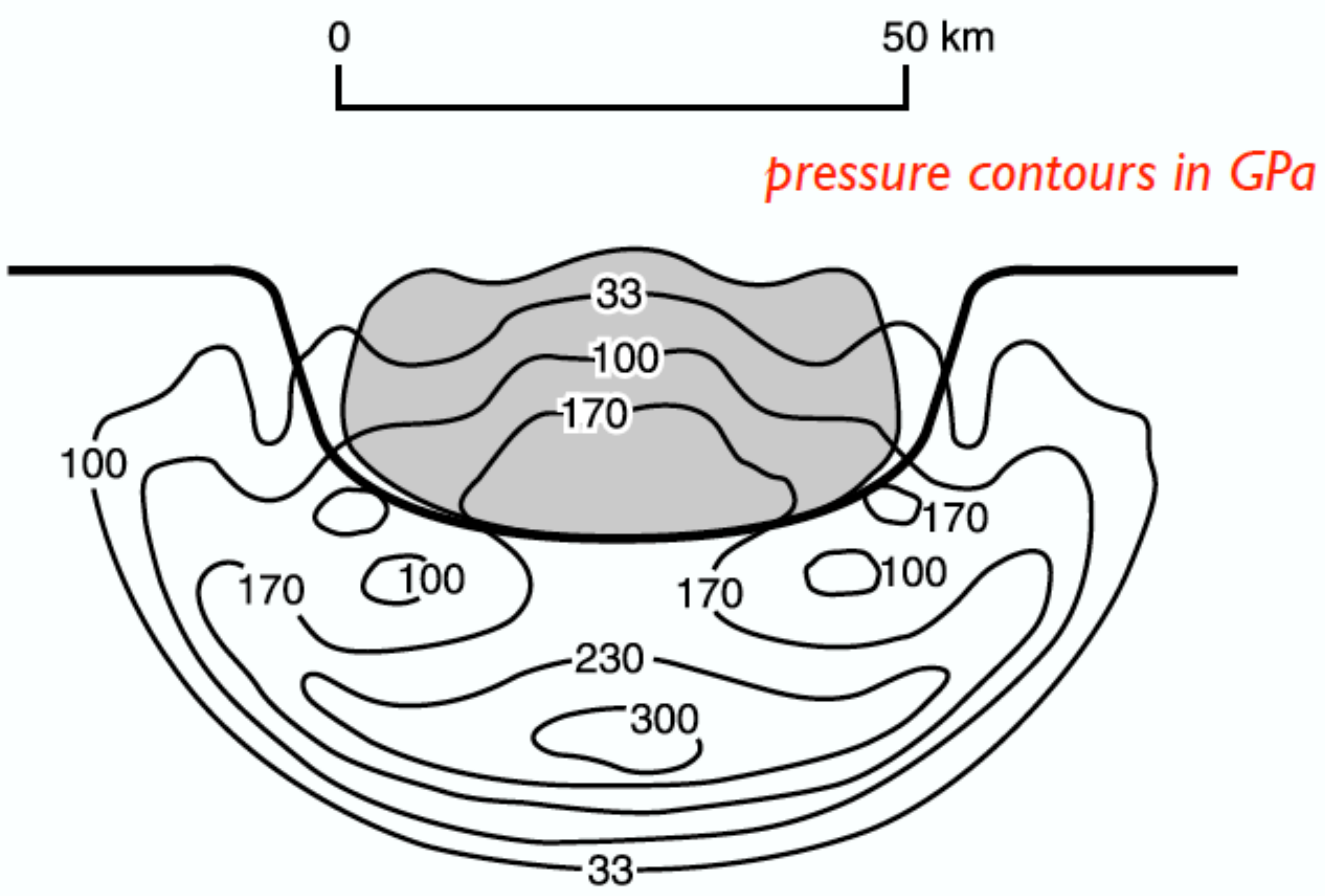


Response Card Question

- A 1 km impactor hits with a velocity of 10 km/s. What is the timescale τ?
  - (A) — 100 seconds
  - (B) — 10 seconds
  - (C) — 1 second
  - (D) — 0.1 seconds
  - (E) — 0.01 seconds

Contact and Compression

- Shock wave (downward through target) loses energy rapidly:
  - Expanding shock front is covering a larger and larger area as it expands radially
  - Heat lost to target rocks through heating, deformation, acceleration

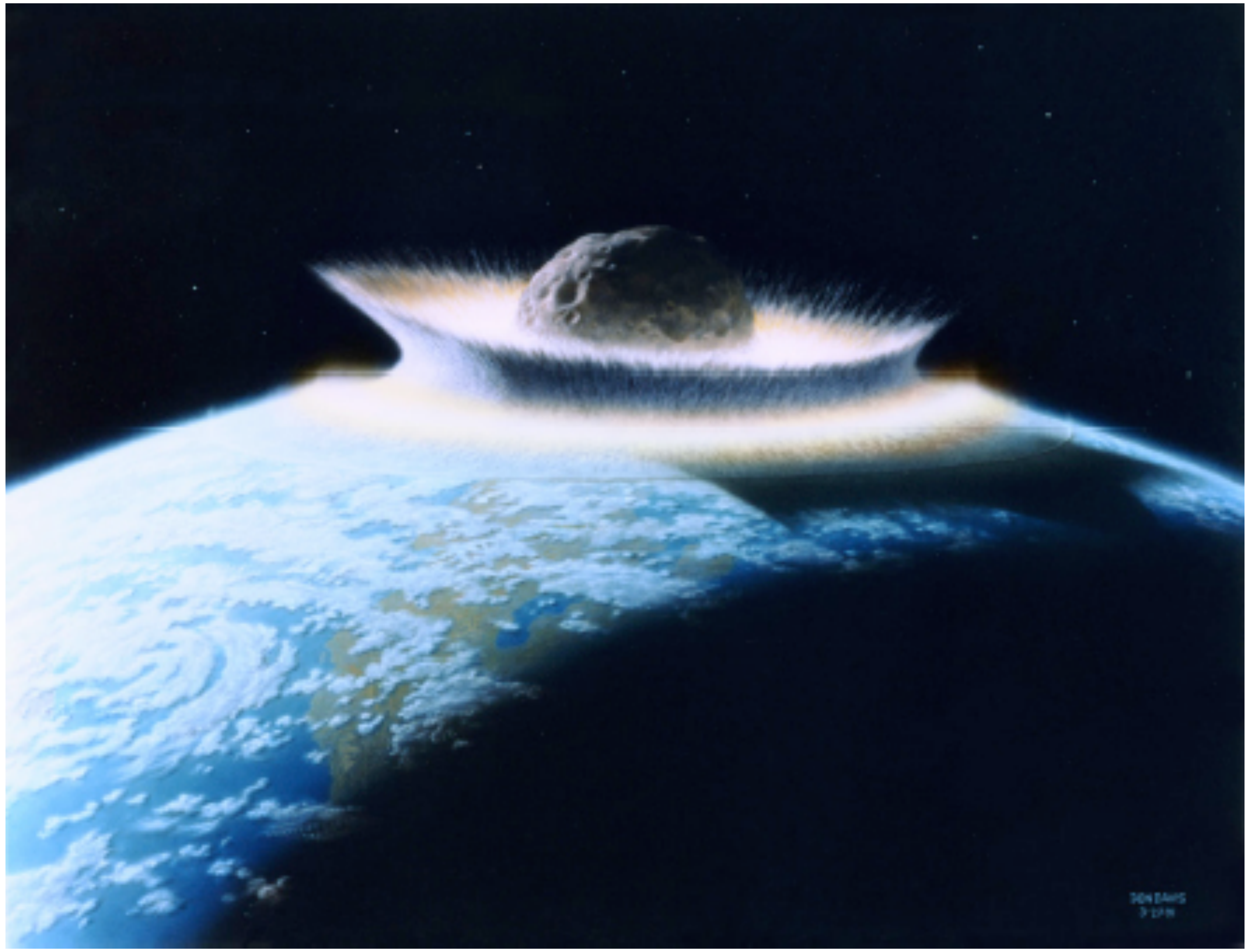


Impact Craters

- Shock wave travels through impactor with timescale

$$\tau = \frac{D}{U} \approx \frac{D}{v_{impact}}$$ (U: shock velocity)

- Contact and compression (first stage of crater formation) takes about 1.5τ
- 15 km impactor at 15 km/s: 1 second timescale



