Fri. Oct. 13, 2017

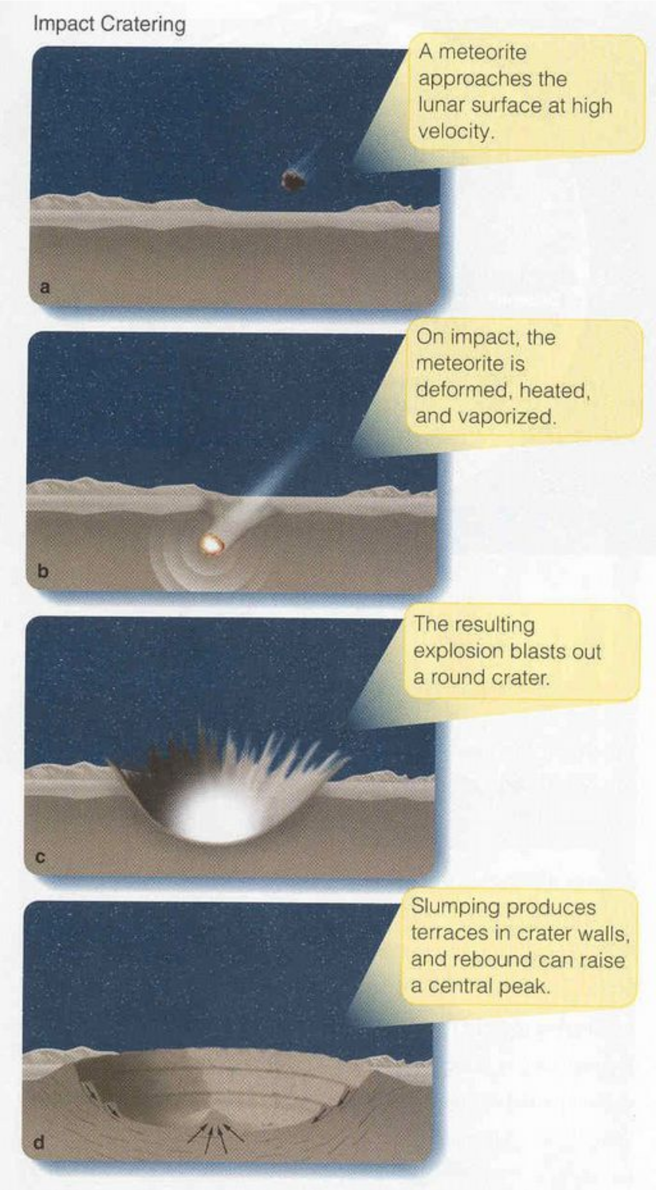
- Reading: For Today
  - Zuber et al. 2013 Grail Lunar Gravity
  - Andrews-Hanna et al. 2013 (GRAIL Procellarium region)

- Reading:
  - For Wed. Oct. 25 Wood Ch. 5 Atmospheres (on reserve)
  - For Friday Oct. 27
    - Stevenson and Halliday 2014 "The origin of the moon" Phil. Trans. of the Royal Soc. 372: 20140289.
    - Hartmann 2014 "The giant impact hypothesis: past, present (and future?)" Phil. Trans. of the Royal Soc. 372: 20130249.
    - Crawford and Joy 2014 "Lunar exploration: opening a window into the history and evolution of the inner Solar System" Phil. Trans. of the Royal Soc. 372: 2013031

No Class Oct. 16, 18, 20

Today: Cratering

Formation of an impact crater



From the Astro 1050 text: Horizons by Seeds

- Crater caused by the explosion
  - Impactor is melted, perhaps vaporized by the kinetic energy released
- Temporary "transient" crater is round
- Gravity causes walls to slump inward forming "terraces"
- Movement of material inward from all sides (trying to fill in the hole) may push up central peak in the middle.
- Final crater is typically ~10 times the size of the impactor

Crater Fundamentals

- Primary craters are "explosion" processes
- Typical crater diameter 10× that of impactor
  - Involves assumption about typical impact velocity
  - Doesn't apply to secondary craters
- For small craters original form largely preserved
  - Typical Depth/Diameter = 1/10
  - See Stöffler et al. 2006 for more detailed scaling
- For larger craters gravity can heavily modify original form

Crater Mechanics

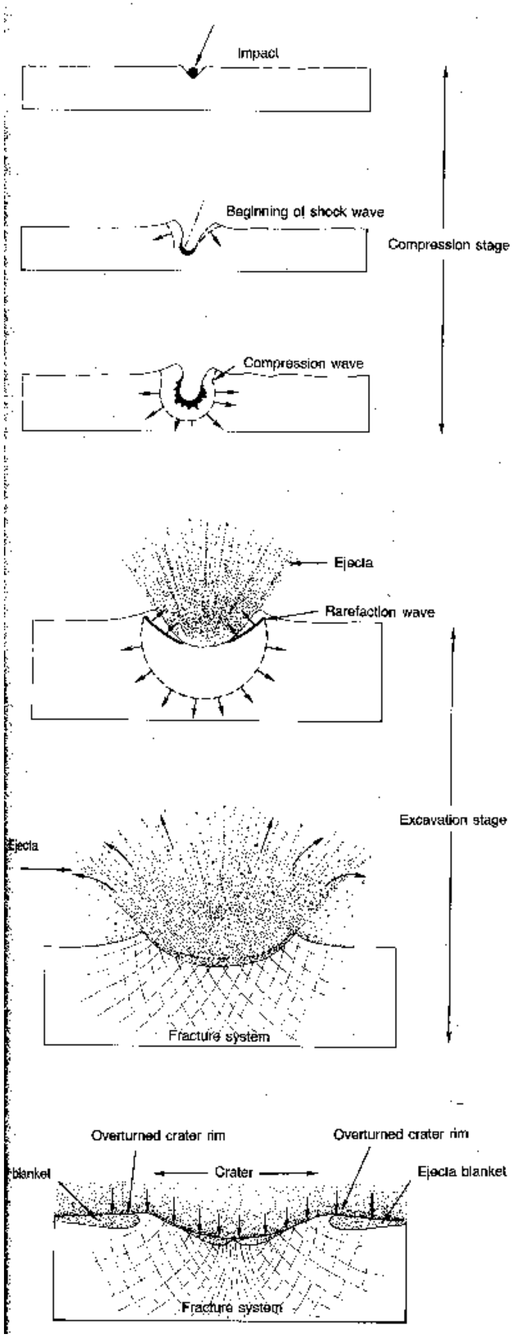
- "Explosion" caused by large kinetic energy of incoming body
  - $E = \frac{1}{2} mv^2$
  - $V \geq V_{esc}$: due to infall <u>plus</u> original (solar) orbital velocity of body
    - V_{esc} = 11.2 km/sec Earth
    - V_{esc} = 2.4 km/sec Moon
    -

$$V_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2G\frac{4}{3}\pi R^3 \rho}{R}} = \sqrt{\frac{8\pi G\rho}{3}}\,R$$

so for similar type objects V_{esc} scales roughly with radius R

- Results insensitive to angle of incoming projectile
  - Only important for grazing angles less that ~15° from horizontal
  - Understanding this was stumbling block to early acceptance of crater mechanism

From the Astro 1050 text: Horizons by Seeds



From text by Christiansen and Hamblin

Crater Mechanics

- Detailed steps in crater formation
  1) Shock wave during collision converts kinetic energy to compression & heat
  2) "Rarefraction wave" releases compression and ejects material
  3) Ejecta falls on surrounding region
  4) Transient crater modified by gravity effects (slumping, rebound)

