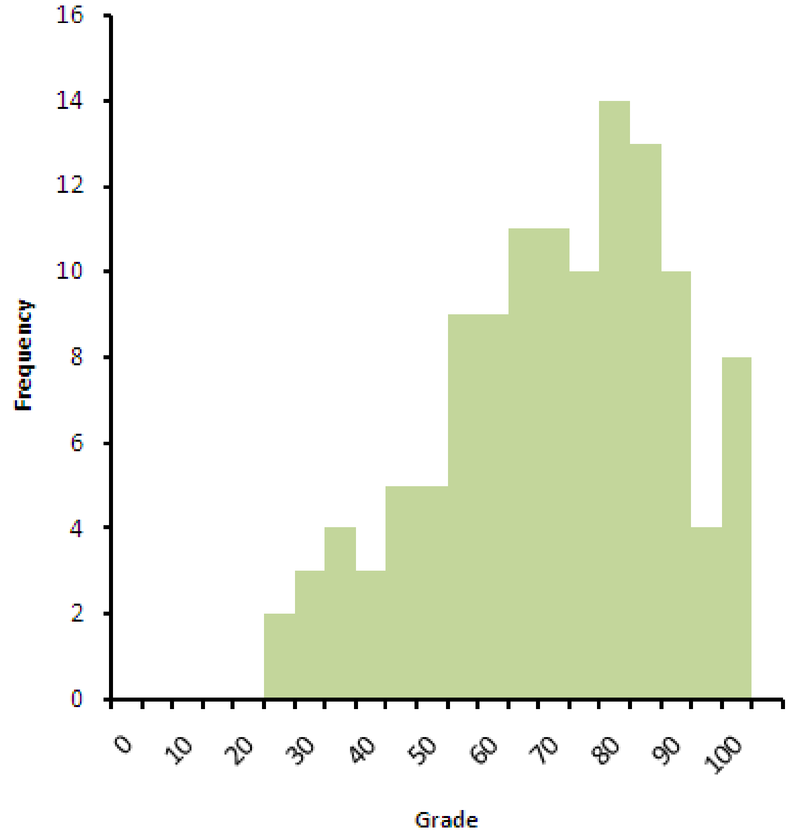
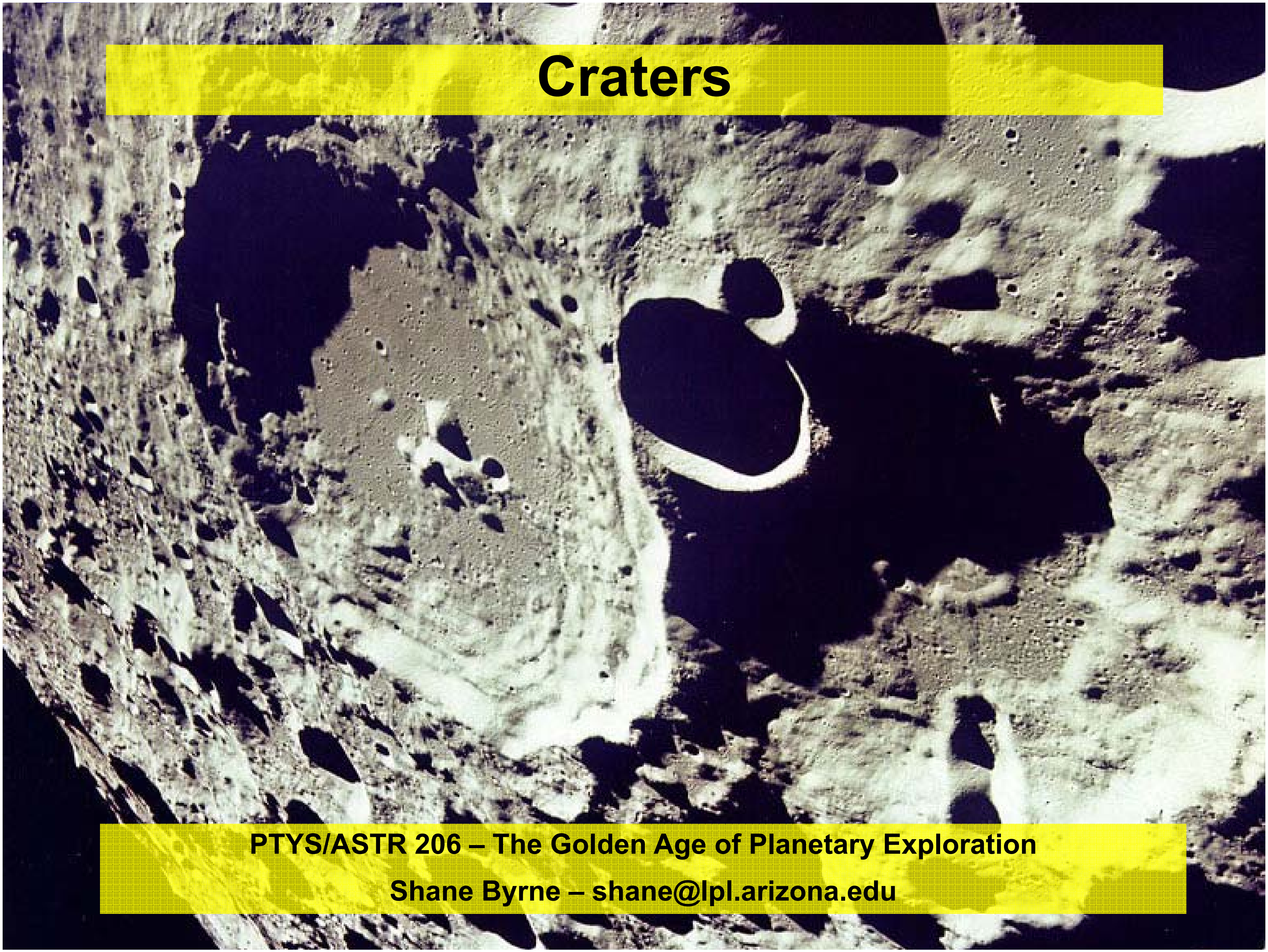
- **Homework #1 returned**
  - **Grades were well distributed – Average was a high C**
    - **Average question results 1 – 5 were 74%, 72%, 77%, 57%, 59%**
  - **We're happy to talk about the homework – tomorrow!**
    - **Solutions posted after this lecture**
    - **No discussions with us for 24 hours**



- **Homework #2 posted on website after this lecture**
  - **One week to finish**

Craters

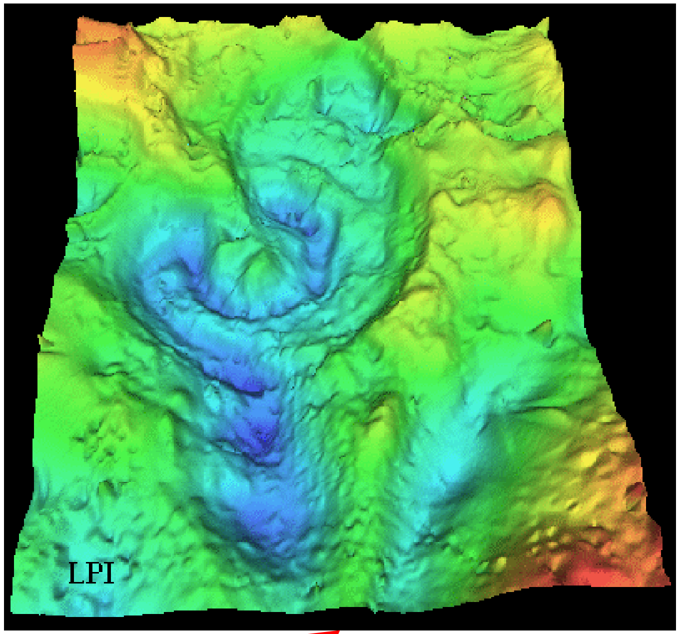


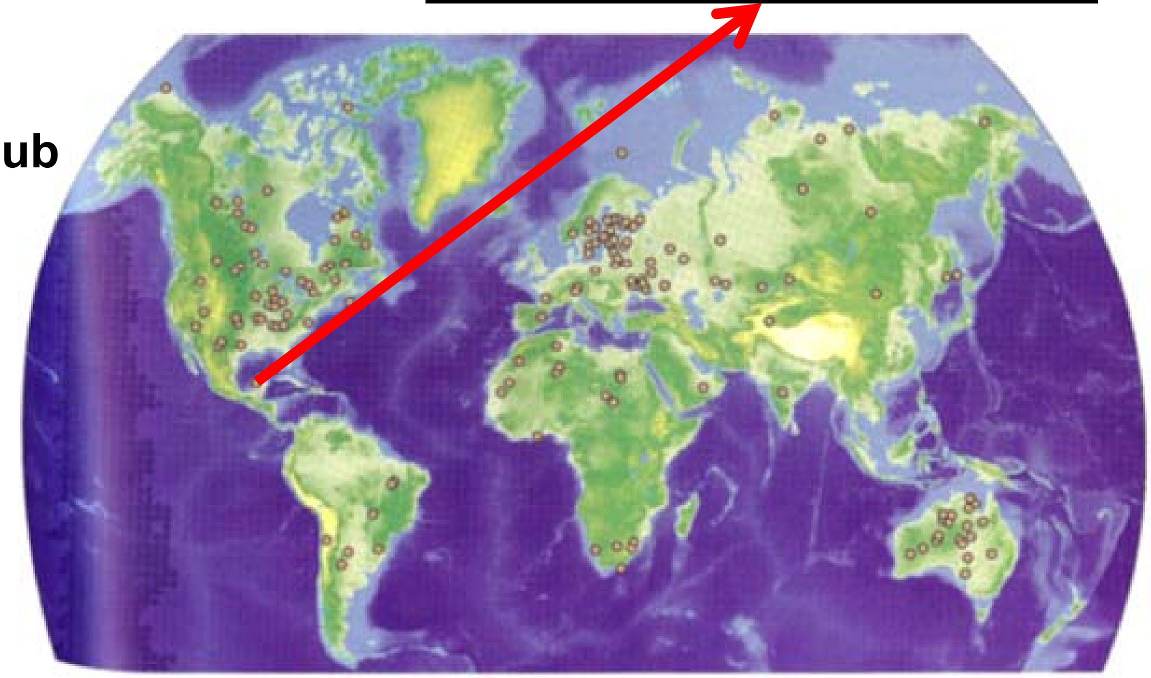
PTYS/ASTR 206 – The Golden Age of Planetary Exploration

Shane Byrne – shane@lpl.arizona.edu

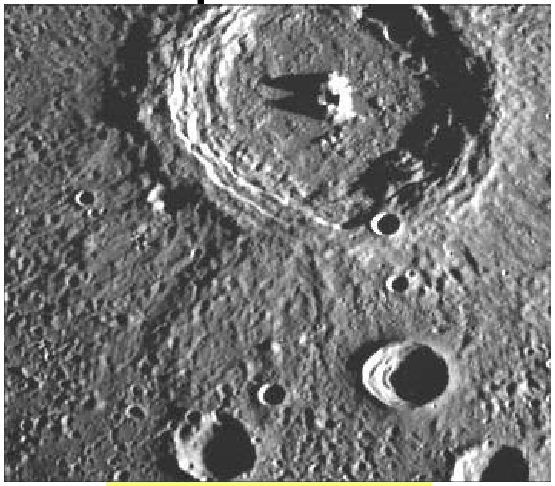
In this lecture…

- Introduction to craters
- Characteristics of craters
  - Bowls, rims and ejecta blankets
  - Nuclear test results
  - Simple vs complex craters
- Crater formation
  - Impacts and Energy
  - Excavation
  - Relaxation
  - e.g. Meteor crater, Chicxulub
- Atmospheric effects
  - E.g. Tunguska
- Crater populations
  - Dating a planetary surface