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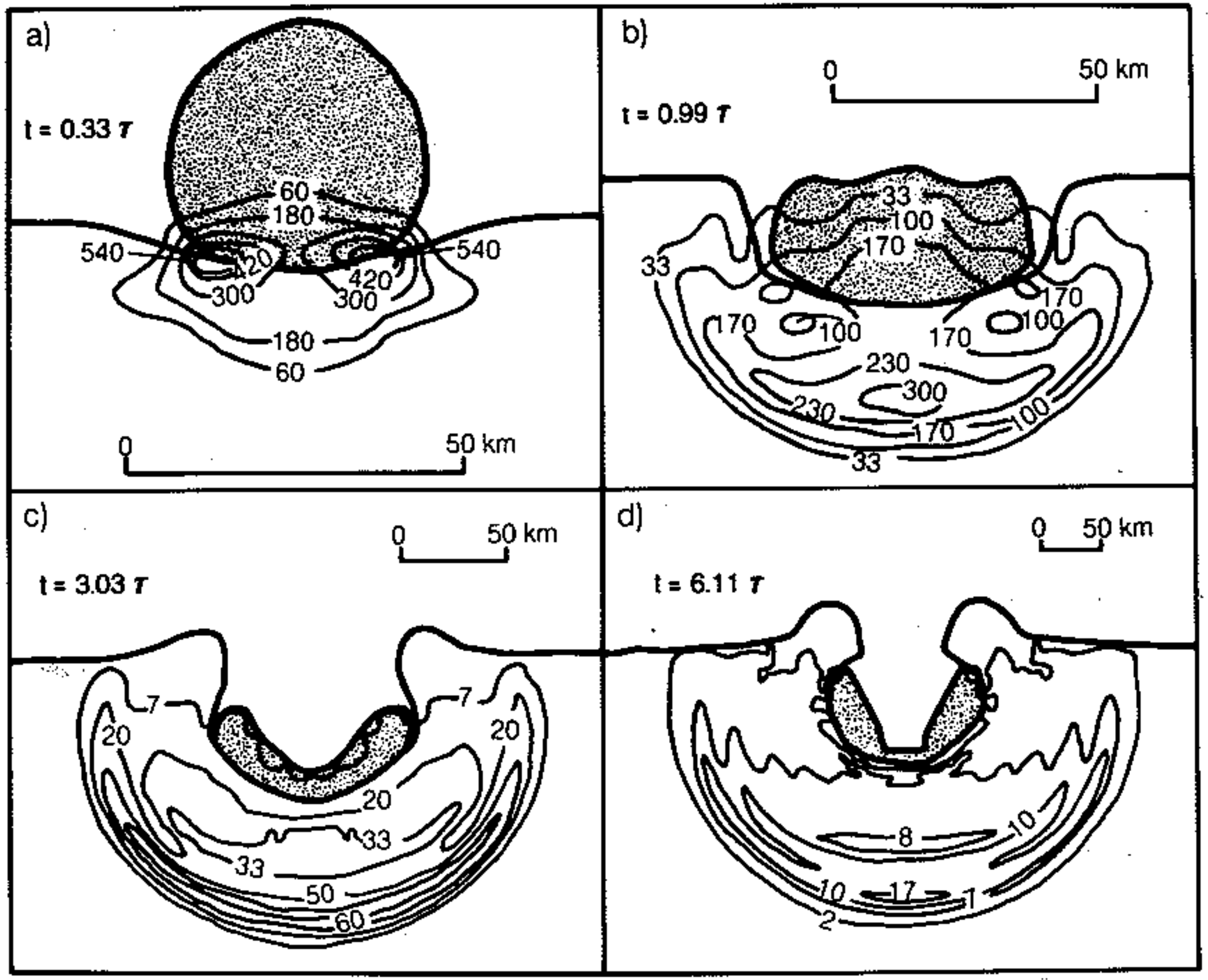
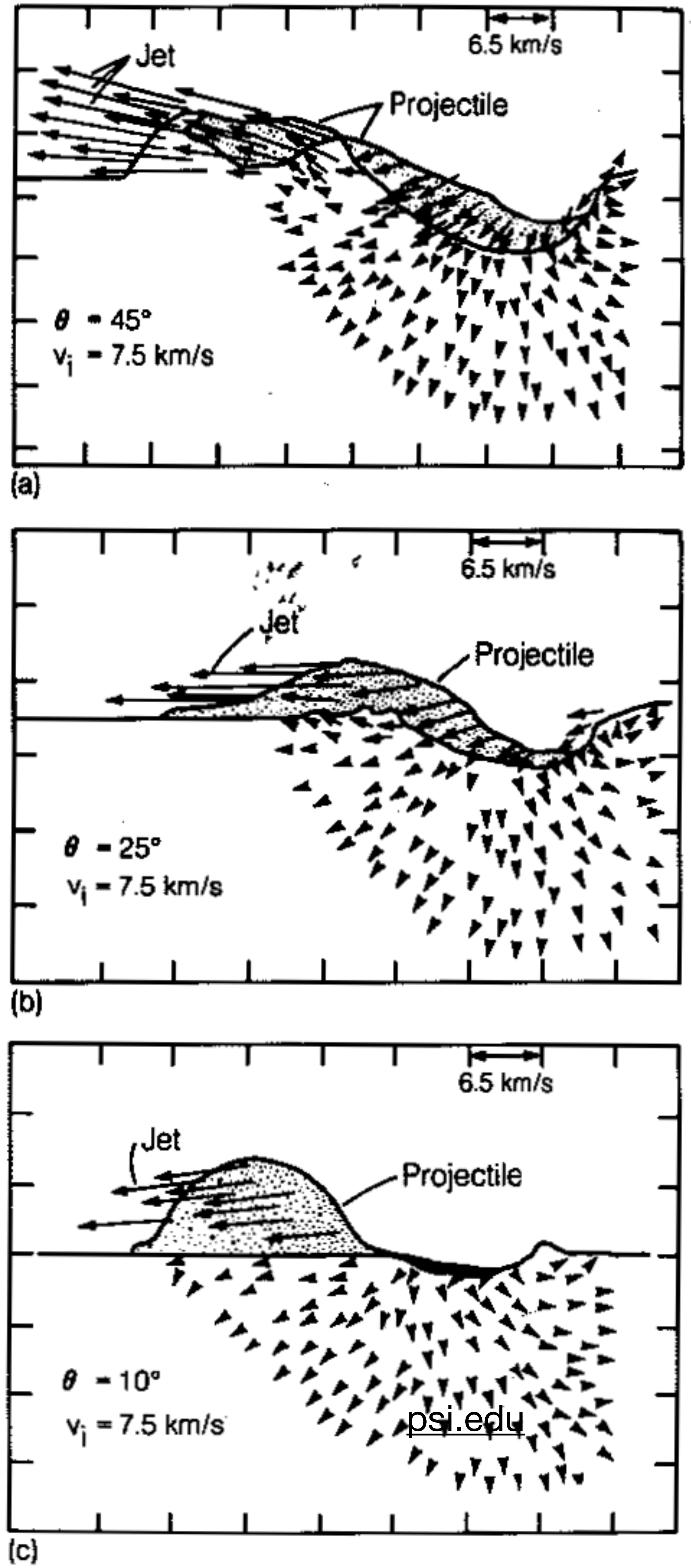


Fig. 4.1 Four snapshots are shown of the vertical impact of a 46.4-km diameter iron projectile on a gabbroic anorthosite target at 15 km/second. The first three frames illustrate different phases in the contact and compression stage and the last frame is a very early phase of the excavation stage. The contour values are pressures in GPa. Times shown are in units of τ, Equation 4.2.1. See the text for individual discussion of the frames. Do not overlook the changes in scale from one frame to the next. *After O'Keefe and Ahrens (1975).*

Jetting

- High speed ejecta squirts out from high-pressure "islands" right after contact
- Happens over short timescales but can eject up to 80% of the projectile mass