Play: deep_impact_pumice_side.mpg

Impact into pumice – 4.5 km/sec, 500 frames per second – from the Deep Impact Team

2-D calculations

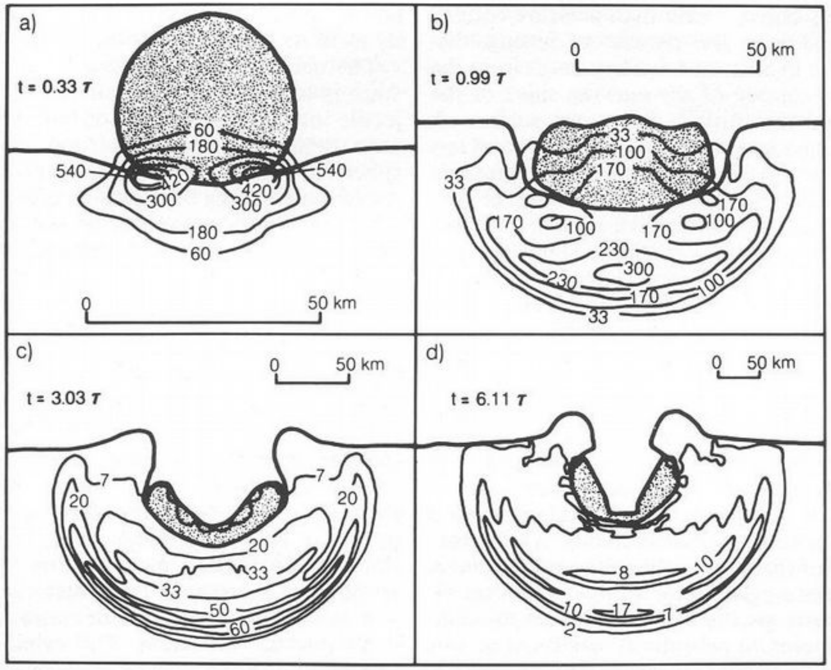
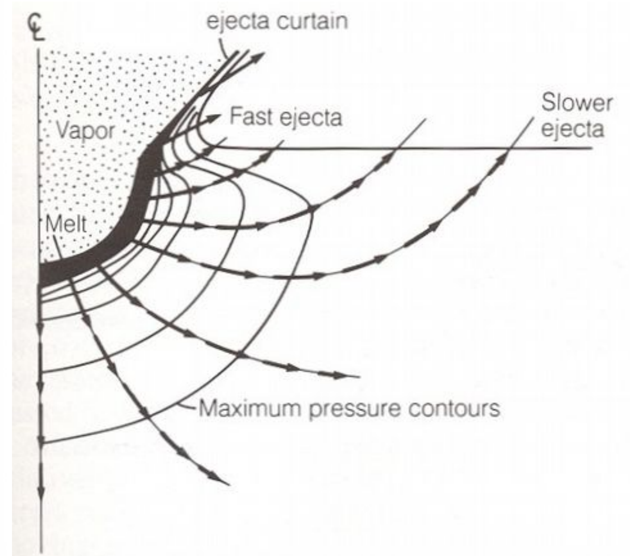


Fig. 4.1 Four snapshots are shown of the vertical impact of a 46.4-km diameter iron projectile on a gabbroic anorthosite target at 15 km/second. The first three frames illustrate different phases in the contact and compression stage and the last frame is a very early phase of the excavation stage. The 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).*



From Melosh 1989: *Impact Cratering: A Geological Process*

As compression and rarefaction wave propagate horizontally, they produce an expanding cone of ejects seen in the next slide

Movie of impact

Calculations and Experiment

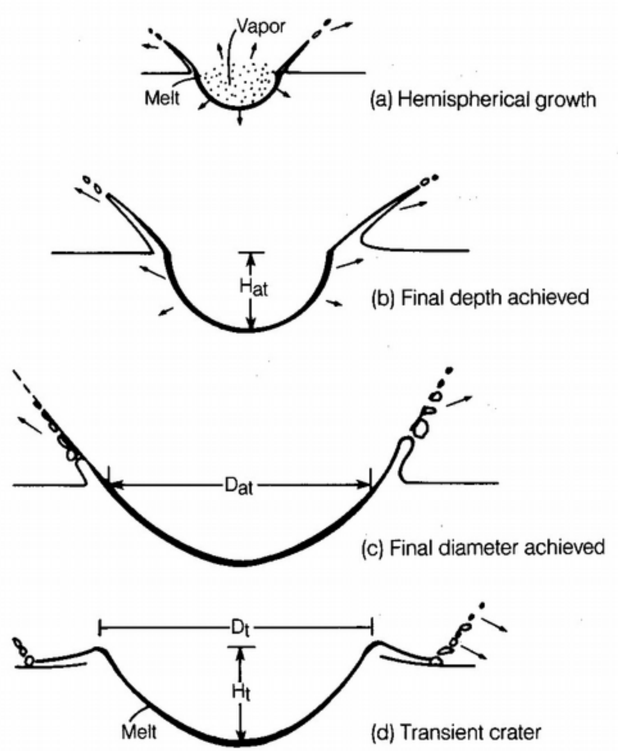


Fig. 5.11 Growth of a crater. The crater becomes hemispherical a short time after the impact (a) and initially expands at a fraction of the impact velocity. Its rate of growth in depth slows and finally ceases (b) before its radial growth halts (c). The resulting crater (d) is called a transient crater because it is subject to further gravitational collapse, described in Chapter 8. At all stages of its expansion the crater is lined with melt or highly shocked rocks originally produced near the site of the impact.

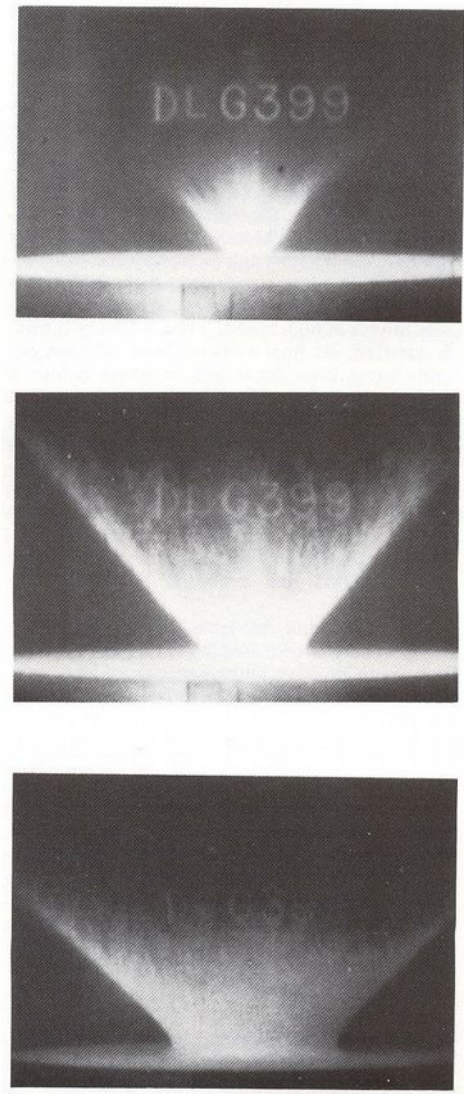


Fig. 5.10 The ejecta curtain produced in a small-scale experiment forms an inverted cone that expands with time. *Photo courtesy of P. H. Schultz.*

Crater only hemispherical <u>initially</u>

By definition the shock waves are barely able to eject material when the crater has expanded to maximum size.