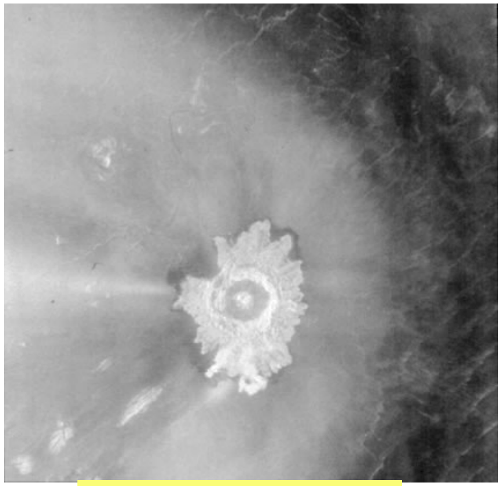




- Where do we find craters? – Everywhere!
  - Cratering is the one geologic process that every solid solar system body experiences…



Mercury



Venus

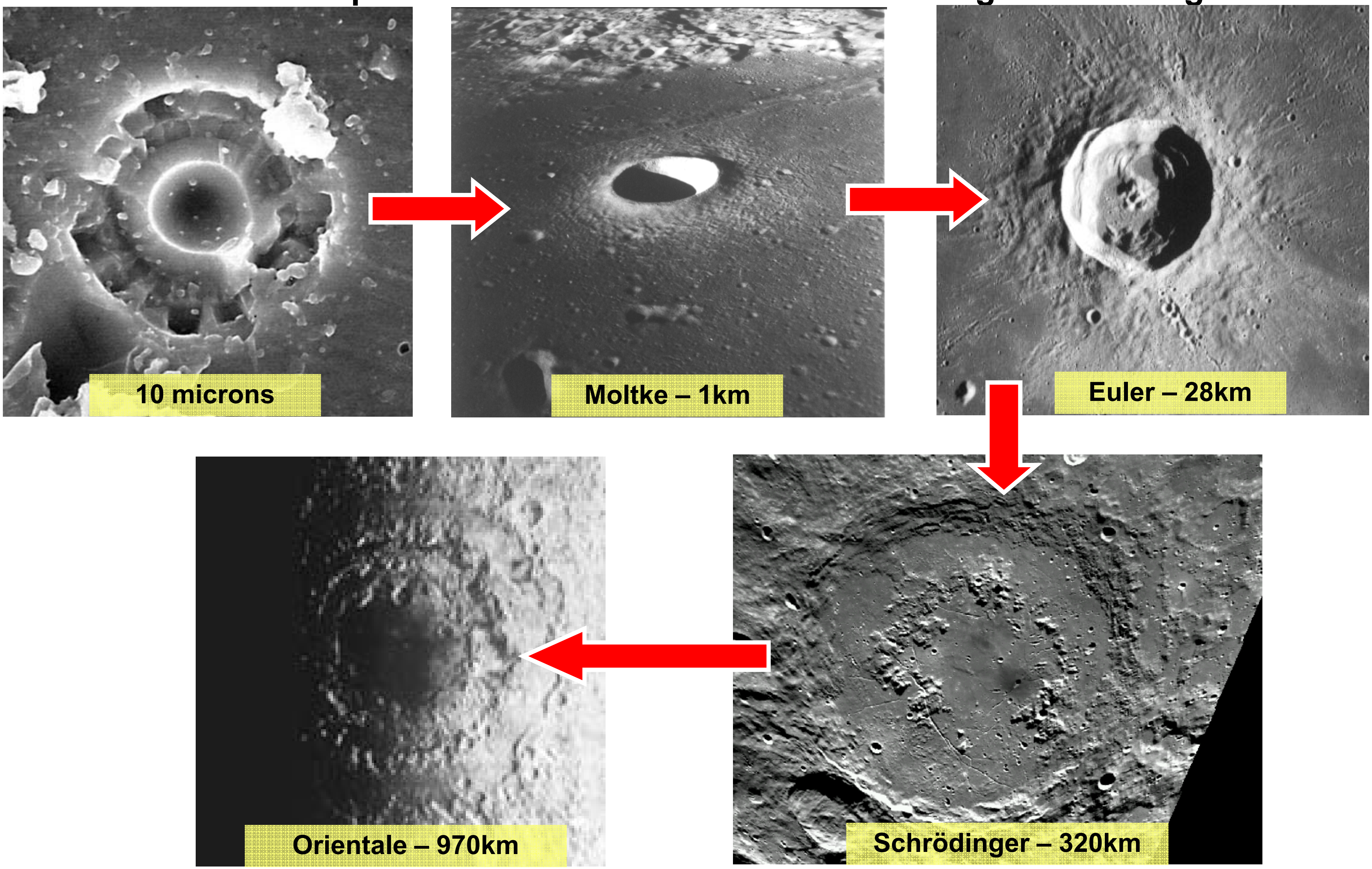
Moon

Earth

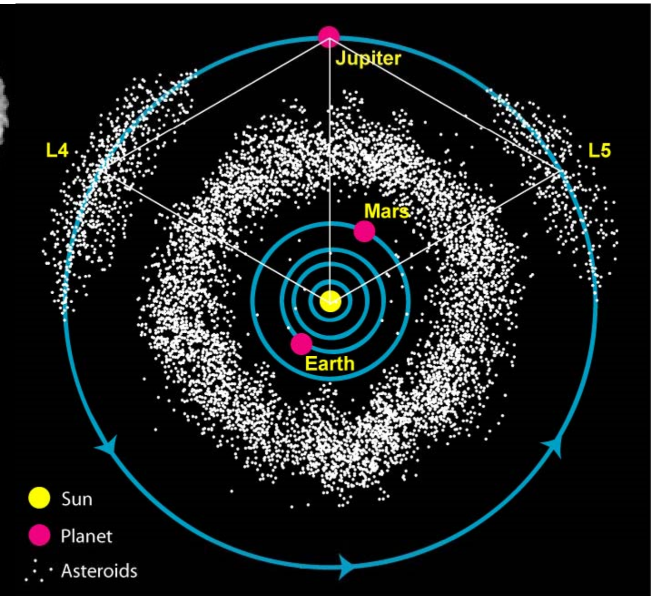
Mars

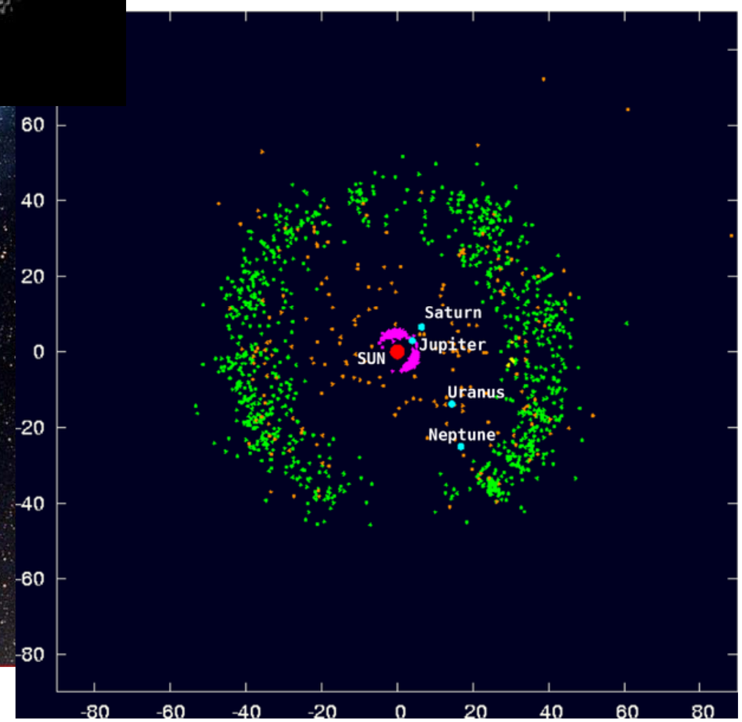
Asteroids

- Morphology changes as craters get bigger
  - Pit → Bowl Shape→ Central Peak → Central Peak Ring → Multi-ring



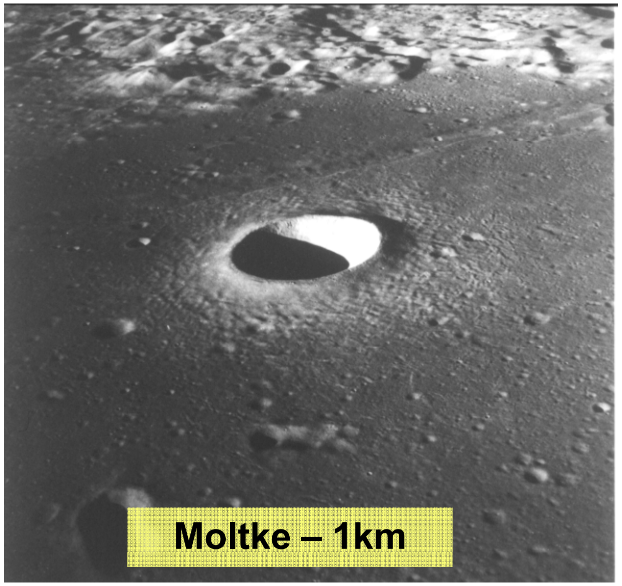
- **Origin of impactor craters**
  - **Asteroid fragments leave the main asteroid belt**
    - **From collisions with each other**
    - **Become Near-Earth Asteroids**
  - **Kuiper Belt Objects leave the Kuiper belt**
    - **From collisions with each other**
    - **Become Jupiter Family Comets**
- **Steady trickle of the objects**
  - **Less common today than billions of years ago**