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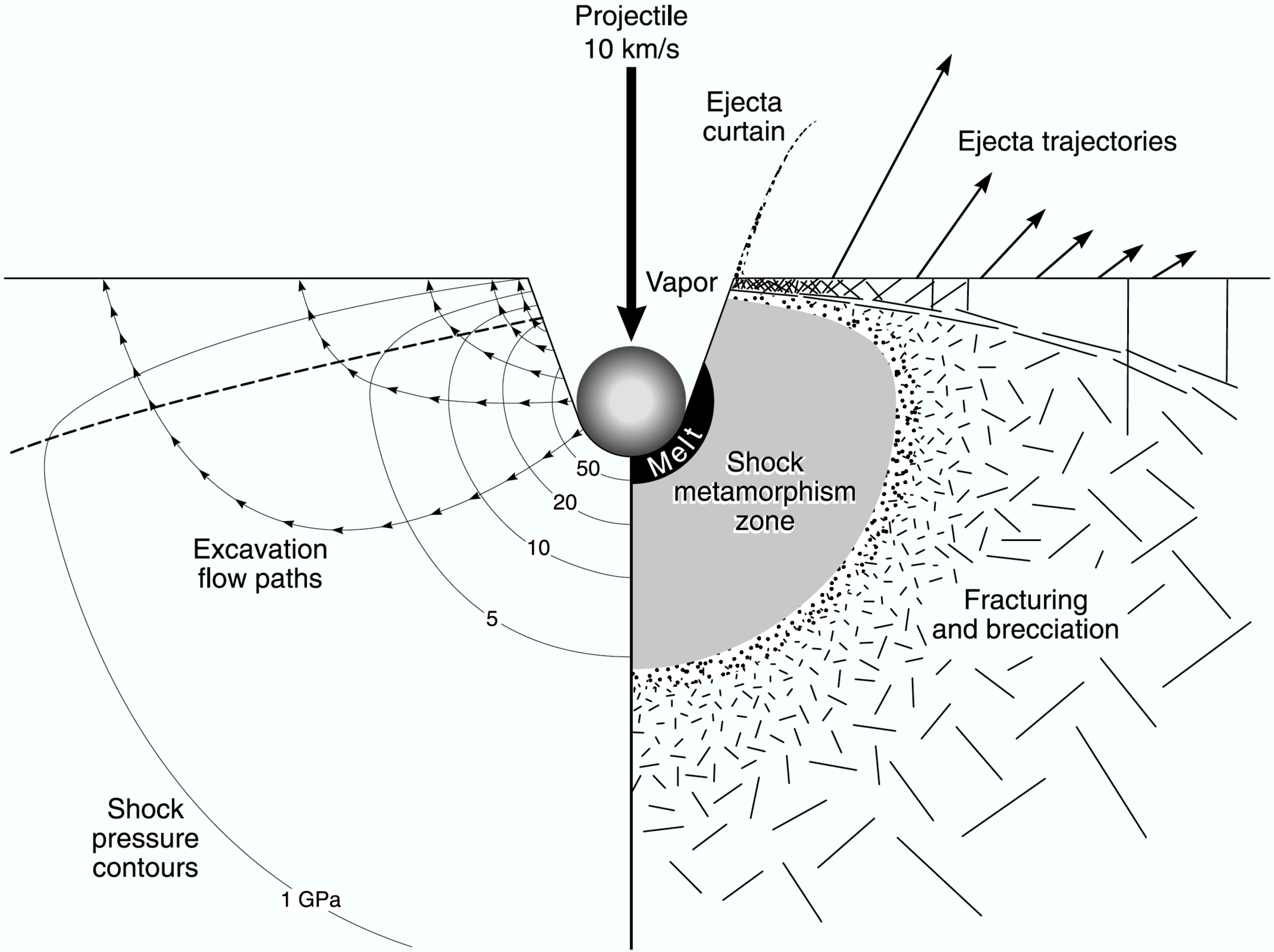
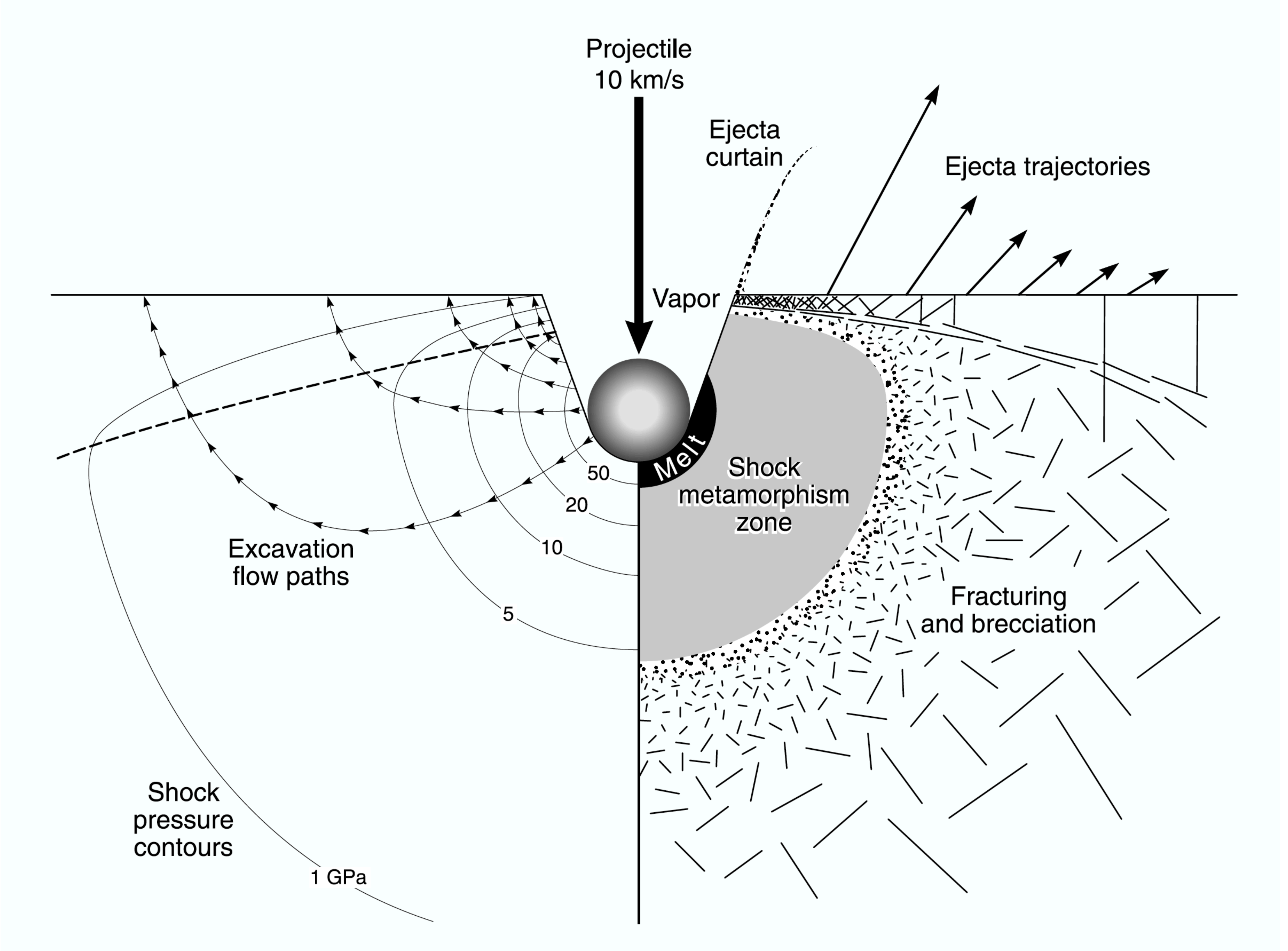

Projectile
10 km/s
Ejecta
curtain
Ejecta trajectories
Vapor
Melt
Shock
metamorphism
zone
50
20
10
5
Excavation
flow paths
Fracturing
and brecciation
Shock
pressure
contours
1 GPa