This last bit of ejected material can form an stratigraphically inverted "flap" just outside the rim.

From Melosh 1989: *Impact Cratering: A Geological Process*

Presence of overturned layer

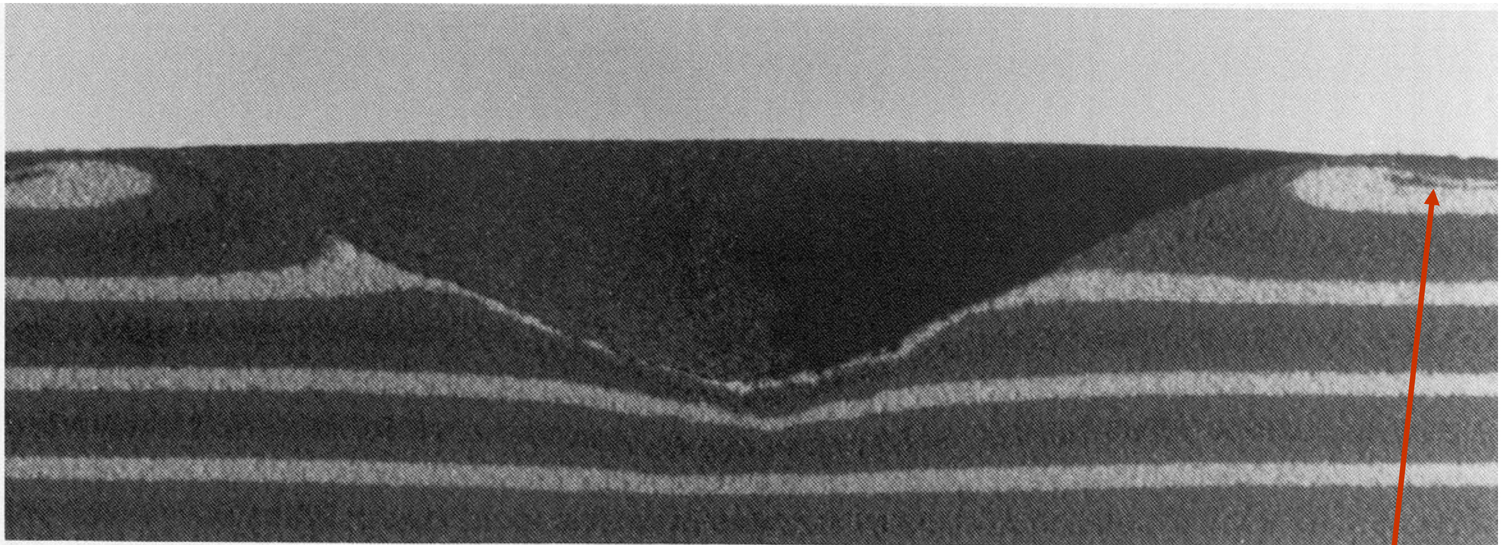


Fig. 5.14 Cross-section of a small-scale impact crater produced in a layered noncohesive sand target. The overturned flap near the rim, uplift of beds near the rim, and downwarp of beds beneath the crater are clearly seen. A white sand layer whose top is about one-third of the transient crater depth below the surface marks the transition between excavation and displacement. *Photo courtesy of P. H. Schultz.*

From Melosh 1989: *Impact Cratering: A Geological Process*

Stratigraphically inverted flap of material

Simple craters retain original shape

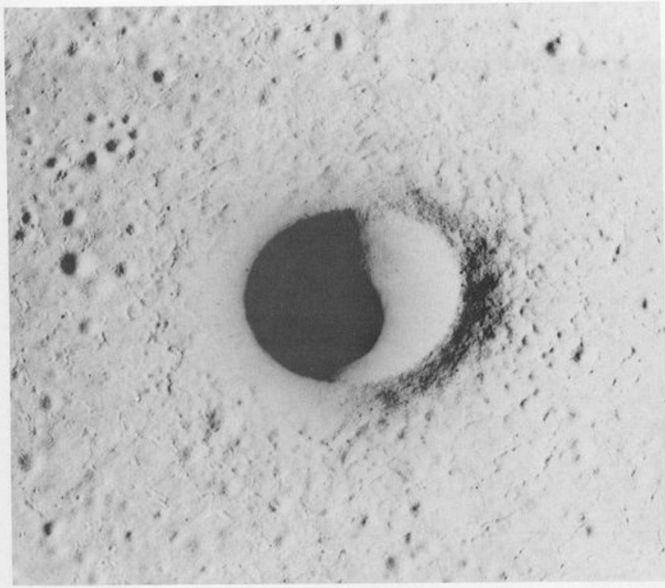


Fig. 2.2 The principal characteristics of a simple crater are illustrated by the 2.5-km diameter crater Linné in western Mare Serenitatis. The bowl-shaped interior is typical of small craters on all planets. *Apollo panoramic photo AS15-9353 (P).*

From Melosh 1989: *Impact Cratering: A Geological Process*

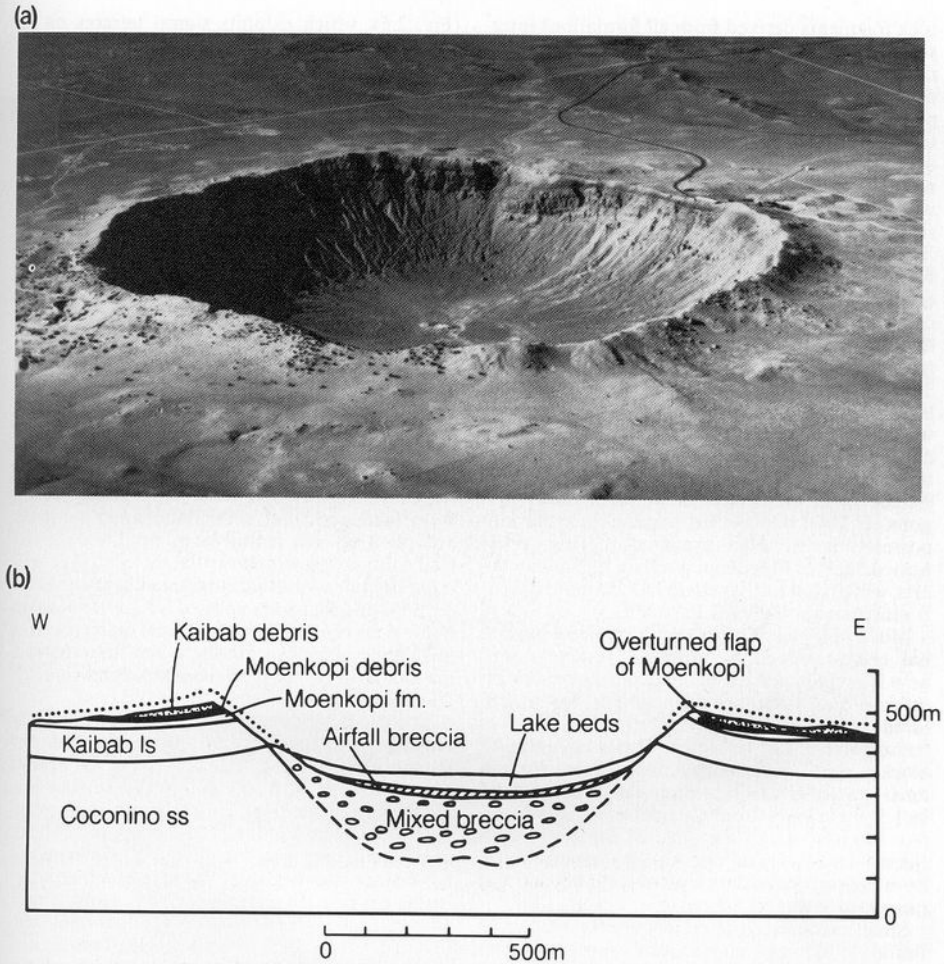


Fig. 2.3 (a) Meteor Crater, Arizona. *(Roddy and Zeller, U.S.G.S. Courtesy D. Roddy.)* A geologic cross-section of the 1-km diameter crater is shown below in (b). *Cross section is after Shoemaker (1960).*