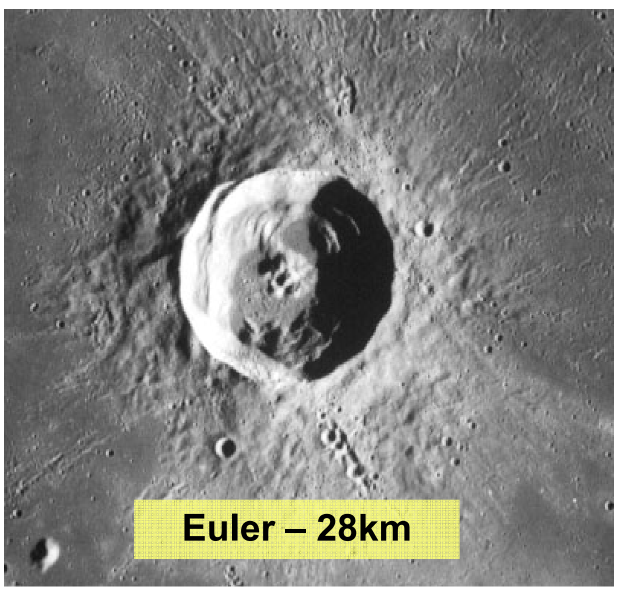


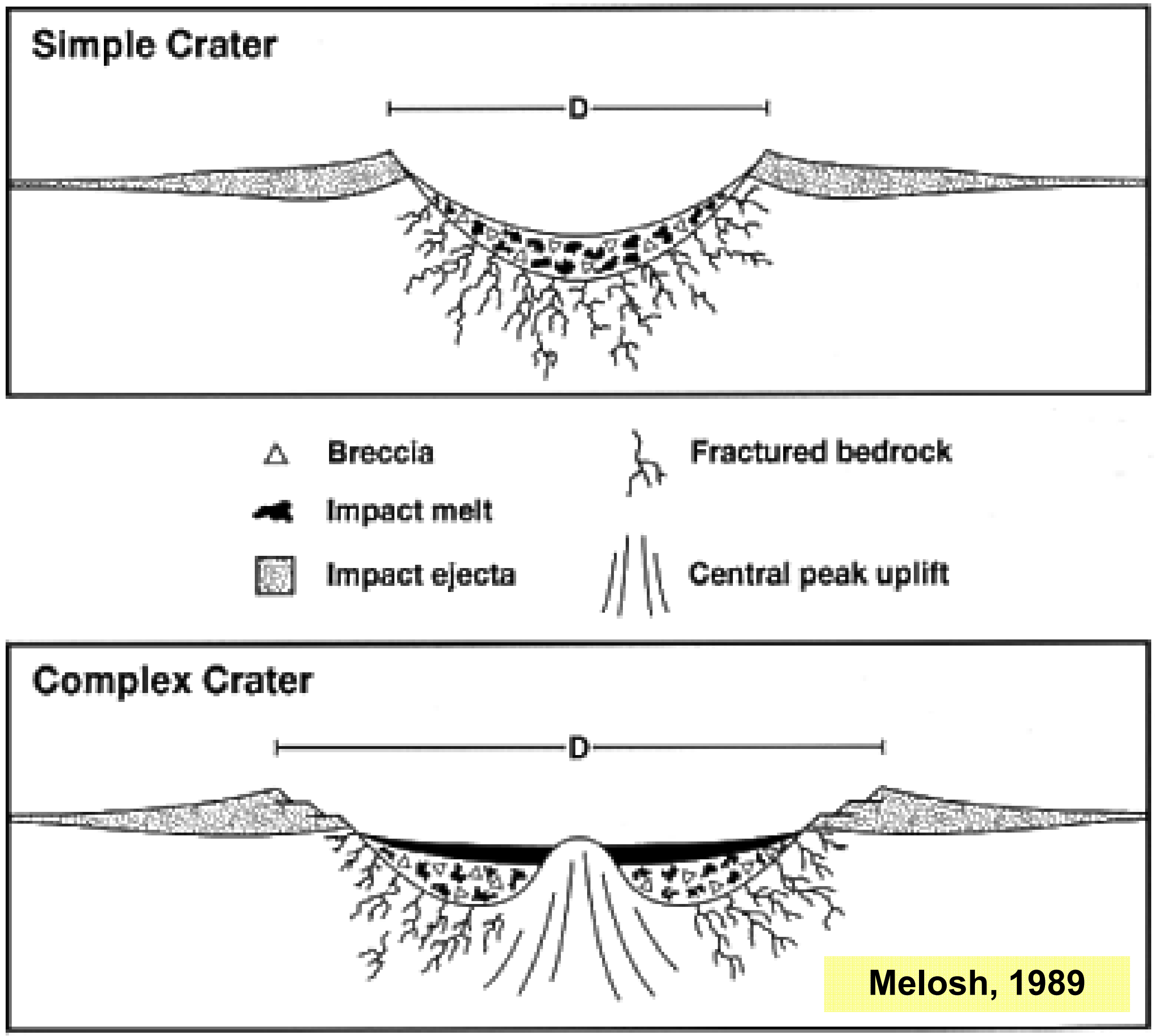


Characteristics of craters

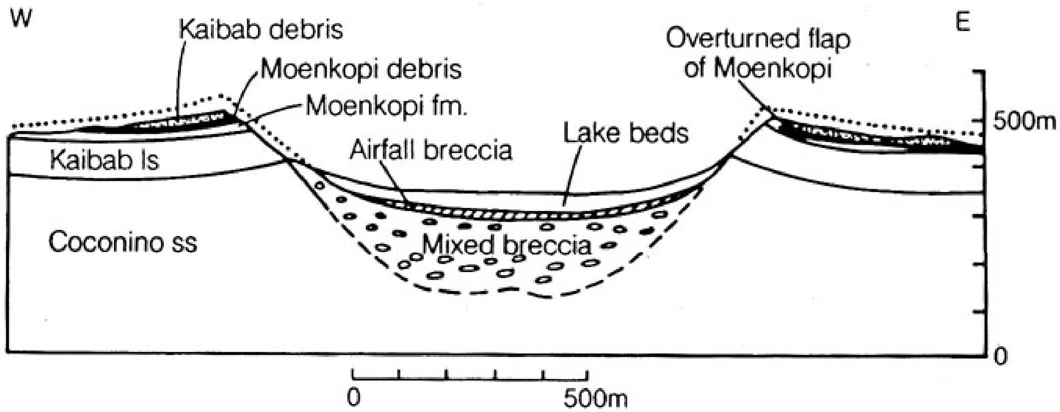
- Simple vs. complex



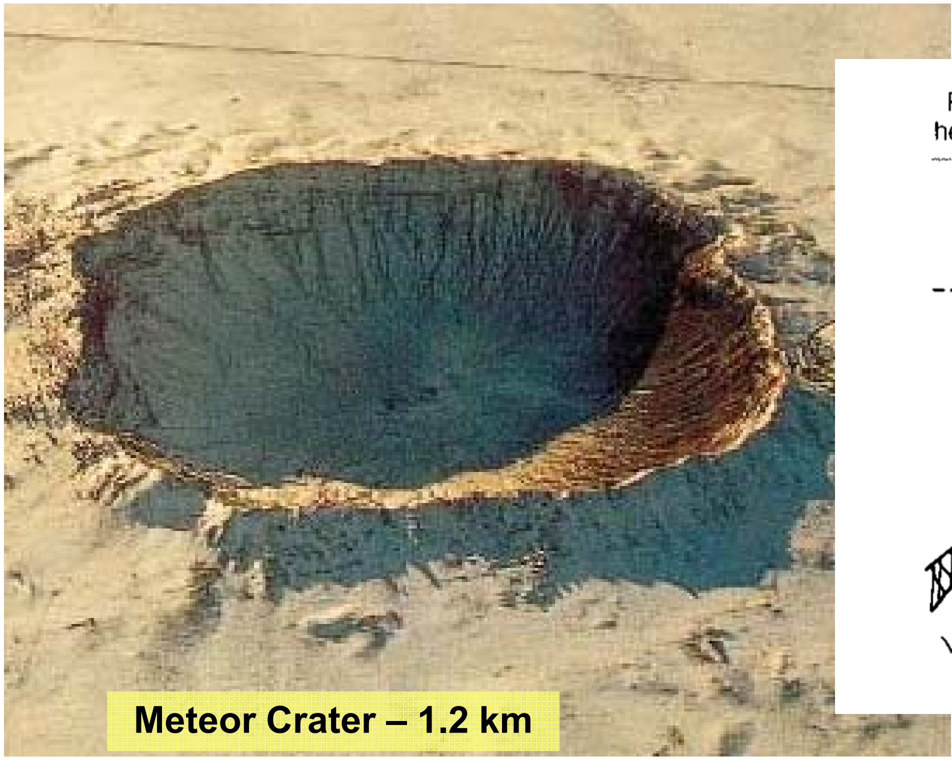




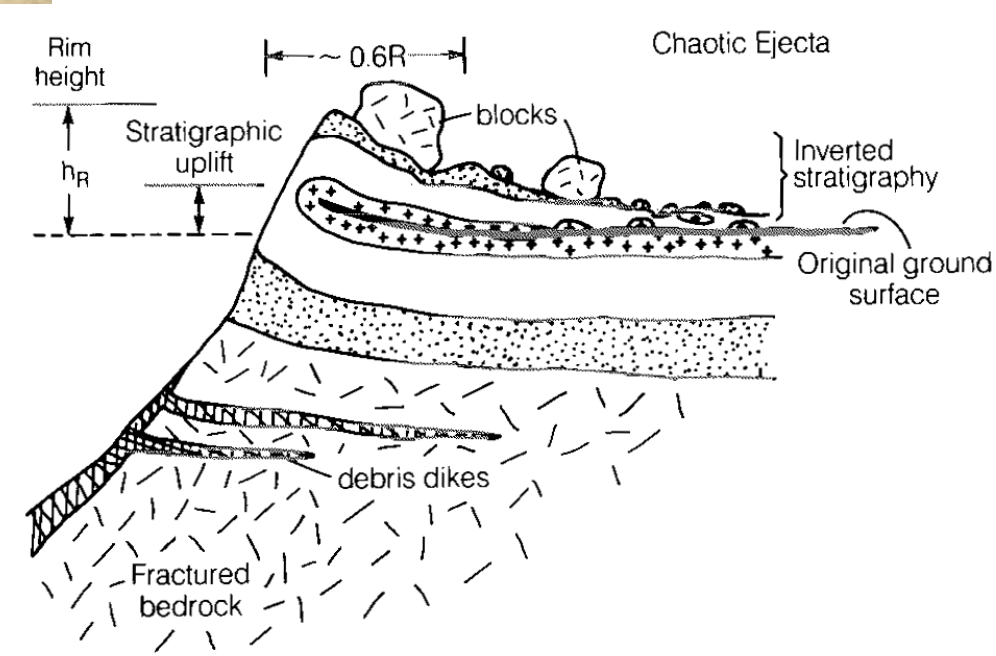
- Common crater features
  - Overturned flap at edge
    - Gives the crater a raised rim
    - Reverses stratigraphy
  - Eject blanket
    - Continuous for ~1 R_c
  - Breccia
    - Pulverized rock on crater floor



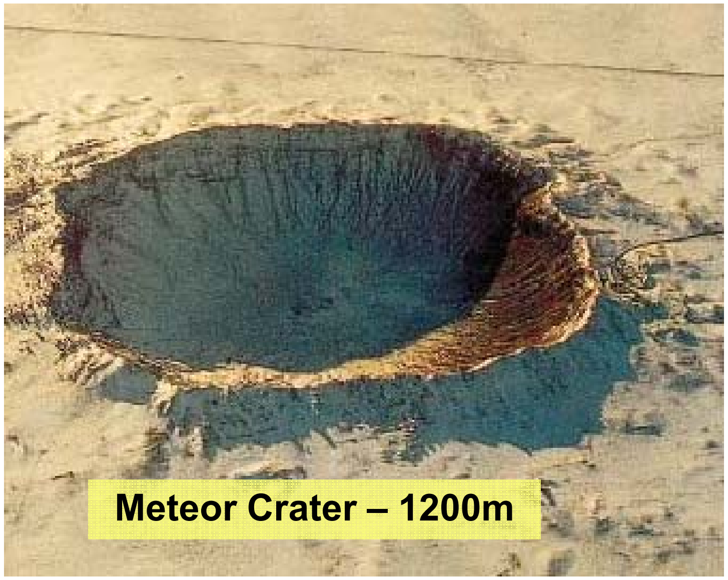
Melosh, 1989



Meteor Crater – 1.2 km



- **Craters are point-source explosions**
  - **Was fully realized in 1940s and 1950s test explosions**

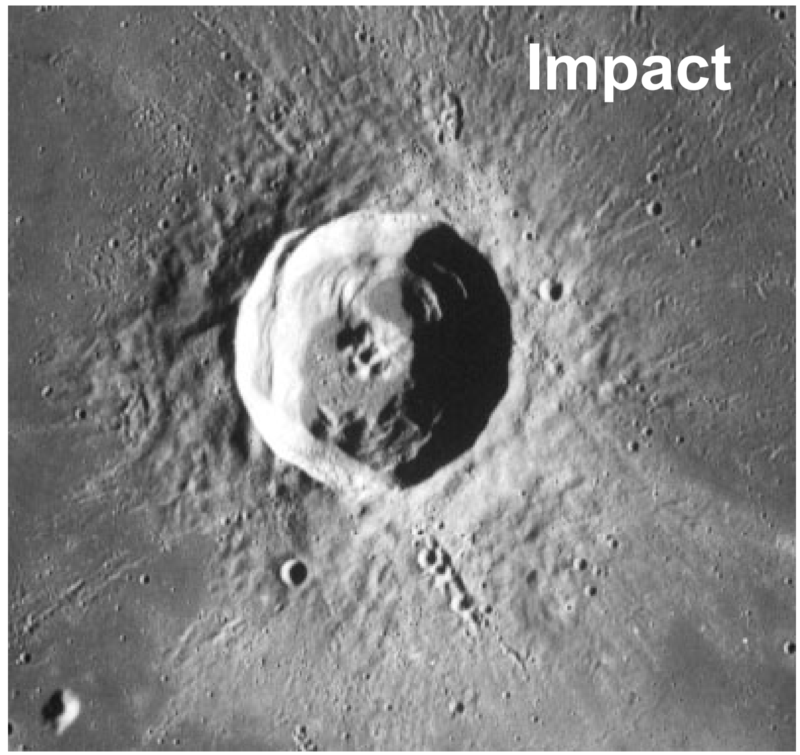


- **Three main implications:**
  - **Crater depends on the impactor's kinetic energy – NOT JUST SIZE**
  - **Impactor is <u>much smaller</u> than the crater it produces**
    - **Meteor crater impactor was ~50m in size**
  - **Oblique impacts still make circular craters**
    - **Unless they hit the surface at an extremely grazing angle (<5°)**