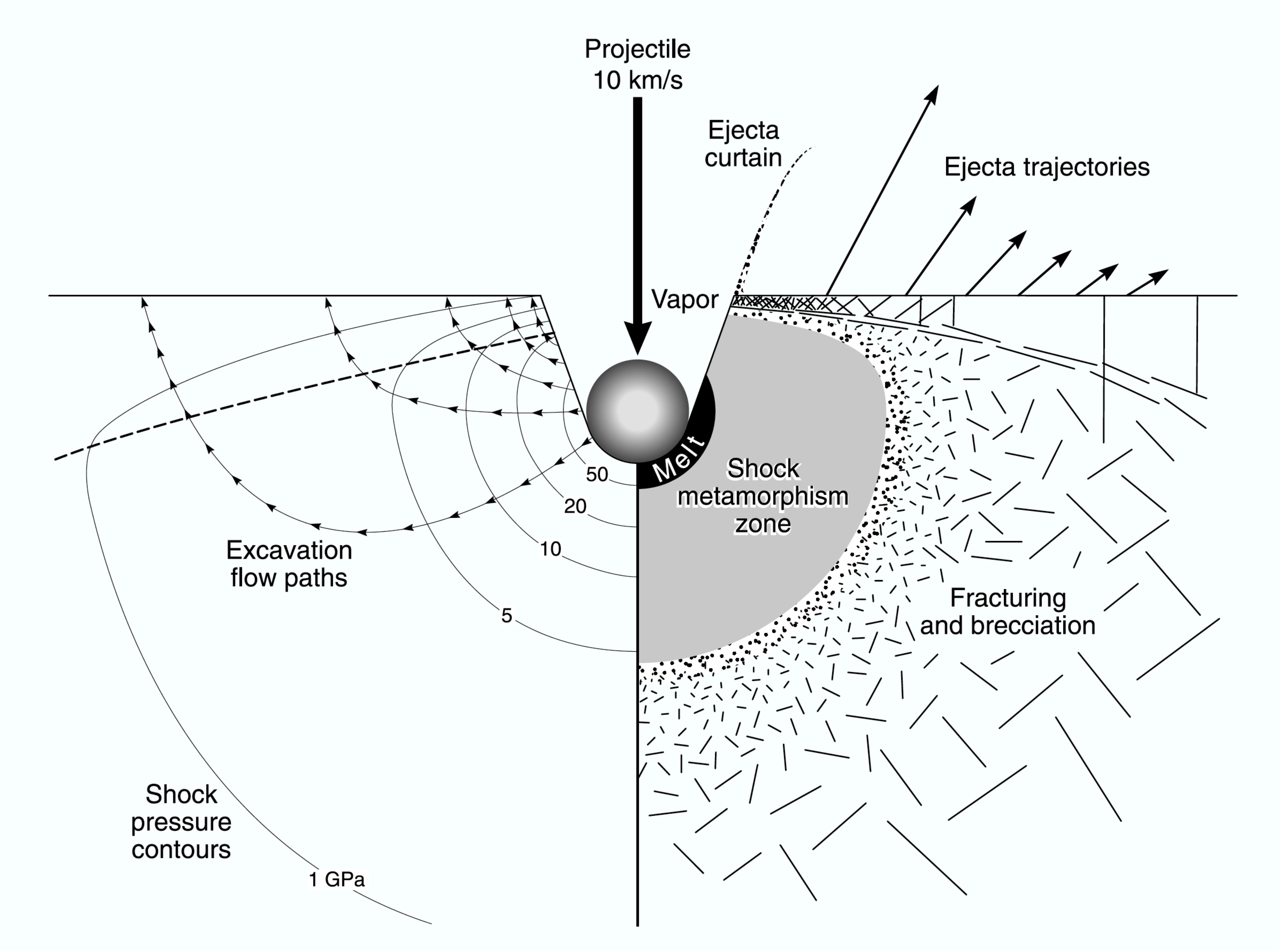
Excavation

- Material is physically removed upward and radially outward from the developing crater
- Flow of material caused by:
  - shock wave hemispherically propagating into target
  - “release” (rarefaction) wave the propagates in the same direction
- Outflow (ejecta) velocity below shock speed and below impact speed: excavation does not accelerate particles to escape velocity



Transient Crater

- At end of excavation phase have a transient crater
- Depth of transient crater set by strength of target material
- After maximum depth is reached, shock wave expanding continues to expand crater horizontally



Transient Crater

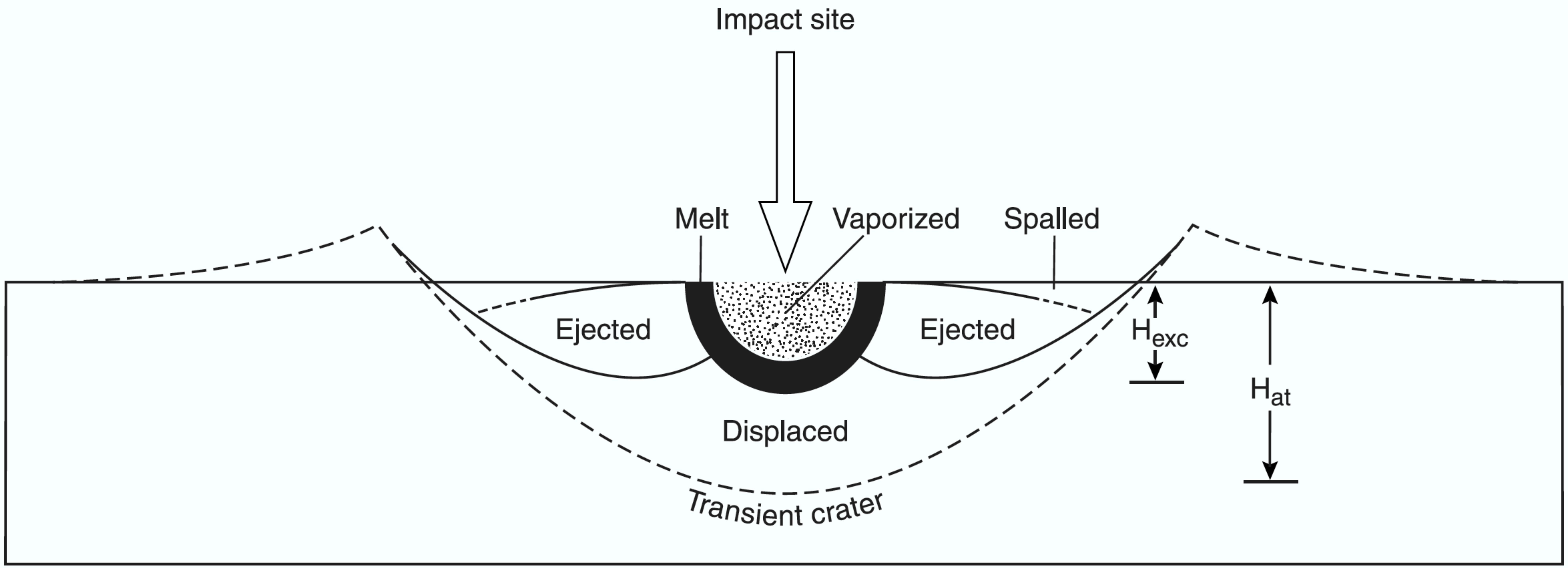
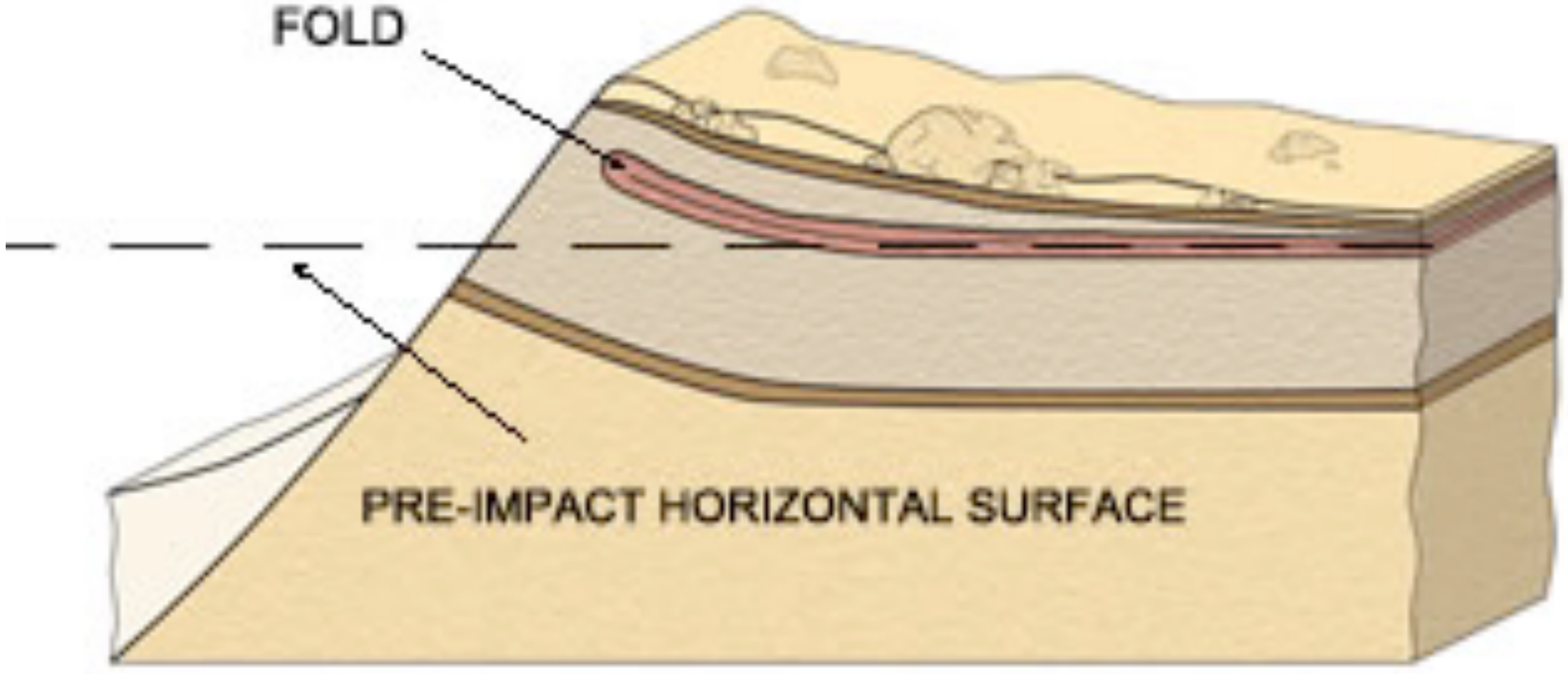


Fig. 3.5. Transient crater: locations of shock-metamorphosed materials. Cross section through a theoretical transient crater, showing discrete zones from which various shock-metamorphosed materials are derived. The "vaporized" zone closest to the original impact point (stippled) contains a mixture of vaporized target rock and projectile, which expands upward and outward into the atmosphere as a **vapor plume**. The adjacent "melt" zone (solid black) consists of melt that moves downward and then outward along the floor of the final transient cavity (for details, see Fig. 6.2). Material in the upper "ejected" zones on either side of the melt zone, which contains a range of shock-metamorphic effects, is ejected outward to and beyond the transient crater rim. The lower "displaced" zone moves downward and outward to form the zone of **parautochthonous** rocks below the floor of the final transient crater. H_{at} = the final transient crater depth; H_{exc} = the depth of excavation, which is significantly less than the total depth. (From *Melosh,* 1989, Fig. 5.13, p. 78.)