Aside: Effect of "regolith" = weak upper layer (separate from size scaling effects described later)

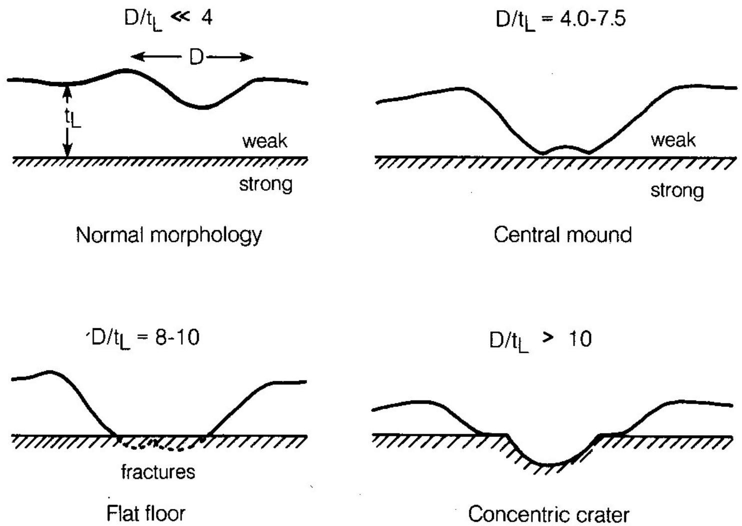


Fig. 5.17 The morphology of craters formed in a weak layer overlying a stronger layer. Depending on the ratio between crater diameter D and weak layer thickness t_L, the crater may be a normal bowl shape, have a low central mound, flat floor, or interior benches on its walls. *After Quaide and Oberbeck (1968).*

From Melosh1989: *Impact Cratering: A Geological Process*

Aside: Effect of "regolith" = weak upper layer (separate from size scaling effects later)

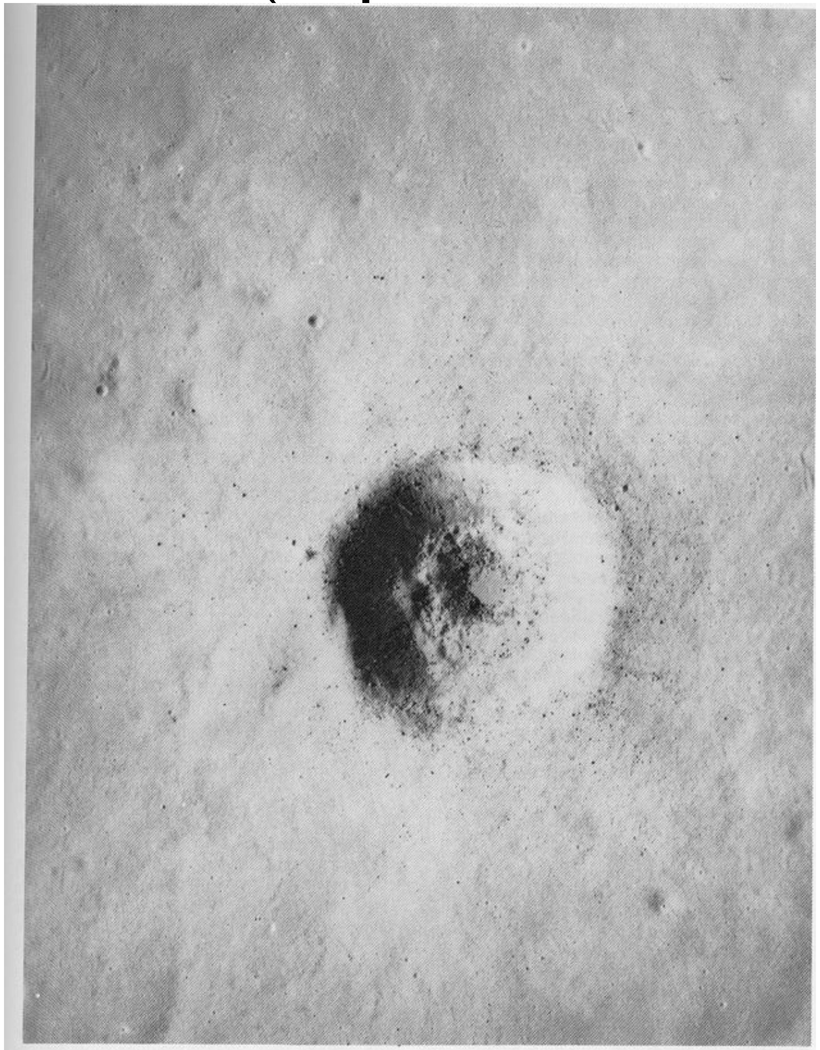


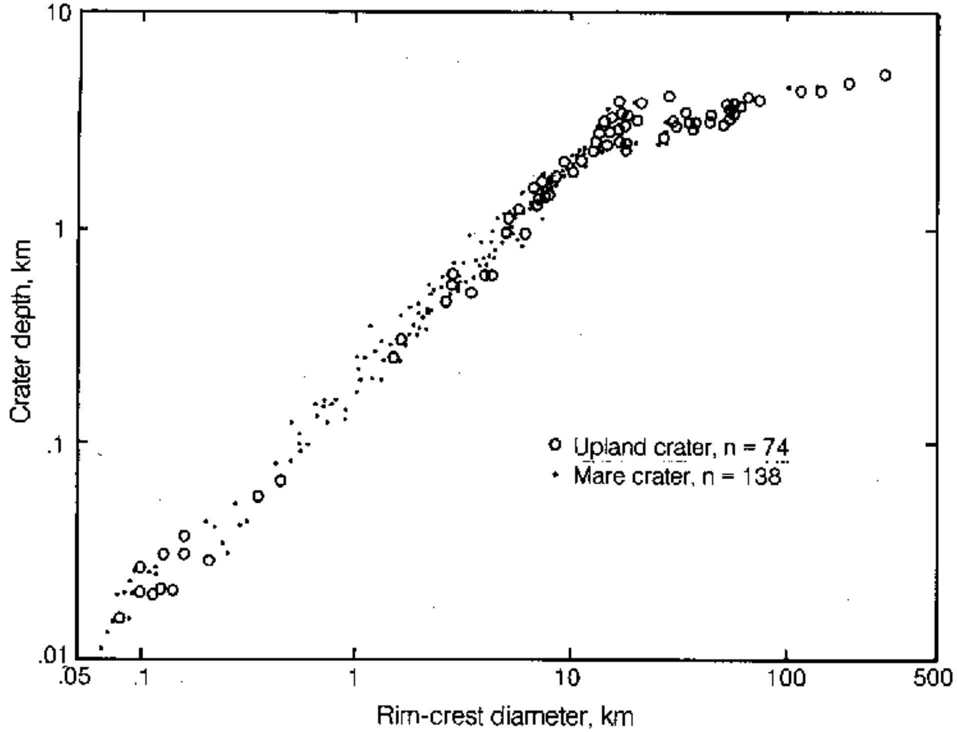
Fig. 5.18 This 1.2-km diameter crater on the moon shows a wide bench low down on its wall, suggesting that the moon's surface in this area consists of a weak layer about 100 m thick overlying a more resistant rock unit. Blocks up to 30 m in diameter litter the crater rim and a small smooth deposit in the very bottom of the crater may be impact melt. *Apollo panoramic photograph AS15-9287.*