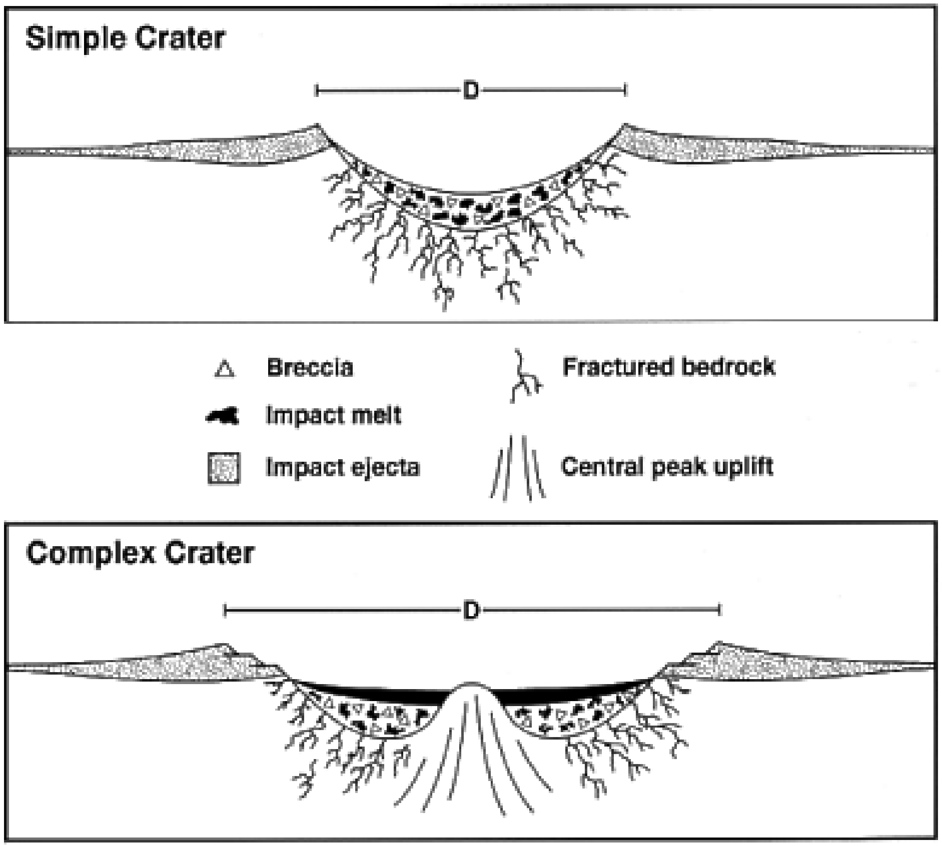
- **Lunar craters – volcanoes or impacts?**
  - **This argument was settled in favor of impacts largely by comparison to weapons tests**
  - **Many geologists once believed that the lunar craters were extinct volcanoes**
- **Which of these is a volcanic caldera?**

- **Lunar craters – volcanoes or impacts?**
  - **This argument was settled in favor of impacts largely by comparison to weapons tests**
  - **Many geologists once believed that the lunar craters were extinct volcanoes**
- **Which of these is a volcanic caldera?**

No Raised Rim – formed by collapse

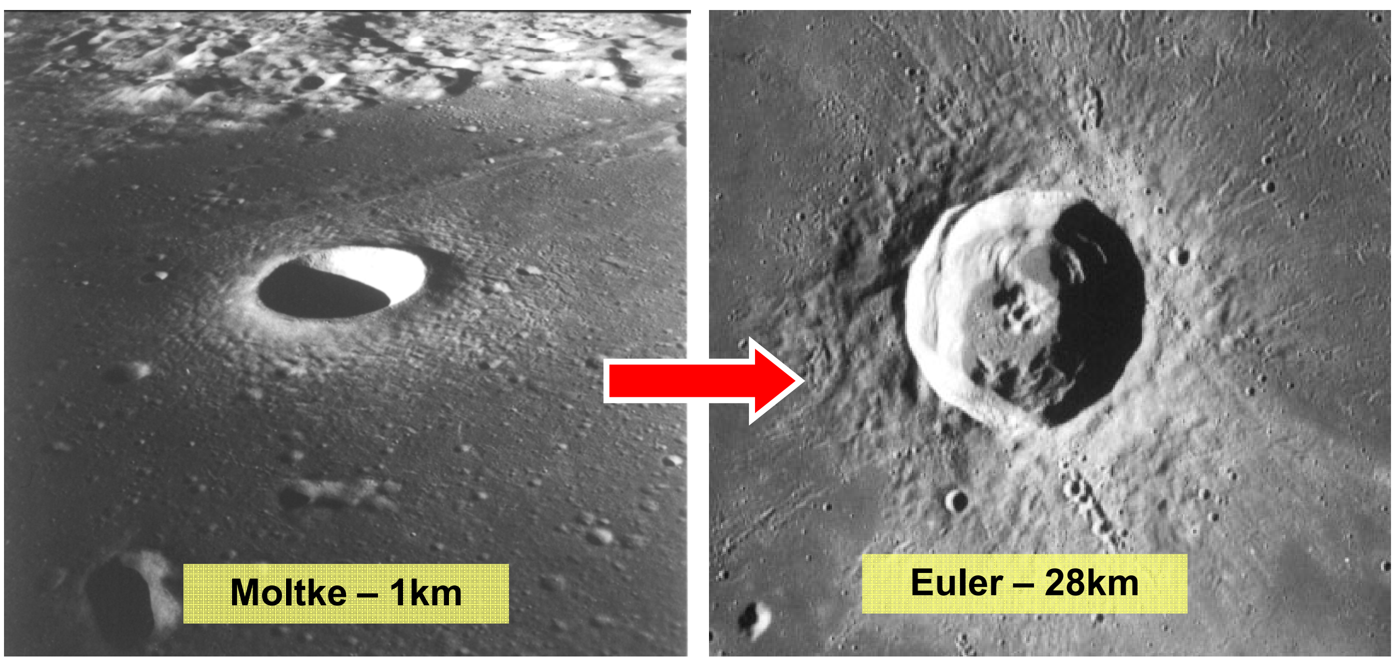


Raised Rim – from explosion



Simple	Complex
Bowl shaped	Flat-floored Central peak Wall terraces
Little melt	Some Melt
depth/D ~ 0.2 Size independent	depth/D smaller Size dependent
Small sizes	Larger sizes
Pushes most rocks downward and outward	Move most rocks outside the crater
Size limited by strength of rocks	Size limited by weight of rocks

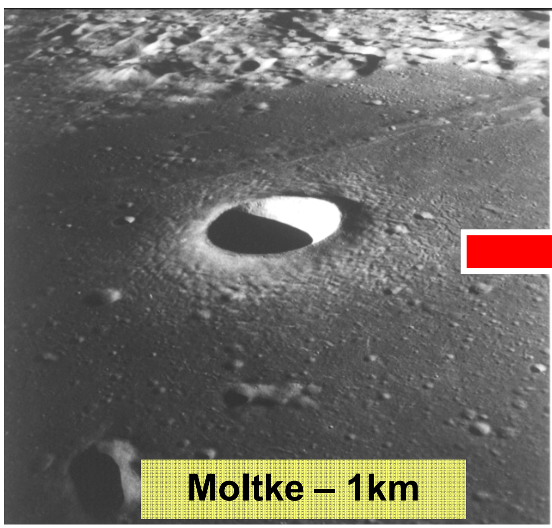
- Crater size depends on impactor energy
- Size of a simple crater depends on the strength of target rock
  - Small craters are in the so called 'strength regime'
  - The stronger the rocks, the smaller the crater
  - The weight of the rocks isn't important
- Size of a complex crater depends on the weight of the target rock
  - Large craters are in the so called 'gravity regime'
  - Weight of target rocks depends on gravity and target-rock density
  - The strength of the rocks isn't important

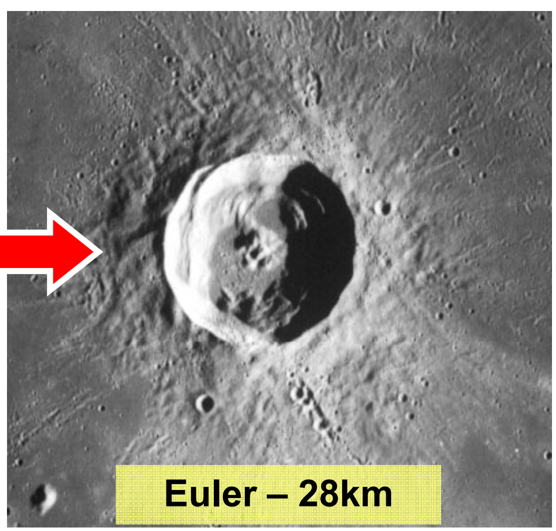


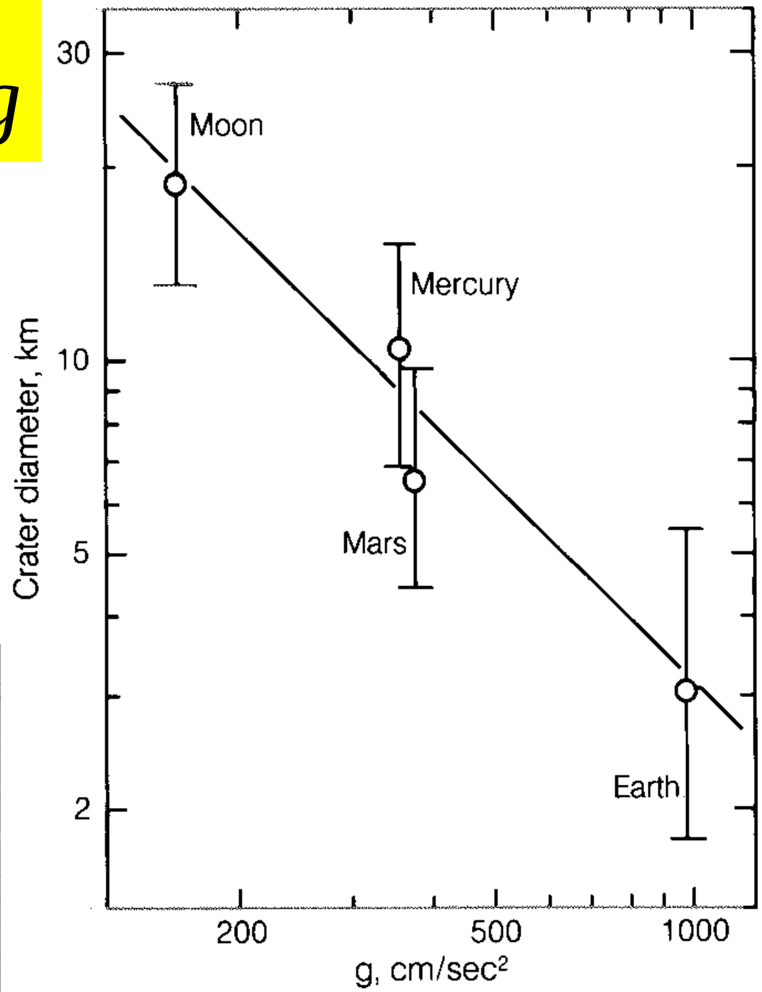
- **When do you switch from the strength regime to gravity regime?**
  - **Transition diameter (D_T)**
    - **Y=rock strength**
    - **ρ=rock density**
    - **g=planetary gravity**

$$D_T \approx Y / \rho g$$

- **Rock strength and density don't vary much**
  - **…but gravity varies quite a bit**
  - **Earth: D_T ~ 3km**
  - **Moon: D_T ~ 18km**