Inverted Stratigraphy

- Fresh craters surrounded by lower hilly terran and small craters (secondary craters) from ejected material
- Crater rim is an overturned flap of target material
- Upper layers of rim contain material from greater depths (and so is older), deeper lays contain shallower (younger) material



Meteor Crater

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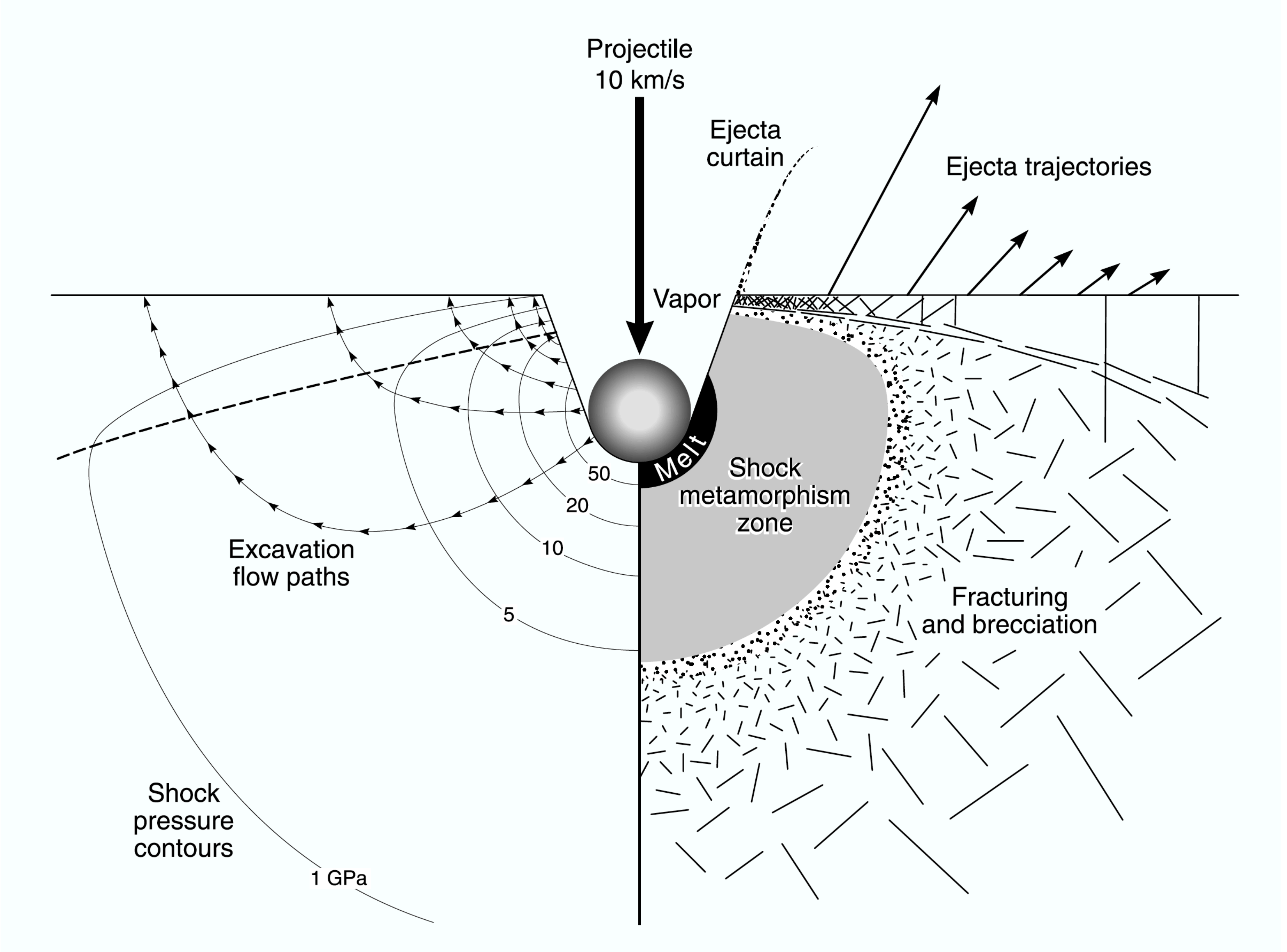
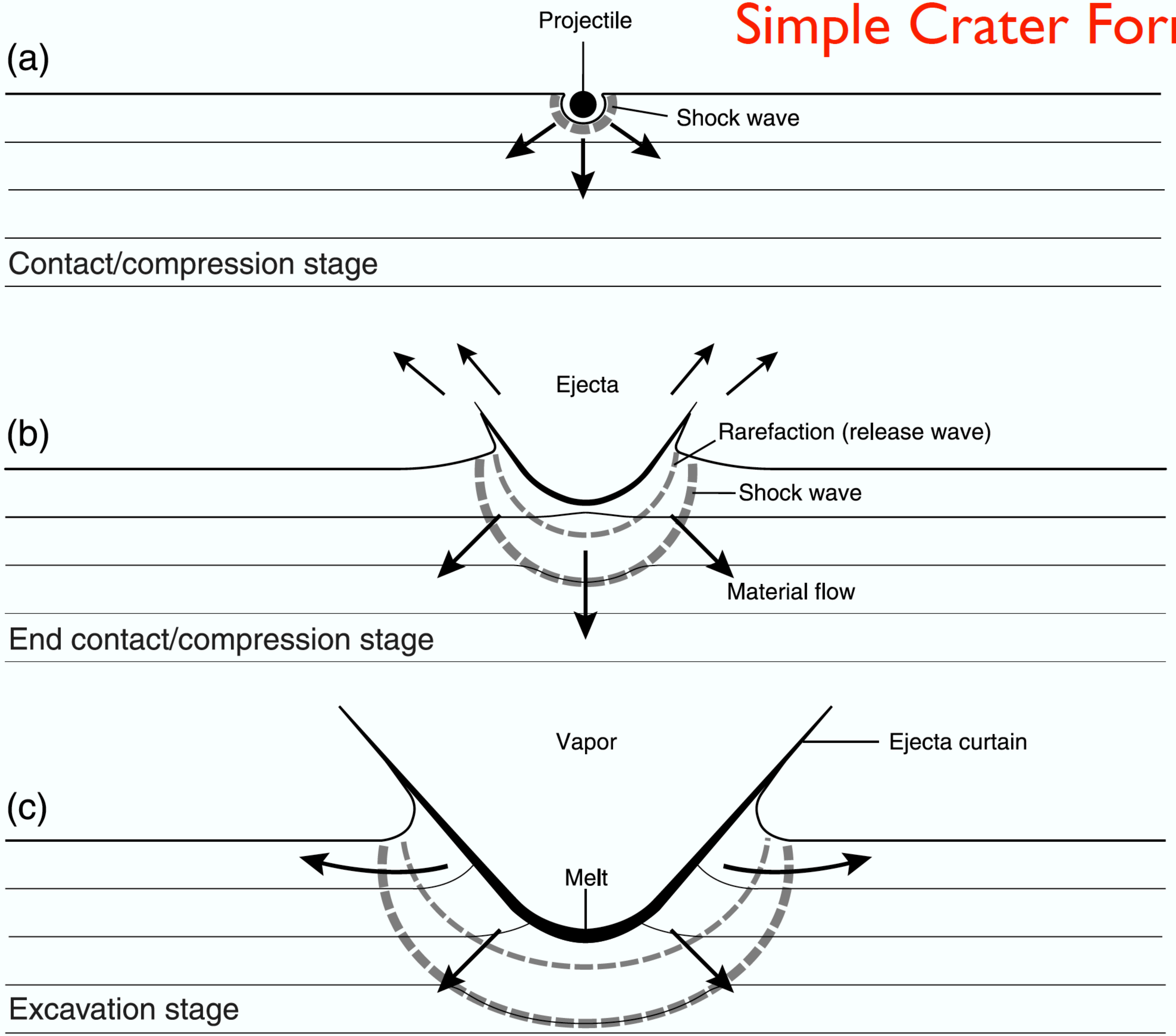
Break