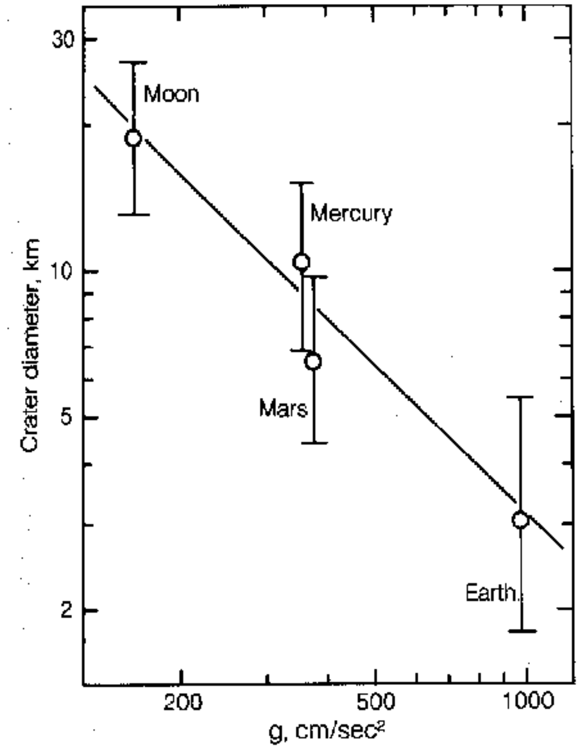
In addition to the "bench" caused by the vertical layering

note the presence of small blocks of rock thrown out from the underlying "bedrock".

From Melosh1989: *Impact Cratering: A Geological Process*

Depth-Diameter (H/D) Break
Strength effect – not regolith depth



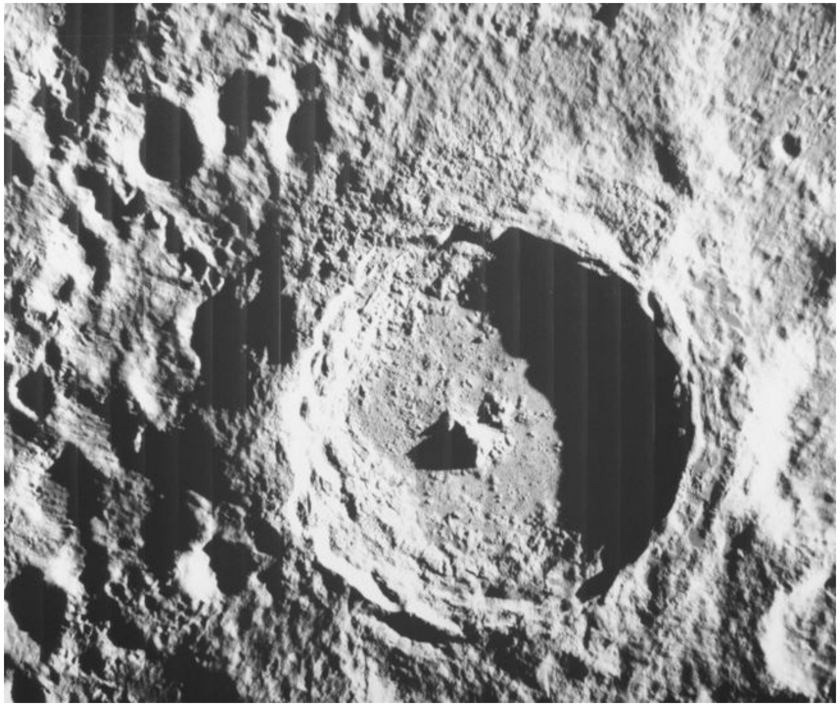


From Melosh1989: *Impact Cratering: A Geological Process*

- Transition from "simple" craters shown clearly by H/D ratio
  - Linear with Depth/Diameter (H/D) ~ 1/5 for simple craters
  - Transition at D ~ 20 km marks onset of major modifications
    - Slumped walls, central peaks
  - Both simple and complex craters exist near transition diameter
  - Transition occurs where gravity effects overcome strength of material
    - Diameter of transition scales with 1/g

Crater Morphology

- Size effects
  - All “transient” craters roughly similar: bowl-shaped
  - With small craters material strength of target preserves bowl-shape
  - With larger craters gravity greater than material yield strength:
    - Walls collapse due to slumping which forms terraces
    - “Isostatic” rebound moves material upward and inward to fill in cavity
      - Motion “collides” in center to form central peak on moderate size craters
      - Central ring forms in slightly larger craters
      - Multiple rings form in very large craters