- **An example:**
  - **Typical rock strength is 10^8 Pa**
  - **Typical rock density is 3000 kg m^{-3}**
  - **What's the transition diameter from simple to complex craters on Mars?**
    - **Martian gravity is 3.72 ms^{-2}**

$$D_T \approx Y/\rho g = 10^8/(3000 \times 3.72) = 8870m$$

  - **About 8.9 km**

- **What about an impact into martian ice**
  - **Strength 10^7 Pa & Density 1000 kg m^{-3}**

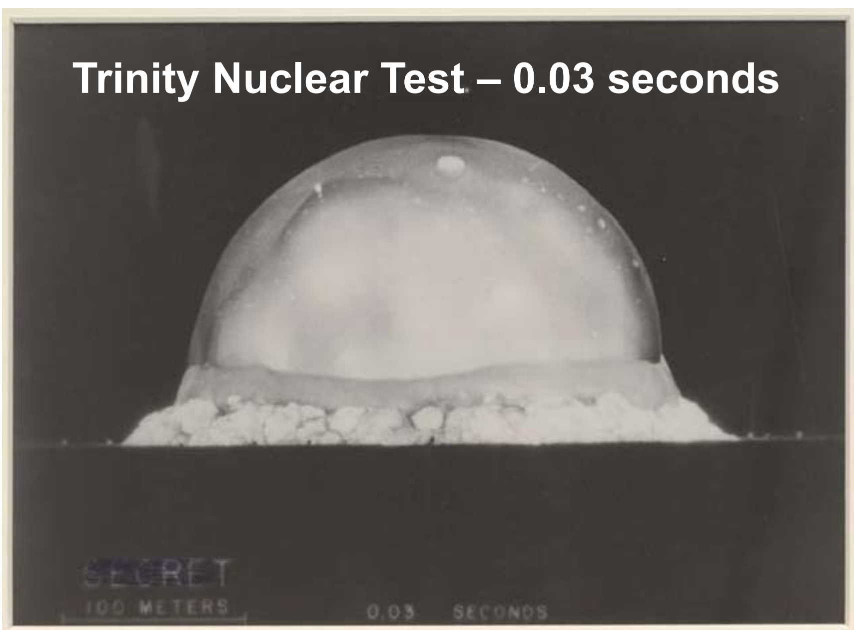
$$D_T \approx Y/\rho g = 10^7/(1000 \times 3.72) = 2690m$$

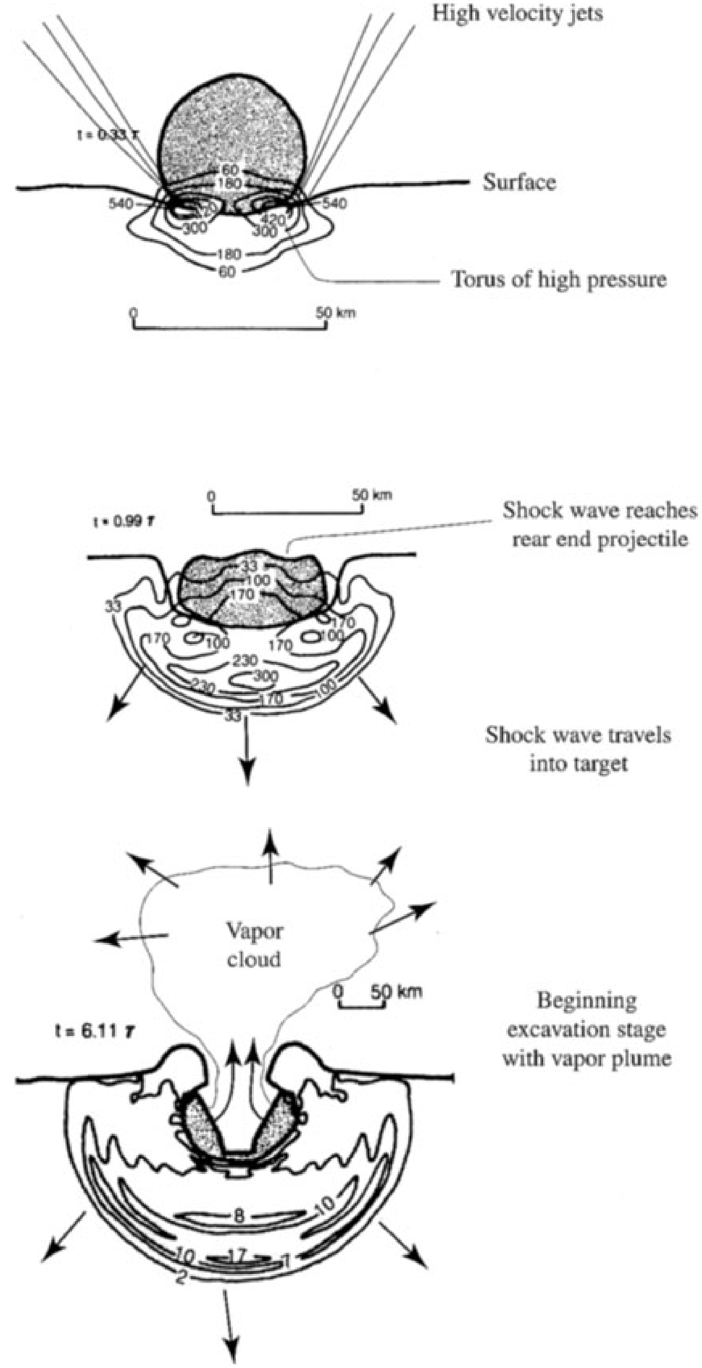
  - **About 2.7 km**

Formation of craters

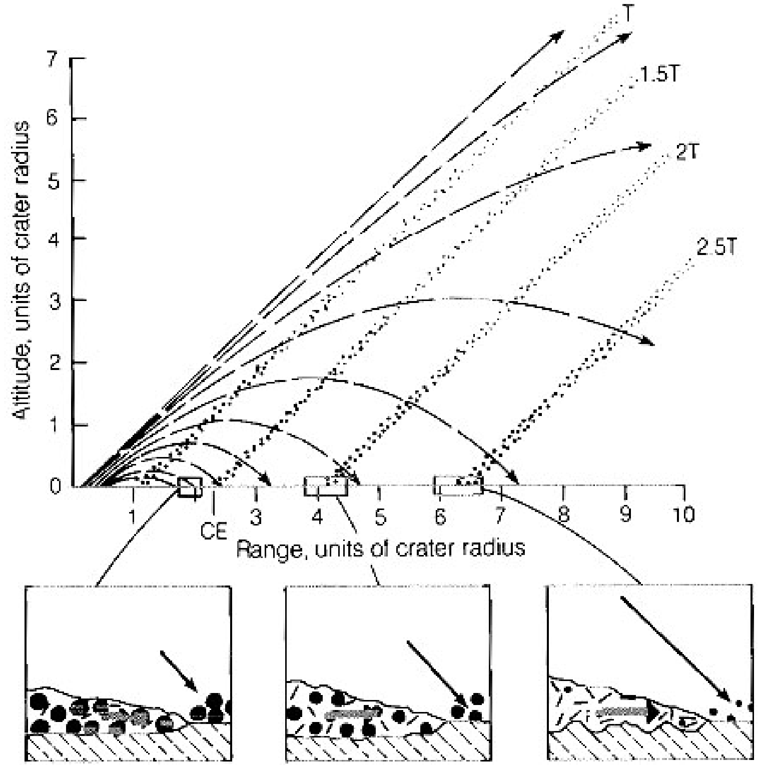
- How to build a crater
- Three stages
  - Contact and explosion
  - Excavation
  - Collapse
- Total energy is $\frac{1}{2}mv^2$
  - m is the mass
  - v is the impactor velocity
  - v is at least 11 km s^{-1} (Earth's escape velocity)
  - v is at most 72 km s^{-1} (A head-on collision with a comet)

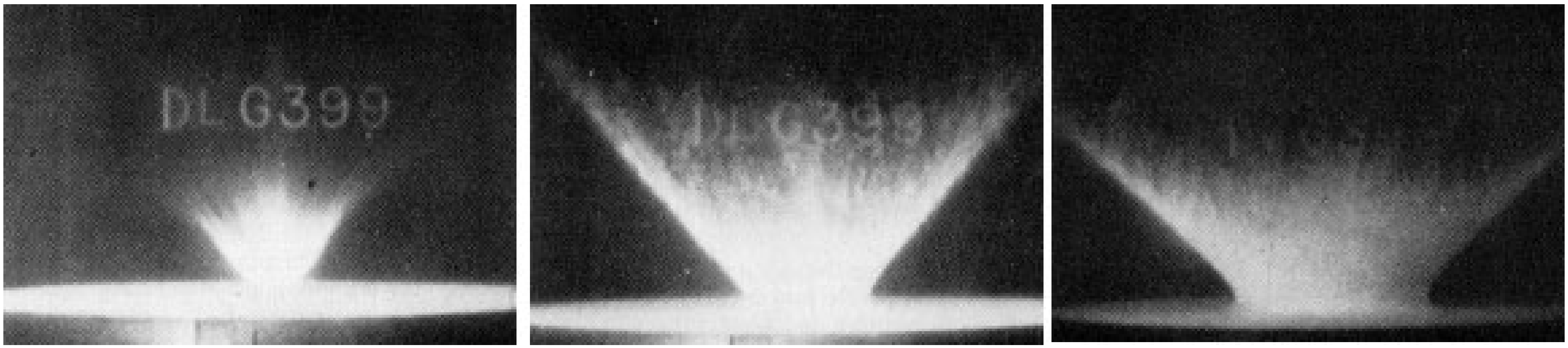
- **Contact stage**
  - **Impactor hits the surface – traveling at several km s^{-1}**
  - **Shockwave start propagating through the impactor and target**
  - **Impactor penetrates the surface**
  - **Shockwave reaches the other side of the impactor – impactor explodes**
    - **Like an underground point-source explosion**