Modification Stage

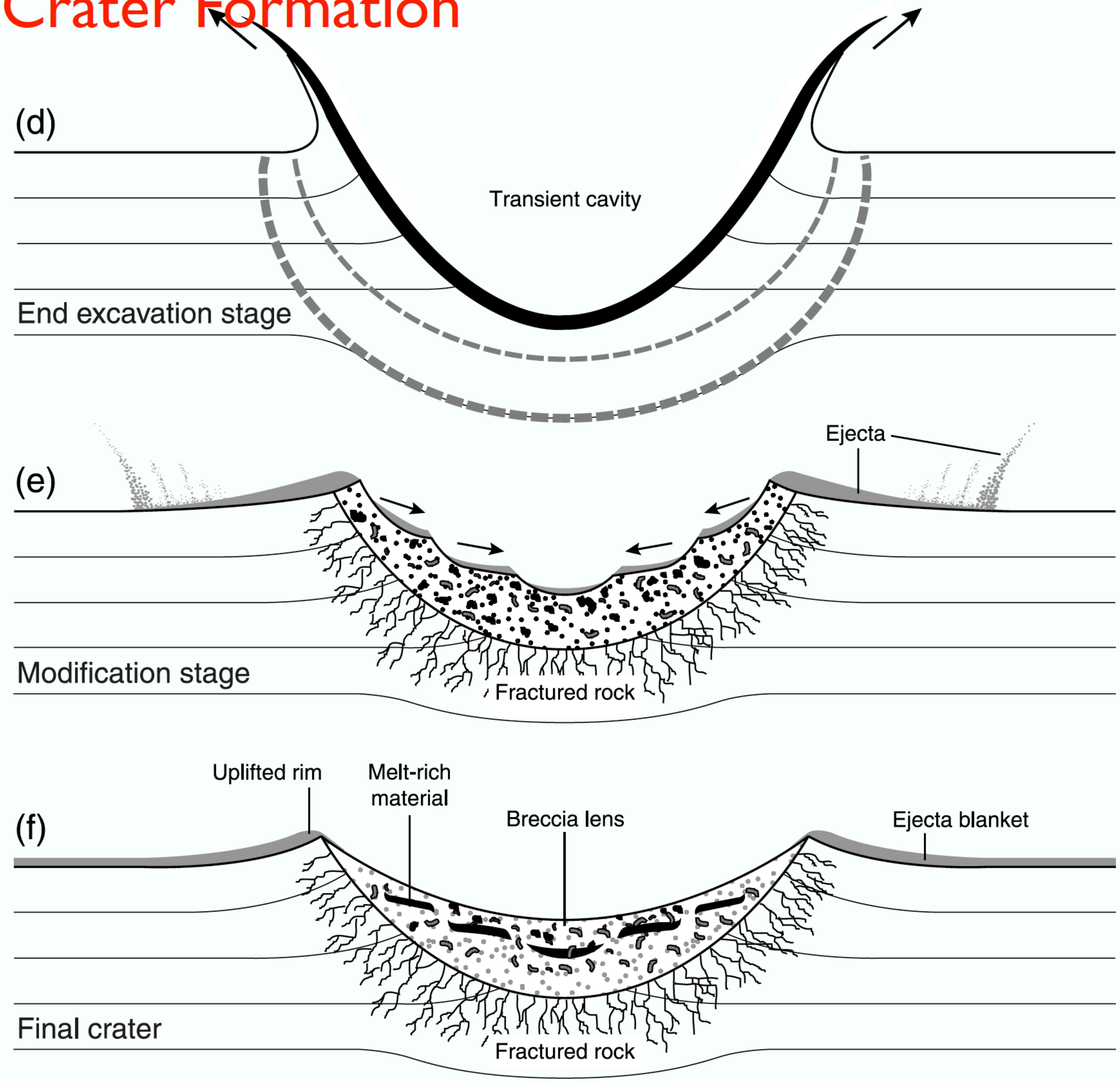
- Shock wave (now weaker) no longer reshapes the target material it passes through
- Transient crater modified by more traditional forces: gravity and rock mechanics
- Modification stage ends when “things stop falling”