Size / Morphology Correlation

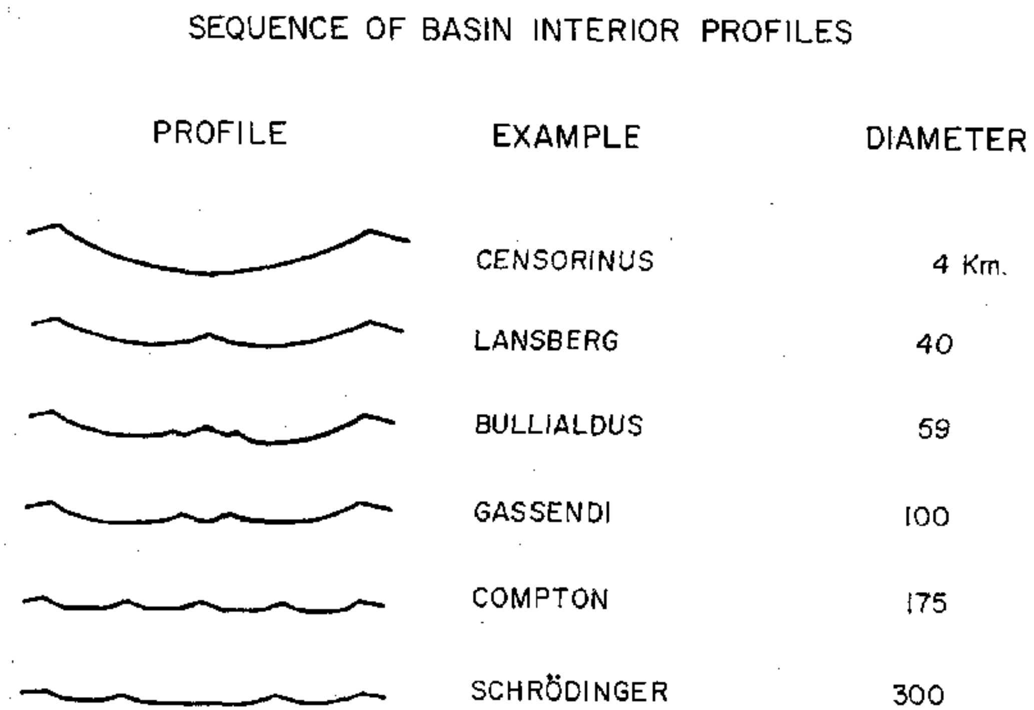
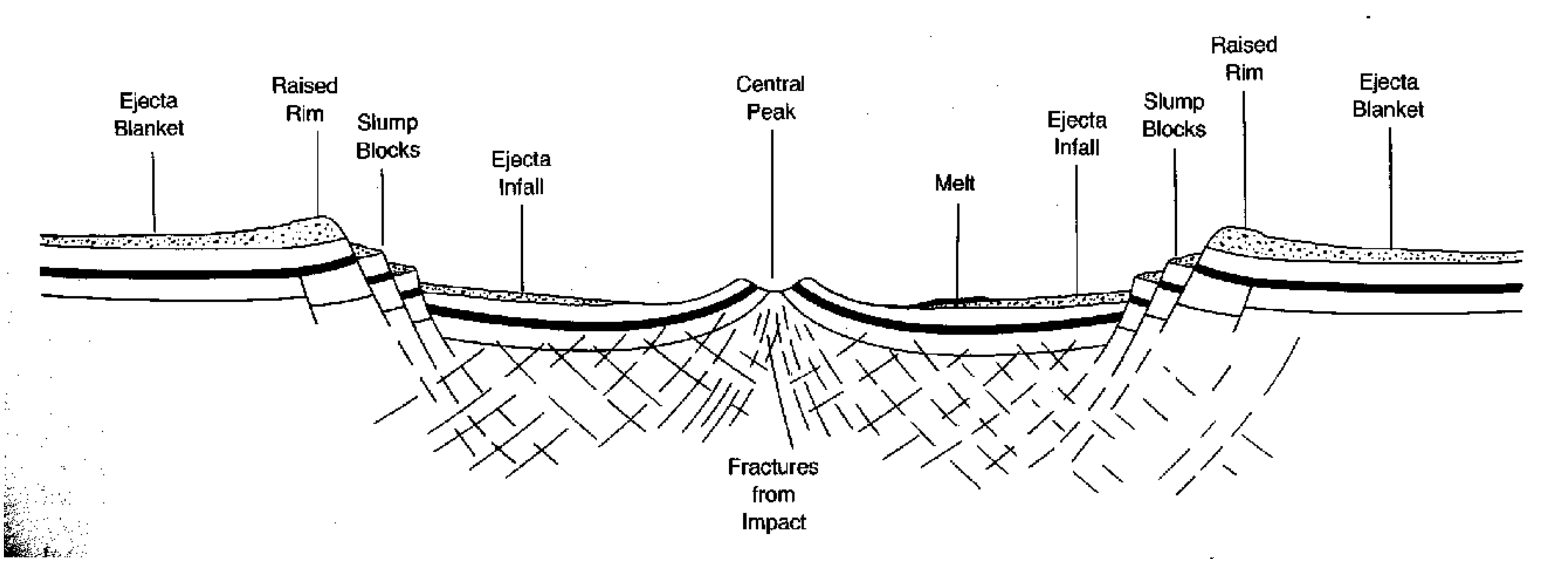


Fig. 42. Schematic size sequence of crater forms, from no central peak (top), through progressively more complex and extended peaks, to peak-rings (bottom).

From Hartmann and Wood 1971

Detailed Form



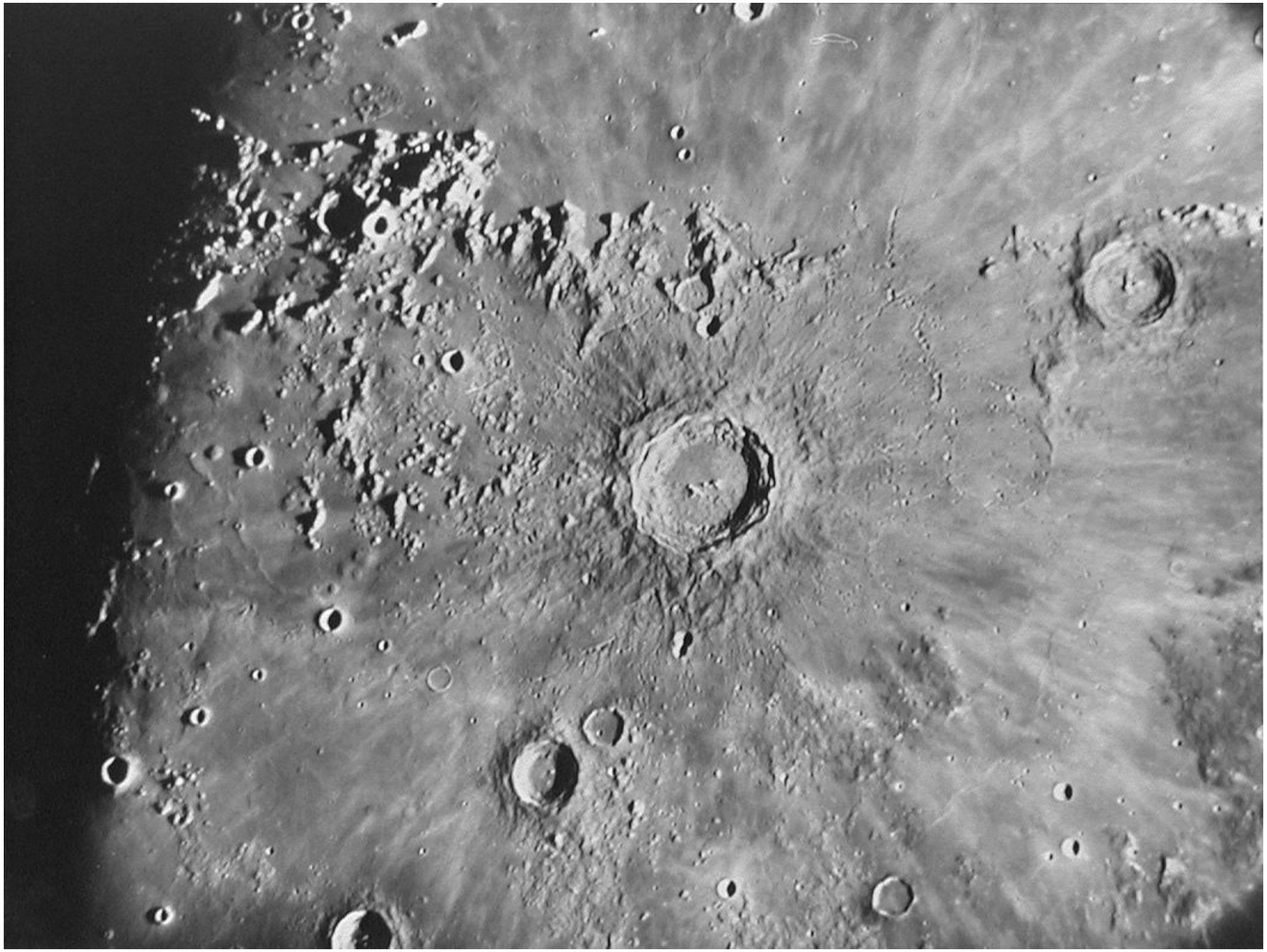
Distinguishing characteristics of craters

- Floor lower than surrounding <u>base level</u>
- Overturned strata at rim (not shown in above drawing)
- Breccia and fractures in crater – dying out at depth
- Shocked minerals
- Ejecta blanket morphology

- Morphology of crater itself changes in characteristic way with size

Secondary Craters and Ejecta Blanket

- Secondary impacts from material thrown out of main crater
  - Lower speed – not pure "explosion" shape so not always round
  - Often occur in groups or chains
  - Affect crater count statistics



Ages from crater counts

- Ignoring complications,
  number of craters (of given size) per unit area
  should be proportional to age.