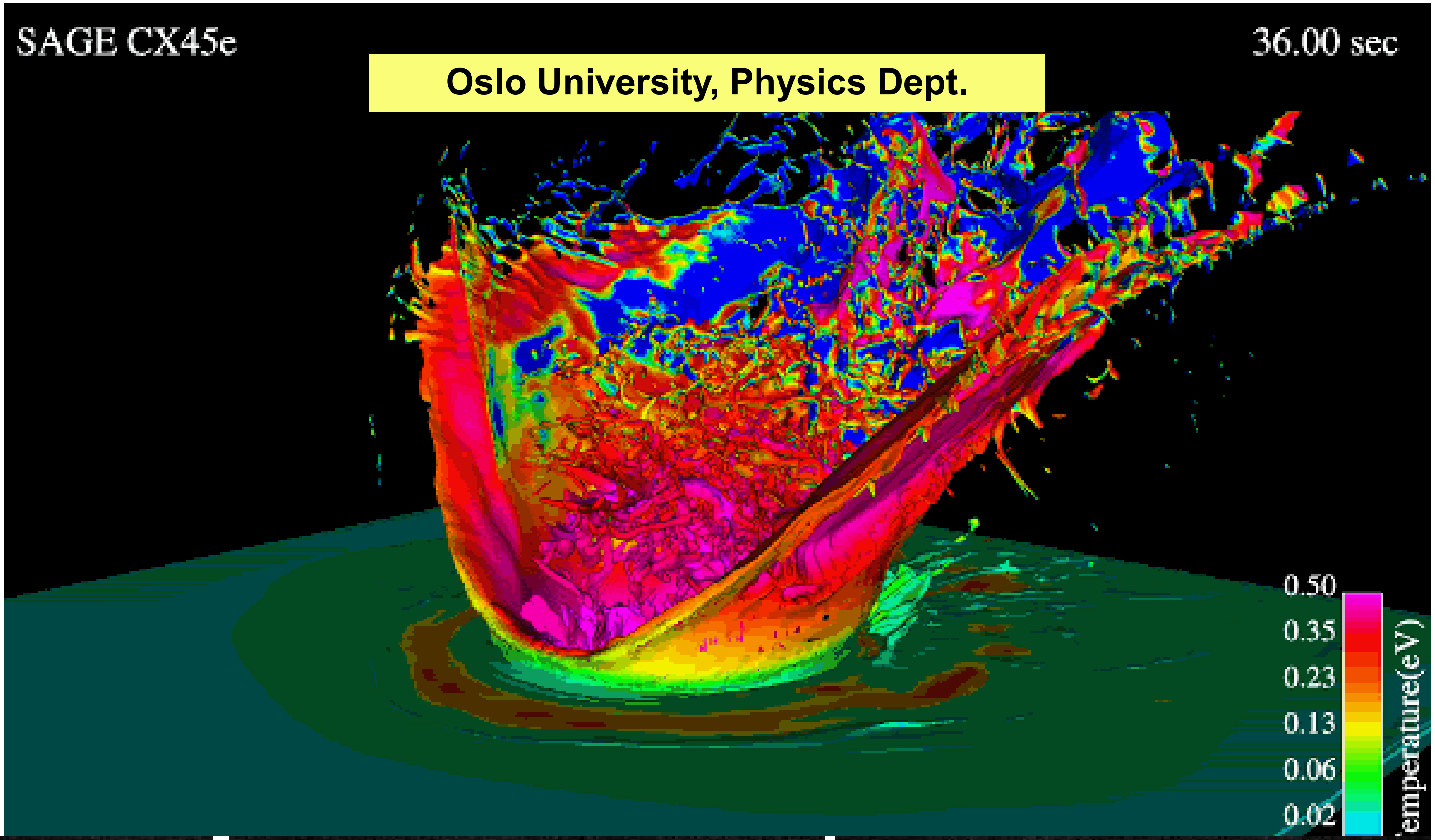


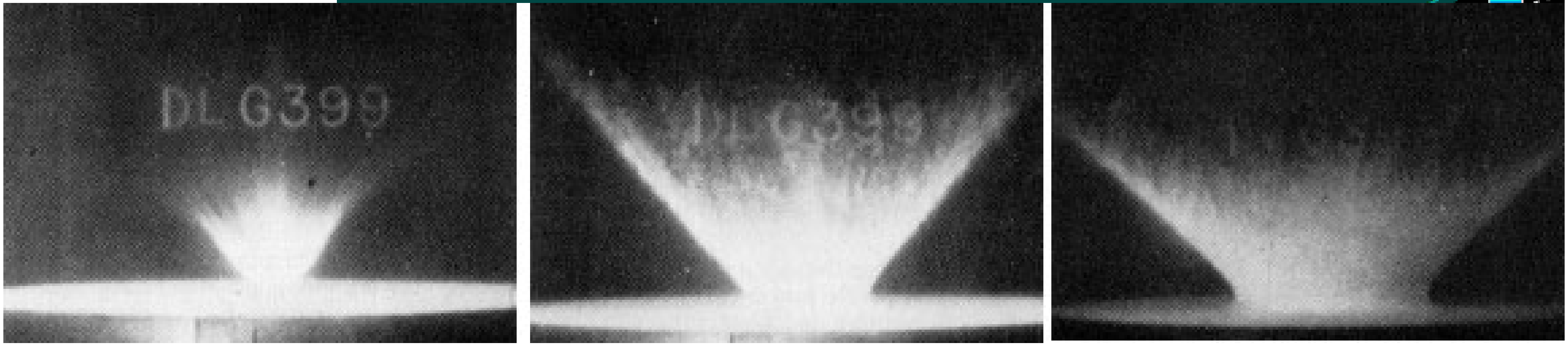
- Excavation stage
  - Bowl shaped cavity forms
  - Material ejected in a cone
    - Particles on balastic trajectories
    - Cone appears to expand



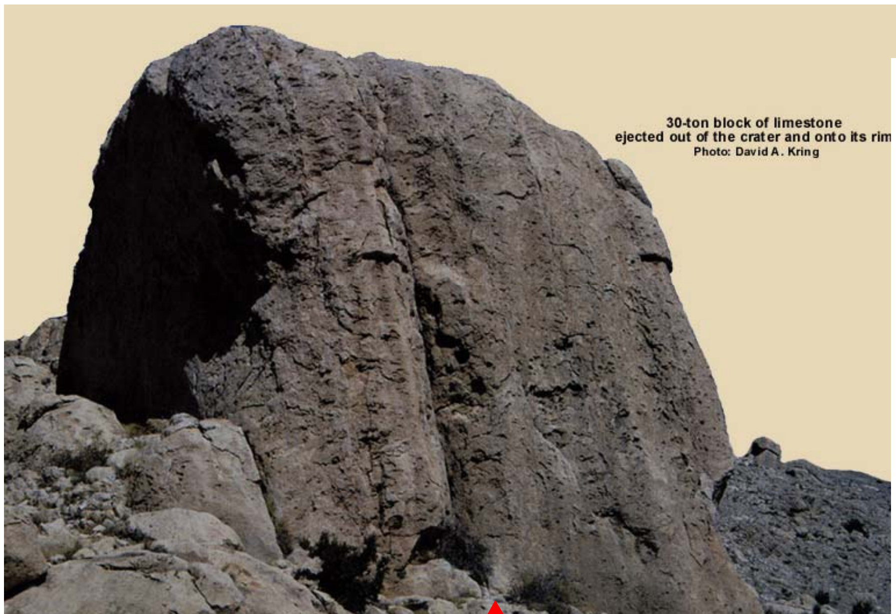


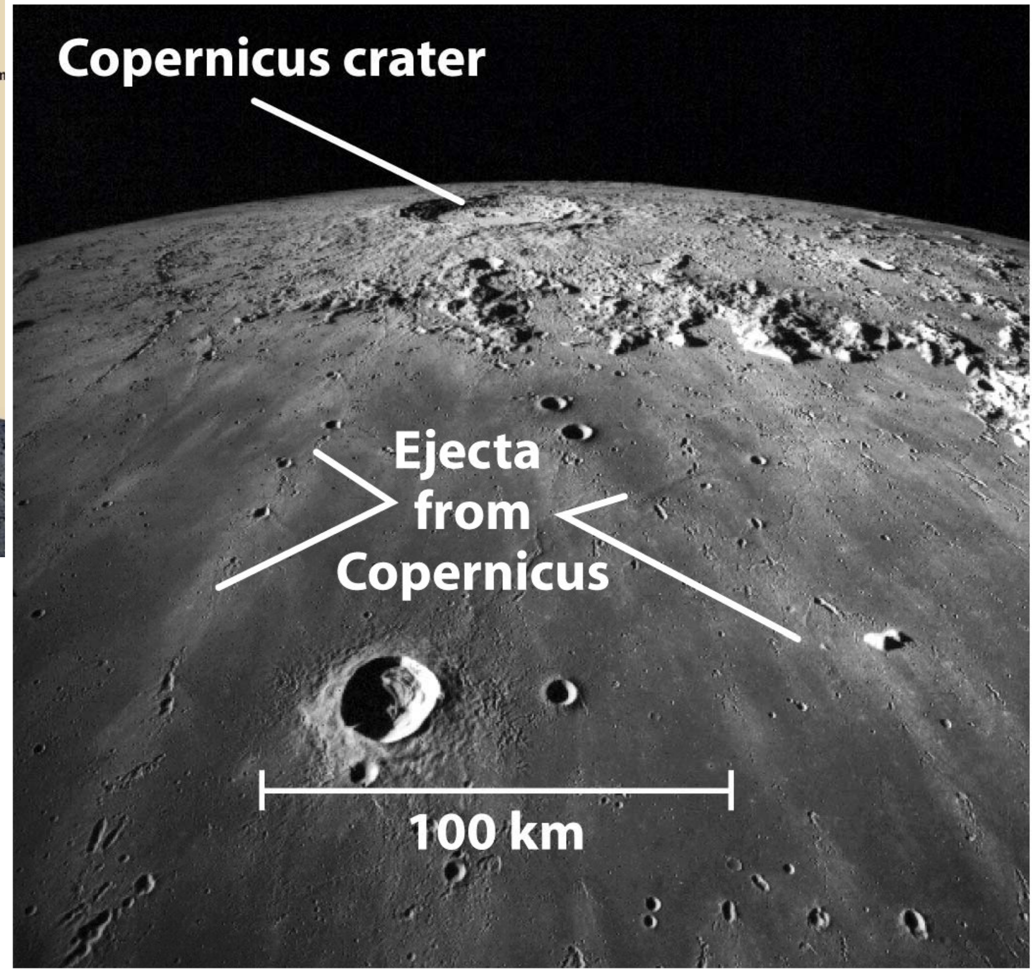
- **Simulations can extend lab work**





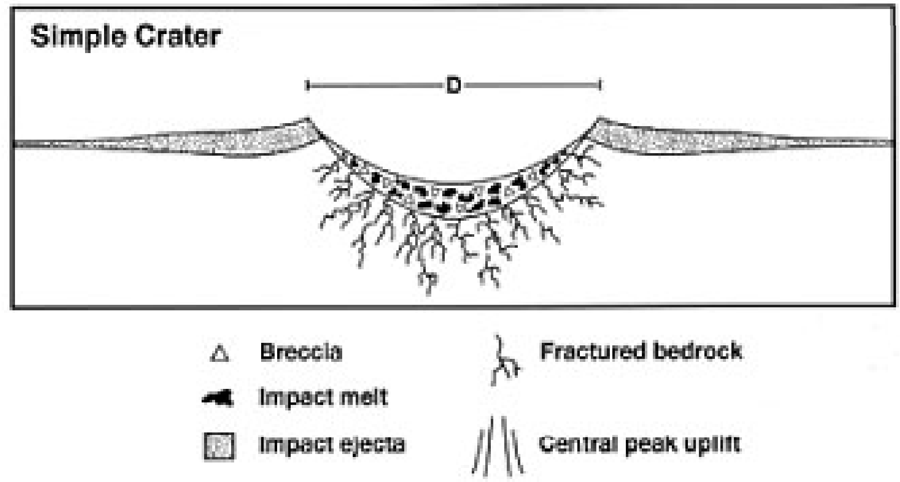
- **Some blocks of ejecta can be very large**
  - **Can form secondary craters**