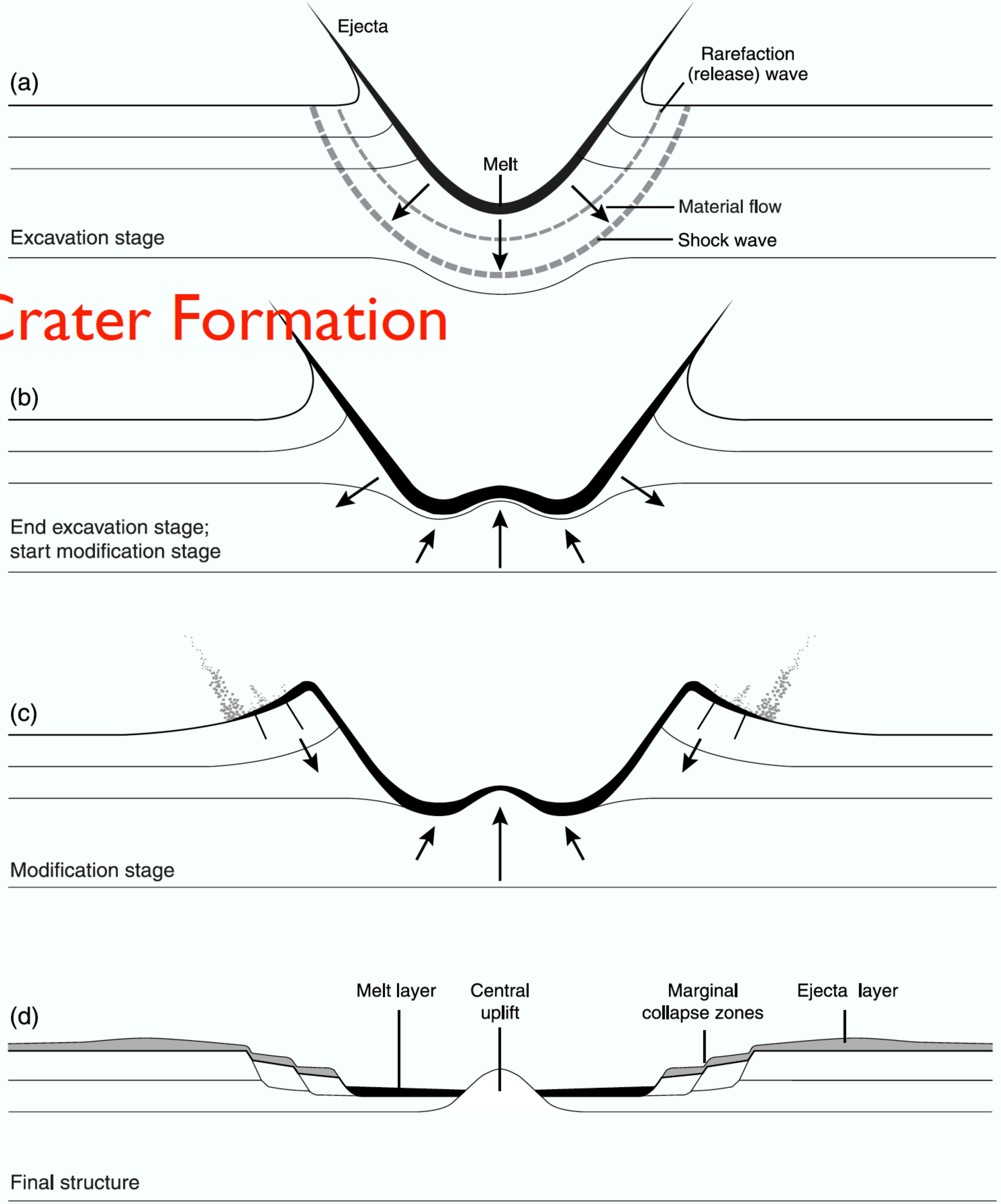
Simple Crater Formation



Simple Crater Formation



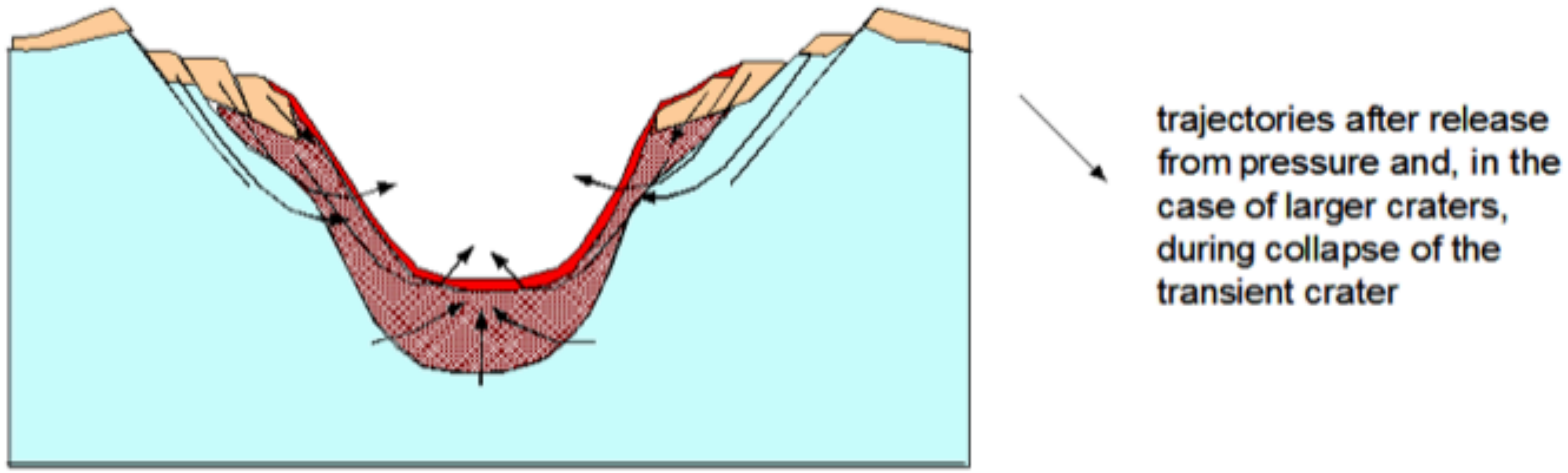
Complex Crater Formation



- During modification stage, material falls back into crater
- Reduces crater depth and diameter compared to transient crater
- For simple craters: $D_{final} = 0.84 D_{transient}$

Modification stage

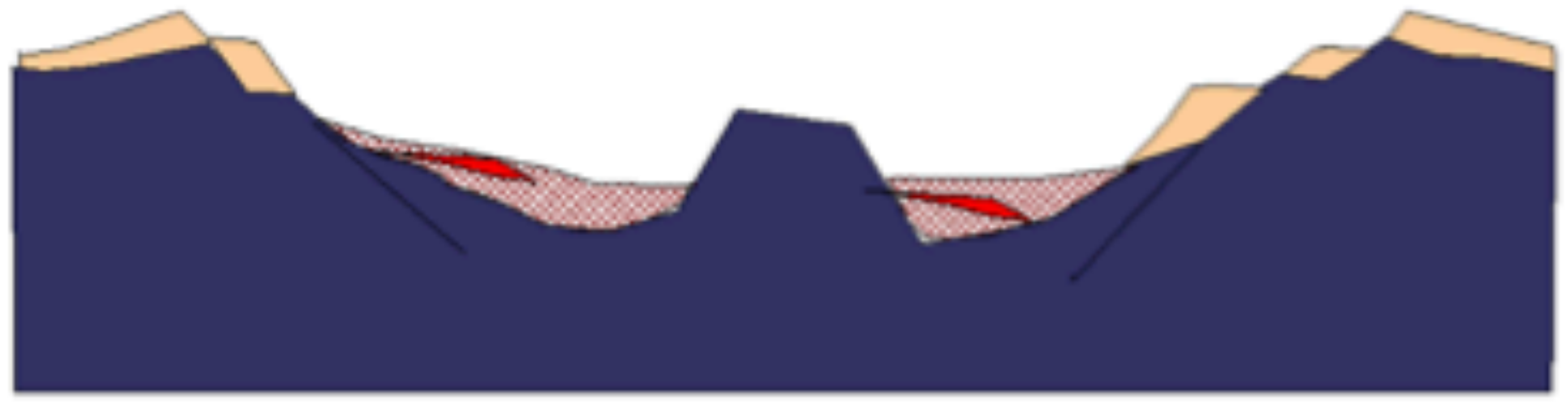
What happens to the transient crater?



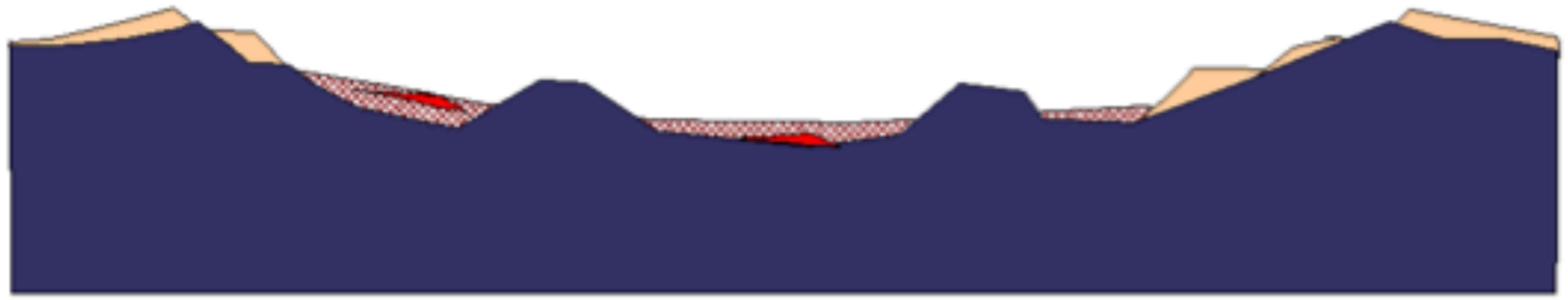
In the modification stage, the transient crater develops into a

small, bowl-shaped crater – a *simple crater*

or into a large *complex crater* exhibiting a central uplift



or into a large *complex crater* exhibiting a ring or several rings



Timescale for Crater Formation

Stage	Time
Contact & Compression	<100 ms
Ejection and Excavation	~1-5 minutes
Collapse and Modification	<15 minutes
(long term smoothing out due to erosion, micrometeorite impacts, tectonic forces, flooding, etc)	months/years/eons