- Complications:
  - For absolute ages, need to know cratering rate
  - Need to distinguish primary from secondary craters
  - Power law distribution of impactor object masses
    Lots of small impactors, fewer larger ones
  - Saturation effects

Crater "saturation"

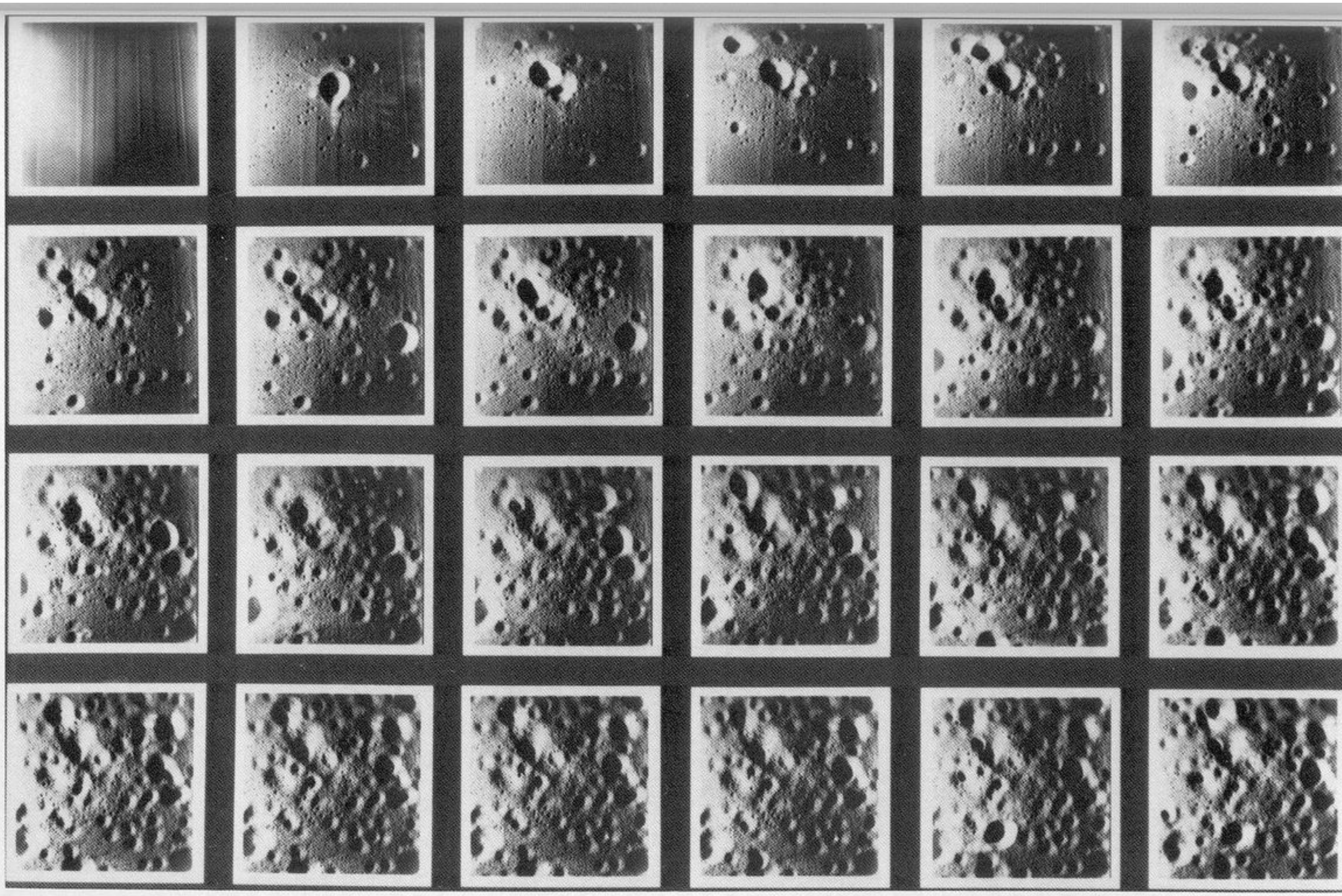


Fig. 10.6 A laboratory scale demonstration of the concept of crater equilibrium. The photographs are of a box 2.5 m square filled 30-cm deep with quartz sand. The sand is topped with 2 cm of carborundum powder to provide a color contrast. Six sizes of projectile were fired into the box at random locations, simulating a production population with slope index $b = 3.3$, similar to that of small craters on the moon. Time increases from upper left horizontally to lower right. Equilibrium is attained about halfway through the simulation: although individual surface details vary from frame to frame, the crater population in the later frames remains the same. *From Gault (1970); photo courtesy of R. Greeley.*