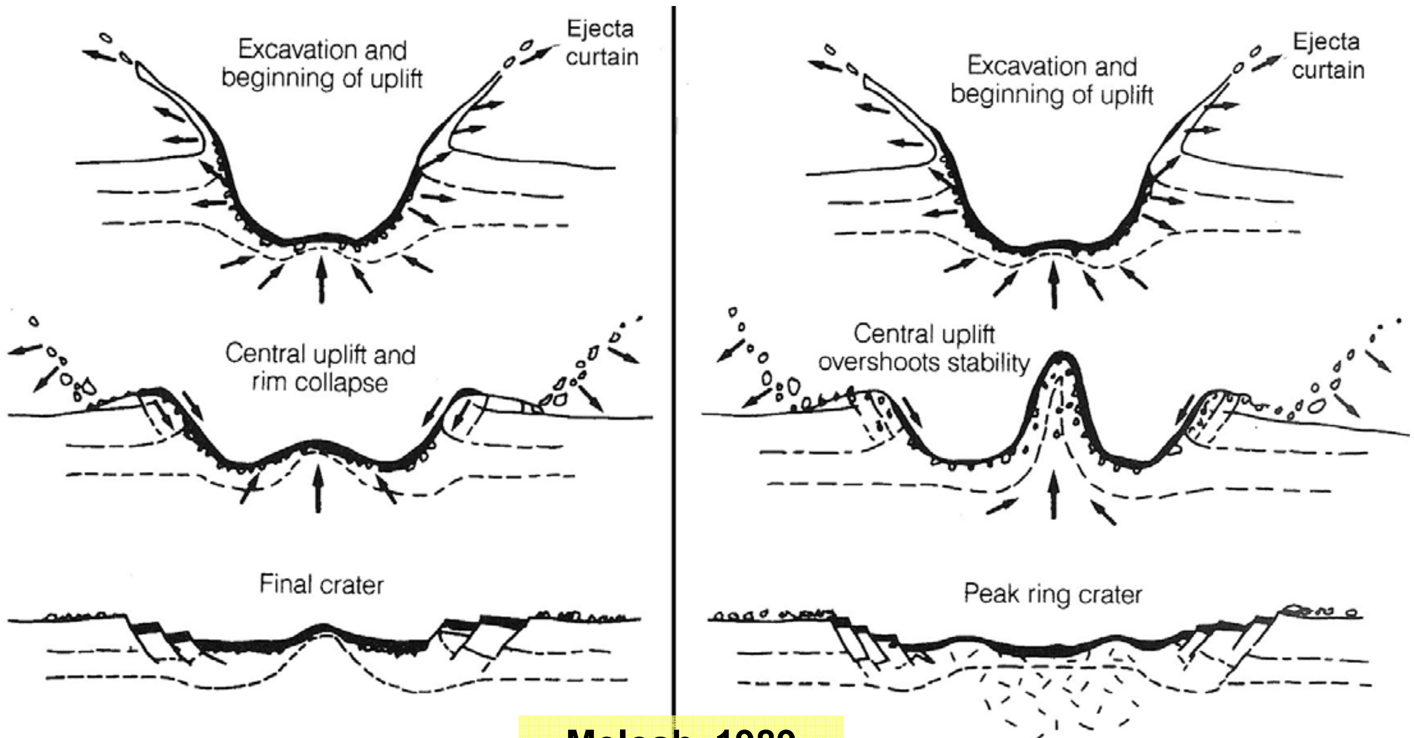




Unnumbered figure pg 182
Universe, Eighth Edition

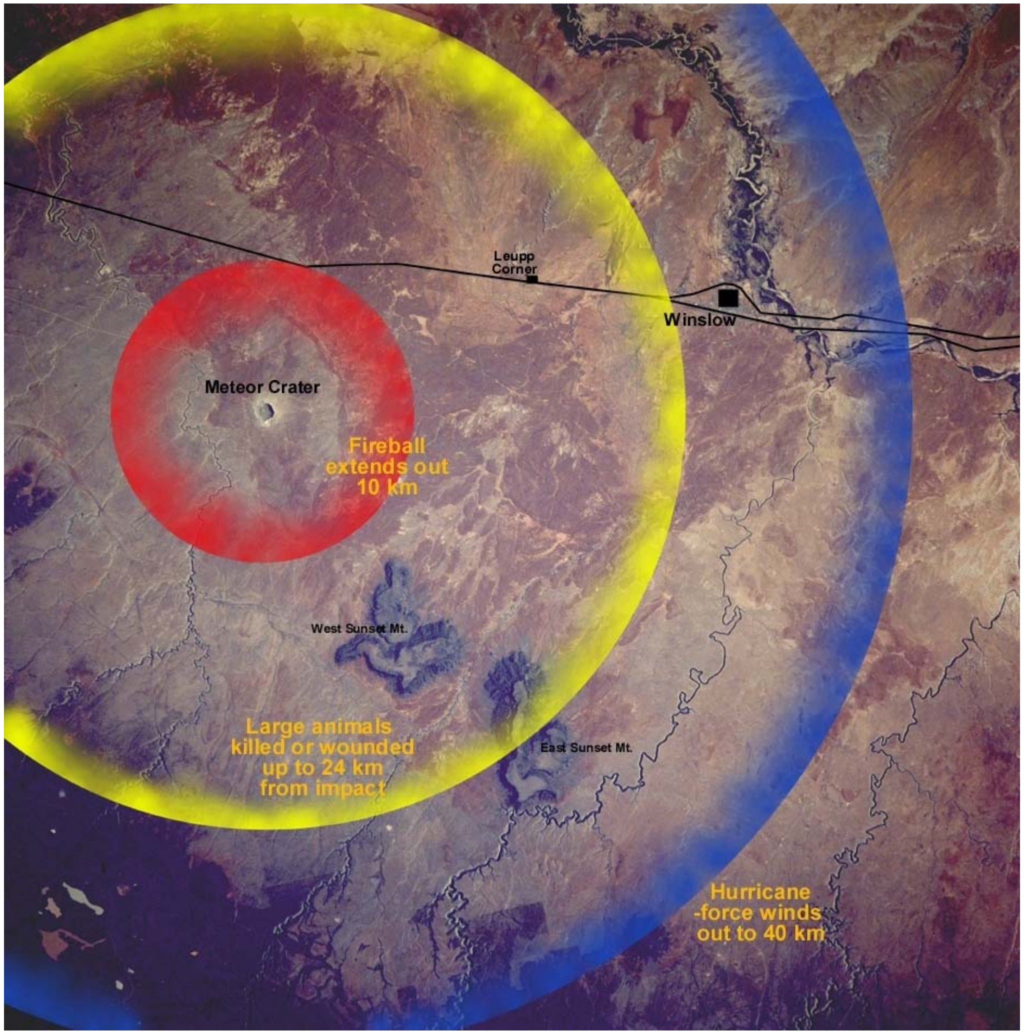
- **Collapse stage**
  - **Initial bowl-shaped crater collapses**
  - **Produces Breccia lens**
- **Small craters form shallower bowls**
  - **Depth/diameter goes from 0.5 to 0.2**
- **Large craters become complex**
  - **Floor rebounds to form a central peak**





Melosh, 1989

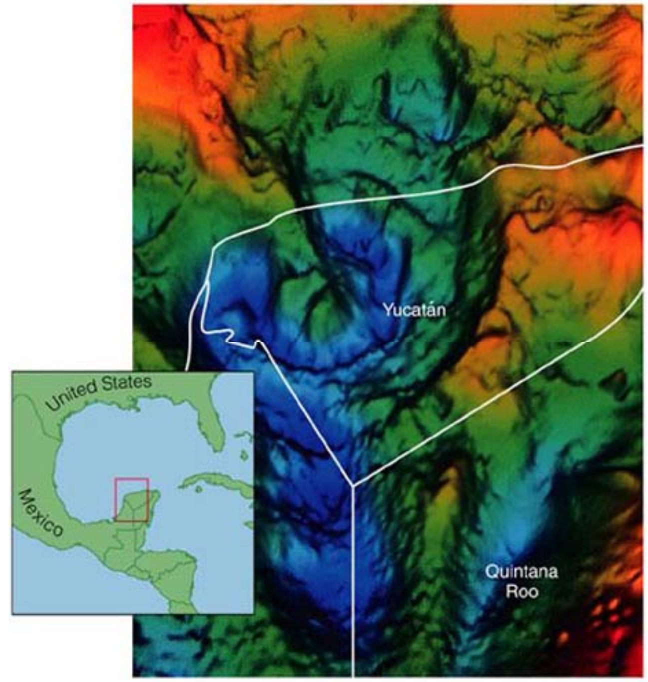
- Meteor crater as an example
  - Occurred about 50,000 year ago
  - Impactor was an iron asteroid ~50m in diameter
  - Crater is about 1200m in diameter
  - Energy ~30,000 kilotons of TNT
  - Hiroshima ~ 15 Kilotons



- In a modern city?
  - Depends on terrain
  - Compete destruction & death
    - Out to several km
  - Out to 10s of km
    - Mostly destroyed
    - Few survivors

- Is this common?
  - Every 10,000 years or so
  - Most of them over the oceans

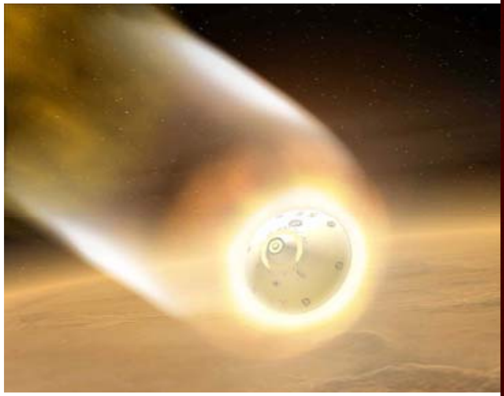
- Chicxulub as an example
  - Occurred about 65 Million year ago
  - Impactor was an asteroid ~10 km in diameter
  - Crater is about 200 Km in diameter
  - Local region was devastated for ~1000km



- Debris blasted into orbit
  - Reenters atmosphere and causes global wild-fires
  - Heat radiation from hot debris boils animals alive
  - Evidence from global soot layer enriched in iridium
  - Sunlight diminished – plants die
- Corresponds to the KT boundary
  - Cretaceous – Tertiary
  - Break in the fossil record where 75% of species went extinct

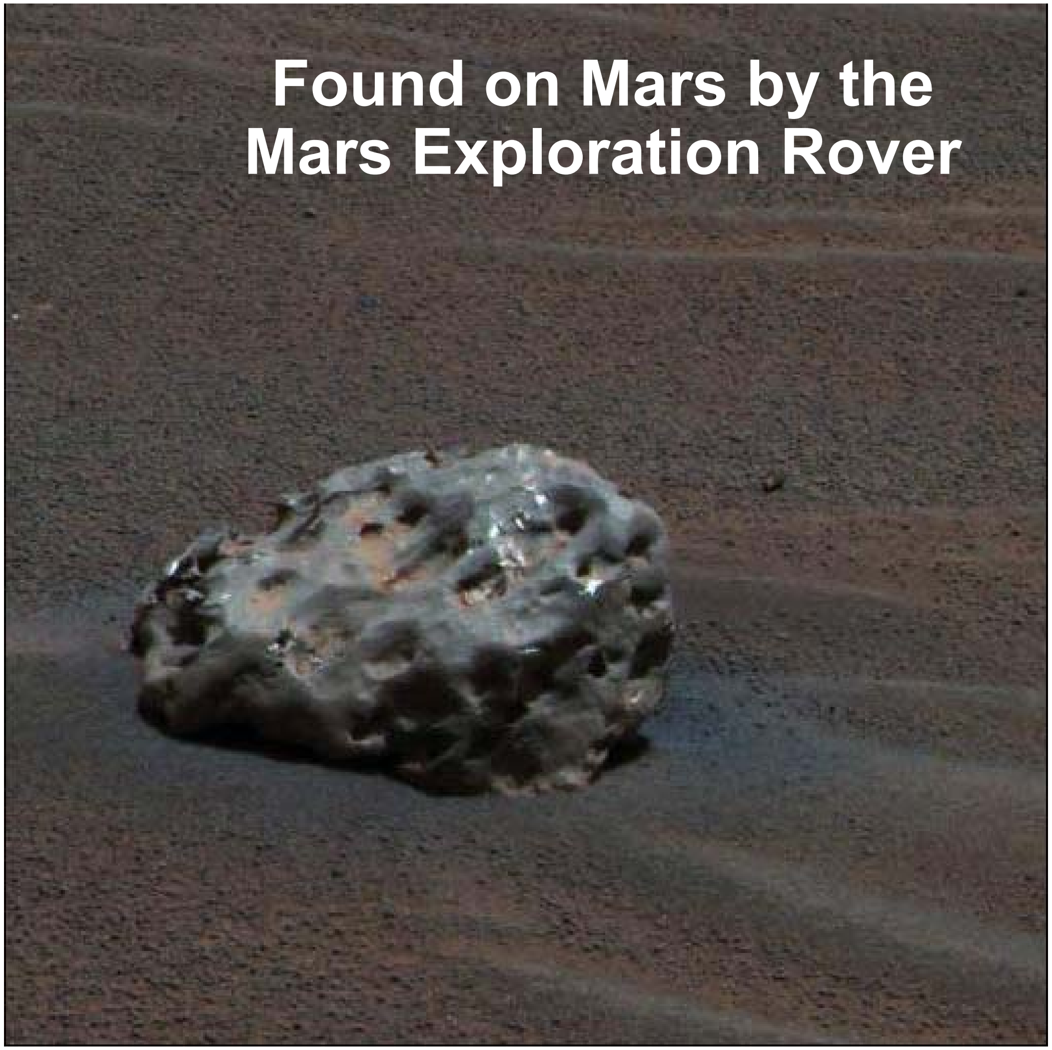
Atmospheric effects

- Pressure builds up on impactor as it passes through the atmosphere
  - Just like we use the atmosphere to slow down spacecraft