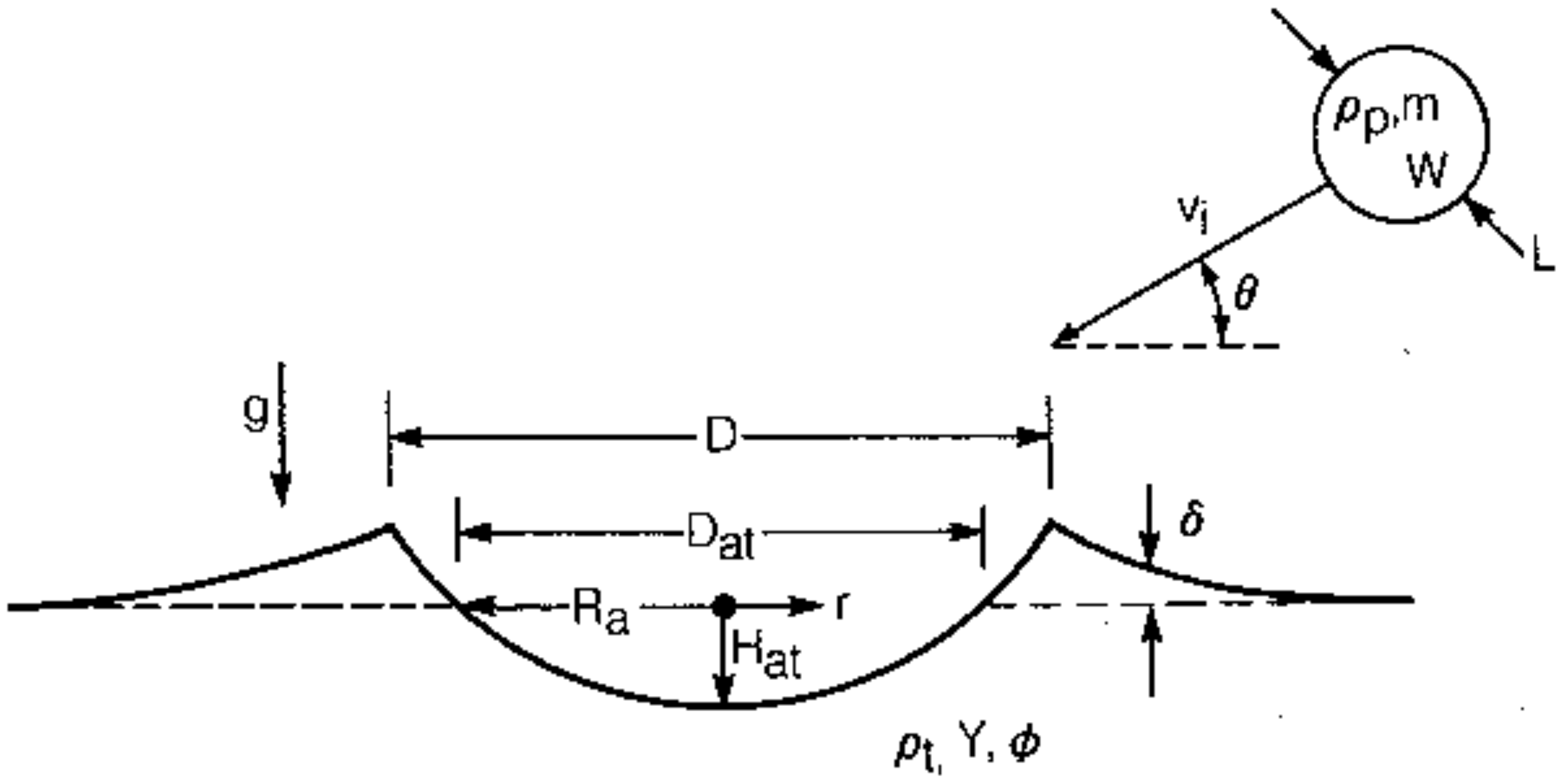
Gault Scaling Relation

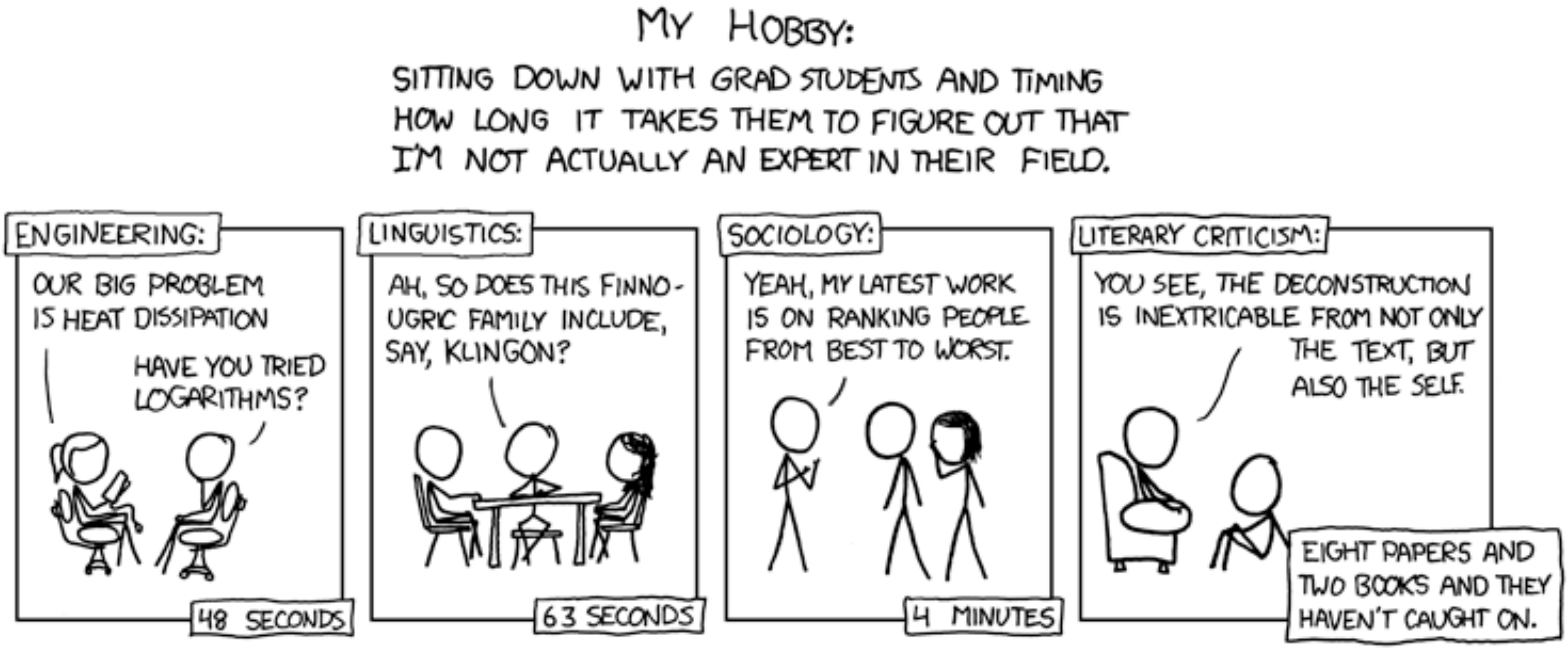
- Derived from experiments and nuclear explosions (Melosh 1989)

$$D \approx 2\rho_m^{0.11}\rho_p^{-\frac{1}{3}}g_p^{-0.22}R^{0.13}E_K^{0.22}(\sin\theta)^{\frac{1}{3}}$$ (everything in mks units)

- D: transient crater diameter
- ρ_m: meteor density
- ρ_p: planet density
- g_p: planet surface gravity
- R: meteor radius
- E_K: kinetic energy
- θ: angle of impact from surface ($90°$ is straight down)

SCALING OF CRATER DIMENSIONS




MY HOBBY:
SITTING DOWN WITH GRAD STUDENTS AND TIMING HOW LONG IT TAKES THEM TO FIGURE OUT THAT I'M NOT ACTUALLY AN EXPERT IN THEIR FIELD.
ENGINEERING:
OUR BIG PROBLEM IS HEAT DISSIPATION
HAVE YOU TRIED LOGARITHMS?
48 SECONDS
LINGUISTICS:
AH, SO DOES THIS FINNO-UGRIC FAMILY INCLUDE, SAY, KLINGON?
63 SECONDS
SOCIOLOGY:
YEAH, MY LATEST WORK IS ON RANKING PEOPLE FROM BEST TO WORST.
4 MINUTES
LITERARY CRITICISM:
YOU SEE, THE DECONSTRUCTION IS INEXTRICABLE FROM NOT ONLY THE TEXT, BUT ALSO THE SELF.
EIGHT PAPERS AND TWO BOOKS AND THEY HAVEN'T CAUGHT ON.

Order of Magnitude: Crater Diameter

- $D \approx 2\rho_m^{0.11}\rho_p^{-\frac{1}{3}}g_p^{-0.22}R^{0.13}E_K^{0.22}(\sin\theta)^{\frac{1}{3}}$ (mks units)

- The K-T impact that wiped out the dinosaurs is thought to have been a 10 km diameter asteroid. How big is the transient crater that resulted? (assume the ground and asteroid are made of rock, and the impact velocity was Earth's orbital velocity around the Sun, and the impact angle was 90 degrees)

- Hint:
  - $\log(xy) = \log(x) + \log(y)$
  - $\log(x^a) = a \log(x)$
  - $\log_{10}(1) = 0$ $\log_{10}(10) = 1$ $\log_{10}(100) = 2$
  - $\log_{10}(3) = 0.5$ $\log_{10}(30) = 1.5$ $\log_{10}(300) = 2.5$

Universal Pictures

Order of Magnitude: Crater Diameter

- $D \approx 2\rho_m^{0.11}\rho_p^{-\frac{1}{3}}g_p^{-0.22}R^{0.13}E_K^{0.22}(\sin\theta)^{\frac{1}{3}}$ (mks units)
- First, let's convert this to log, and keep one significant figure on the multiplication:
- $\log D \approx \log 2 + 0.1\log\rho_m - 0.3\log\rho_p - 0.2\log g_p + 0.1\log R + 0.2\log E_K + 0.3\log\sin\theta$
- log(3) is 0.5, and log(1) is 0, so let's say log(2) = 0.3
- R is 5 km, or in mks, 5000 m log(5000) ~ log(10000) = 4
- g is 10 in mks (9.8 m/s/s) log(10) = 1
- density of rock is about 3 g/cc, or 3000 kg/cubic meter log(3000) = log(3) + log(1000) = 3.5
- Assume the same for the asteroid: log(3000) = 3.5
- Assume head-on collision, sin(90) = 1, log(1) = 0

Order of Magnitude: Crater Diameter

- $D \approx 2\rho_m^{0.11}\rho_p^{-\frac{1}{3}}g_p^{-0.22}R^{0.13}E_K^{0.22}(\sin\theta)^{\frac{1}{3}}$ (mks units)
- That just leaves the kinetic energy, $\frac{1}{2}mv^2 = \frac{1}{2}\frac{4}{3}\pi\rho R^3 v^2 \approx 2\rho R^3 v^2$
- Let's assume it hits at Earth's orbital velocity, 30 km/s = 30000 m/s
- $E_K = 2(3000kg/m^3)(5000m)^3(30000m/s)^2 = 2(3x10^3)(5x10^3)^3(3x10^4)^2$

$= (2x6x125x9)(10^3x10^9x10^8) = (10000)(10^{20}) = 10^{24}J$ $\log E_K = 24$

- Plugging it all in:

$\log D \approx 0.3 + 0.1(3.5) - 0.3(3.5) - 0.2(1) + 0.1(4) + 0.2(24) + 0.3(0)$

$= 0.3 + 0.35 - 1 - 0.2 + 0.4 + 4.8 = 4.65$

$D = 10^{4.65} \approx 100{,}000m = 100km$

For next time

- Reading: de Pater & Lissaeuer Chaper 5, section 5.4.4
- Homework 2 will be due TONIGHT at 11:59pm