From Melosh1989: *Impact Cratering: A Geological Process*

Cratering Rates

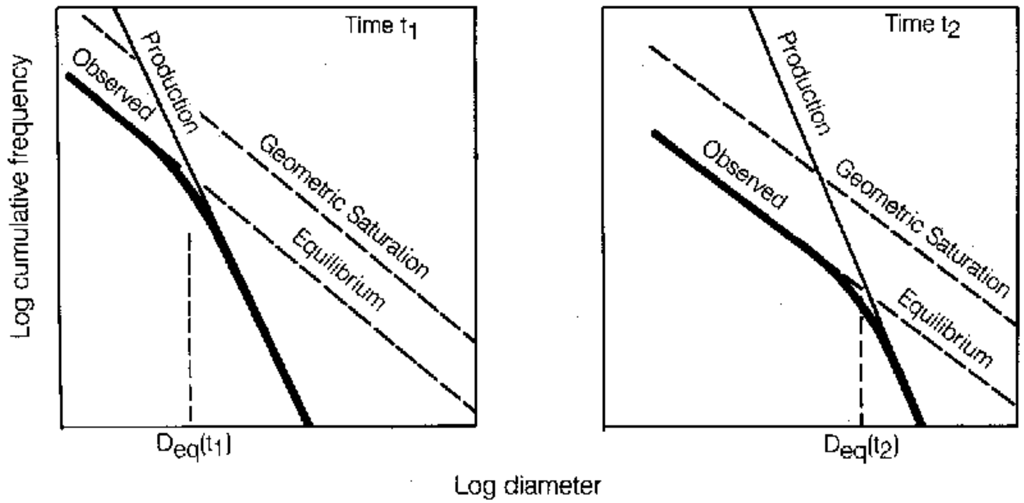


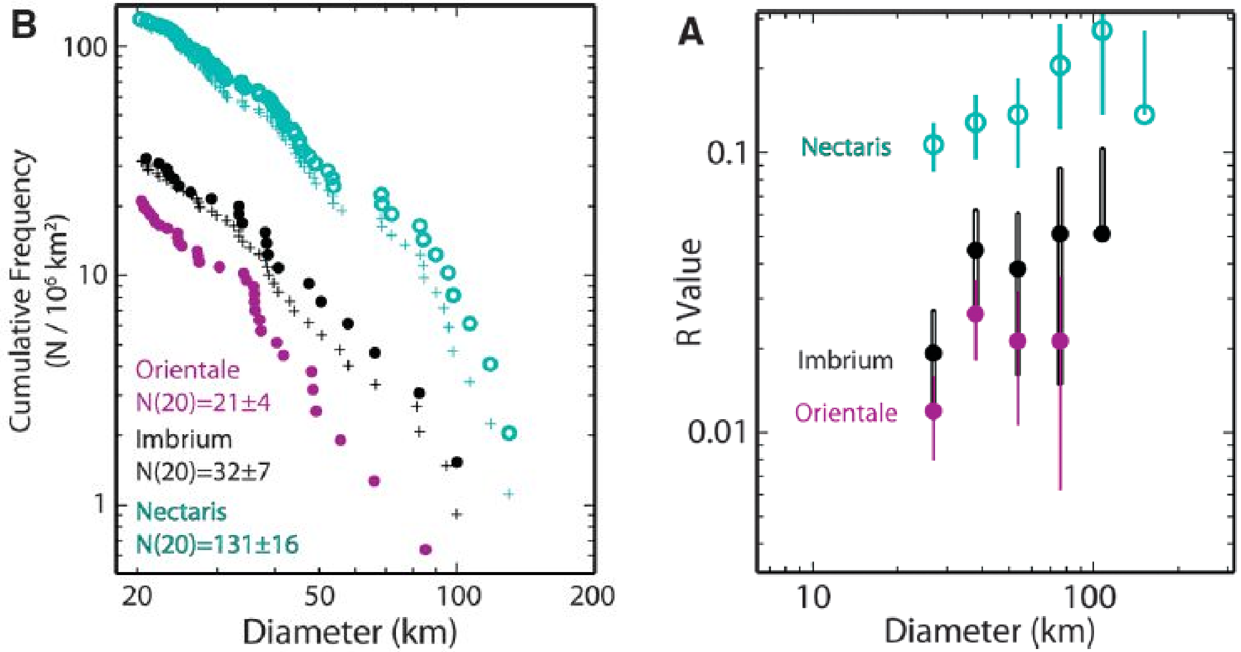
Fig. 10.5 Evolution of a crater population with slope $b > 2$. The production population exceeds the equilibrium line at small crater diameters. Small craters are thus in equilibrium up to some diameter D_{eq}, above which the observed population follows the production population. The left panel illustrates the population at a relatively early time t_1 and the right panel shows how the population has changed at a later time t_2. The equilibrium diameter D_{eq} clearly increases as a function of time, although this increase is generally not linear.

From Melosh1989: *Impact Cratering: A Geological Process*

- These plots assume a steep production power law $N \propto D^{-b}$ (i.e. relatively few large impactors compared to small ones)

- The saturation curve has the form $N \propto D^{-2}$ where the "2" comes from the fact that Area $\propto$ (Diameter)^2 so the number of craters you can fit in a given area must go down as D^{-2}.

Different types of Frequency Plots



From Head et al. 2010
Global Distribution of Large
Lunar Craters

- The left "cumulative" histogram shows the number of all craters of diameter greater than a specified D: (N with diameter ≥ D).

- Other types are "differential" showing the number of craters in a given size diameter bin: (dN/dD)
- The cumulative plots can be obtained by integrating the incremental plots and (for power law distributions) look similar. The index (exponent) just changes by 1 when you integrate.

- On the right another variant called an "R" plot is shown:
It is the incremental plot divided by (normalized by) an expected D^{-3} power law so $R = D^3\, dN/dD$
It gives a horizontal line when the actual curve agrees with that expected D^{-3} shape

Effects of resurfacing

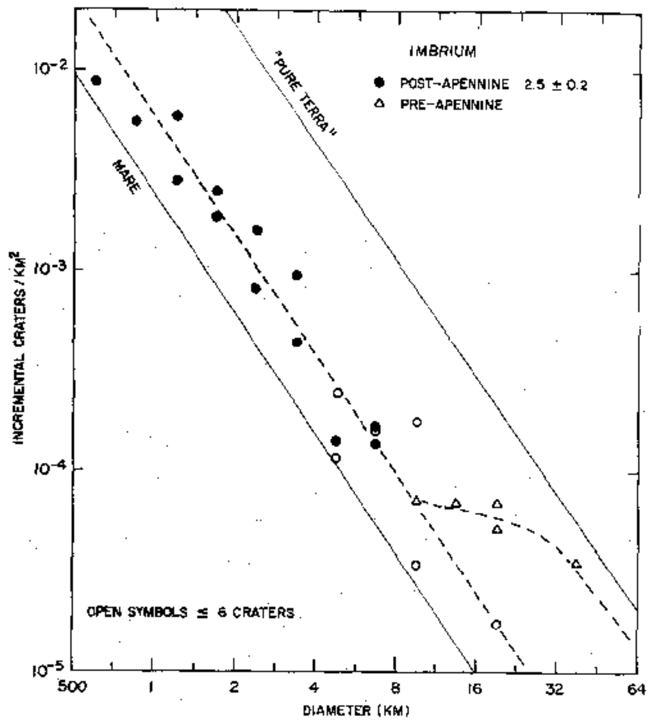


Fig. 3. Crater diameter distribution on Apennine ejecta blanket of Imbrium basin. In all following crater curves, open symbols represent lower-weight points based on ⩽ 6 craters.

From Hartmann and Wood 1971

- Observed crater counts can show a relative deficiency of small craters – the opposite of what would be predicted from the previous argument.
- That can be explained by resurfacing, which obliterates small (but not large) craters

Ages and Depths of resurfacing

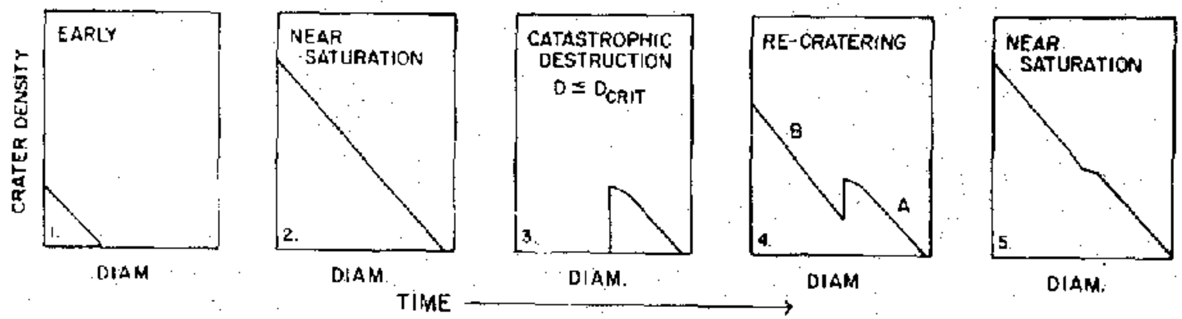


Fig. 1. Time sequence of crater diameter distributions, starting with a nearly-uncratered surface (1) which accumulates craters, undergoes an event which destroys small craters, and then is re-cratered.

From Hartmann and Wood 1971

- Crater counts for diameters below the break give the age of the resurfacing
- The diameter of the break (when multiplied by the depth-to-diameter ratio of the craters) gives the depth of resurfacing