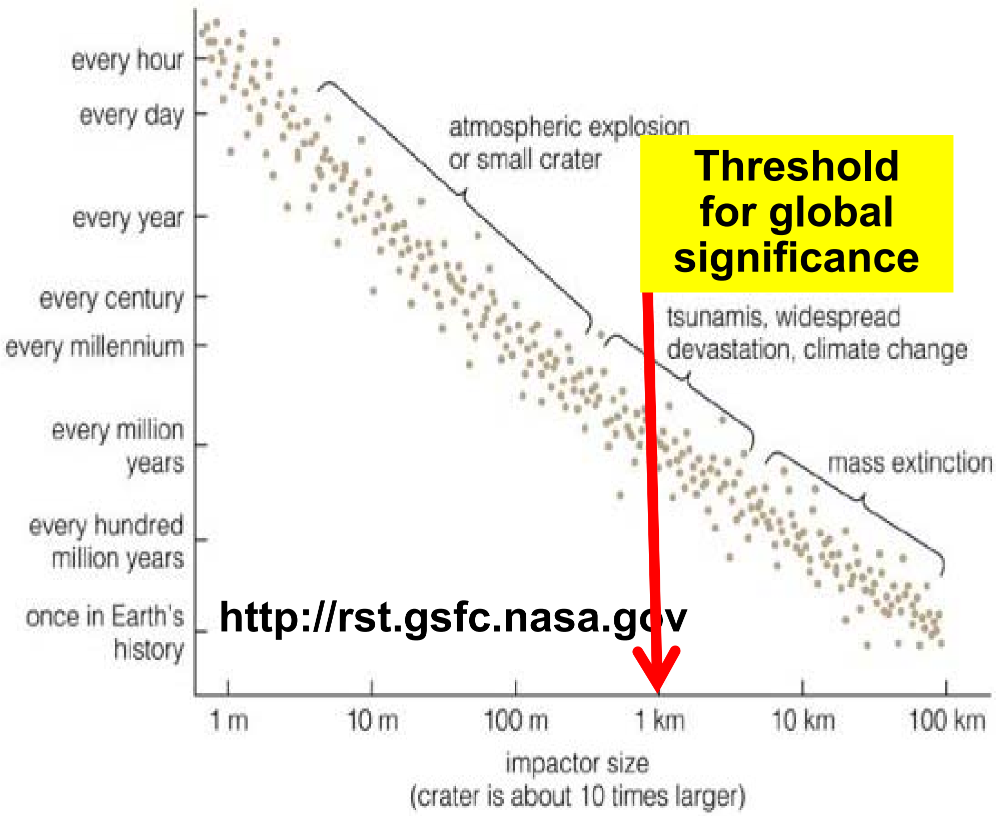
  - ‘ram pressure’ can exceed the asteroid strength
  - Asteroid fragments explosively
  - Atmospheric shock wave can level trees 100s of km away
- Tunguska 1908 – A once per century event
  - 80m diameter stony asteroid, 22 km s^{-1}
  - No Casualties
  - Next one more likely to be a problem – population increase

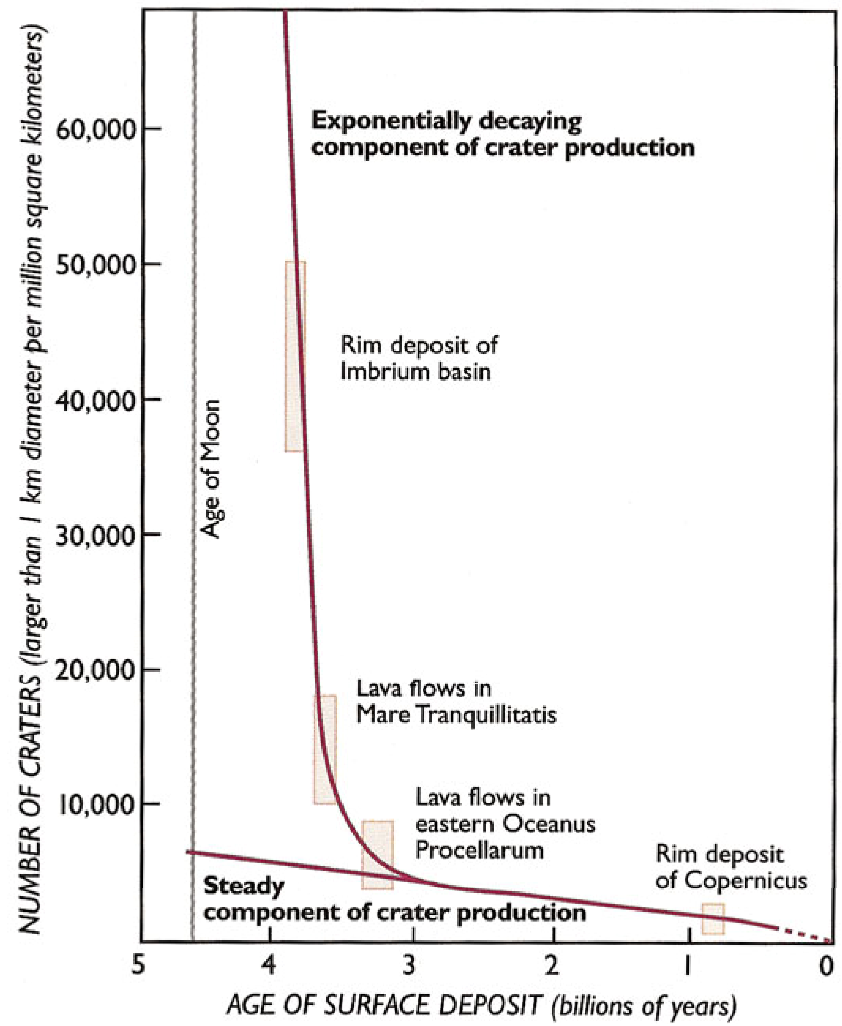
- **Strong objects can survive the forces needed for deceleration**
  - **E.g. iron meteorites**



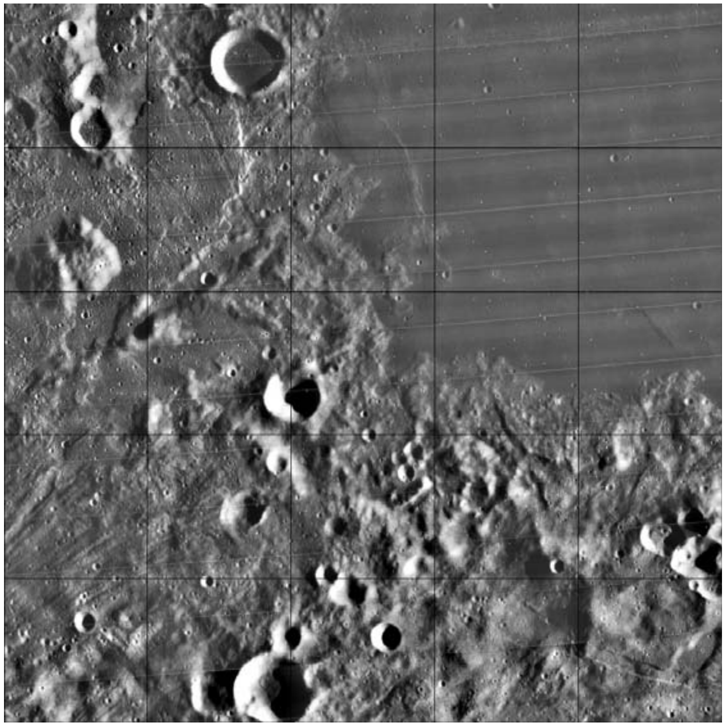
Crater Populations

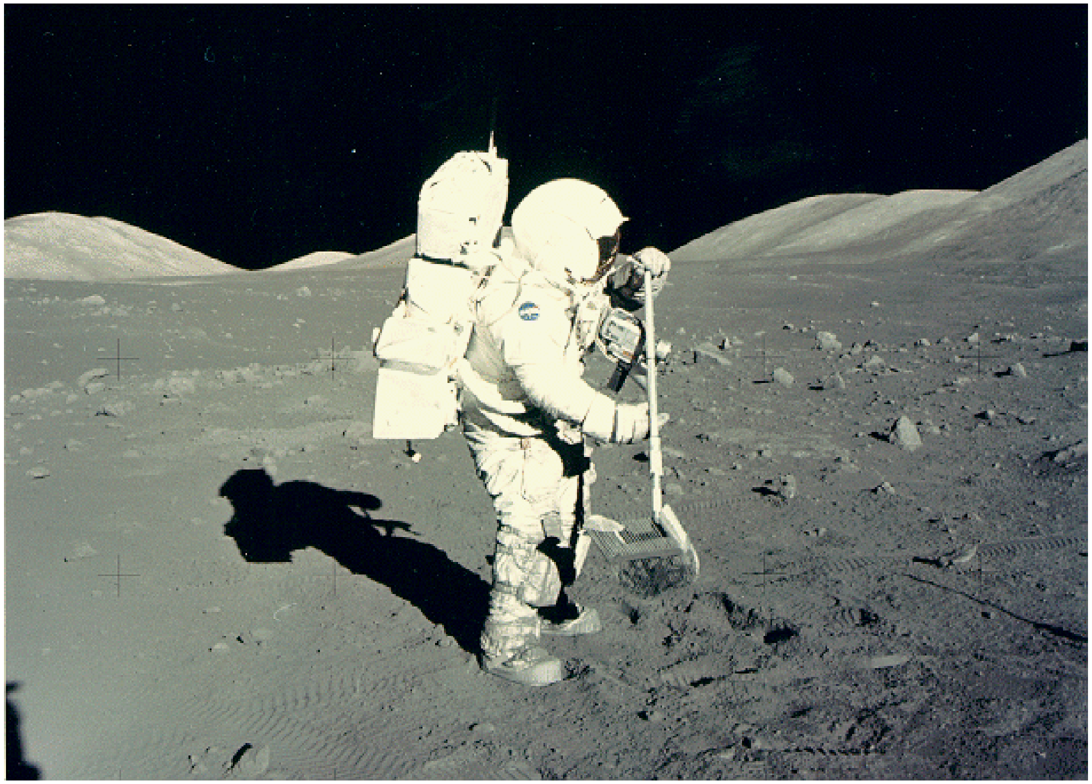
- **Larger impacts are rarer than smaller ones**
  - **Time between large events is long (on average)**
  - **Impact rates have slowed down a lot!**





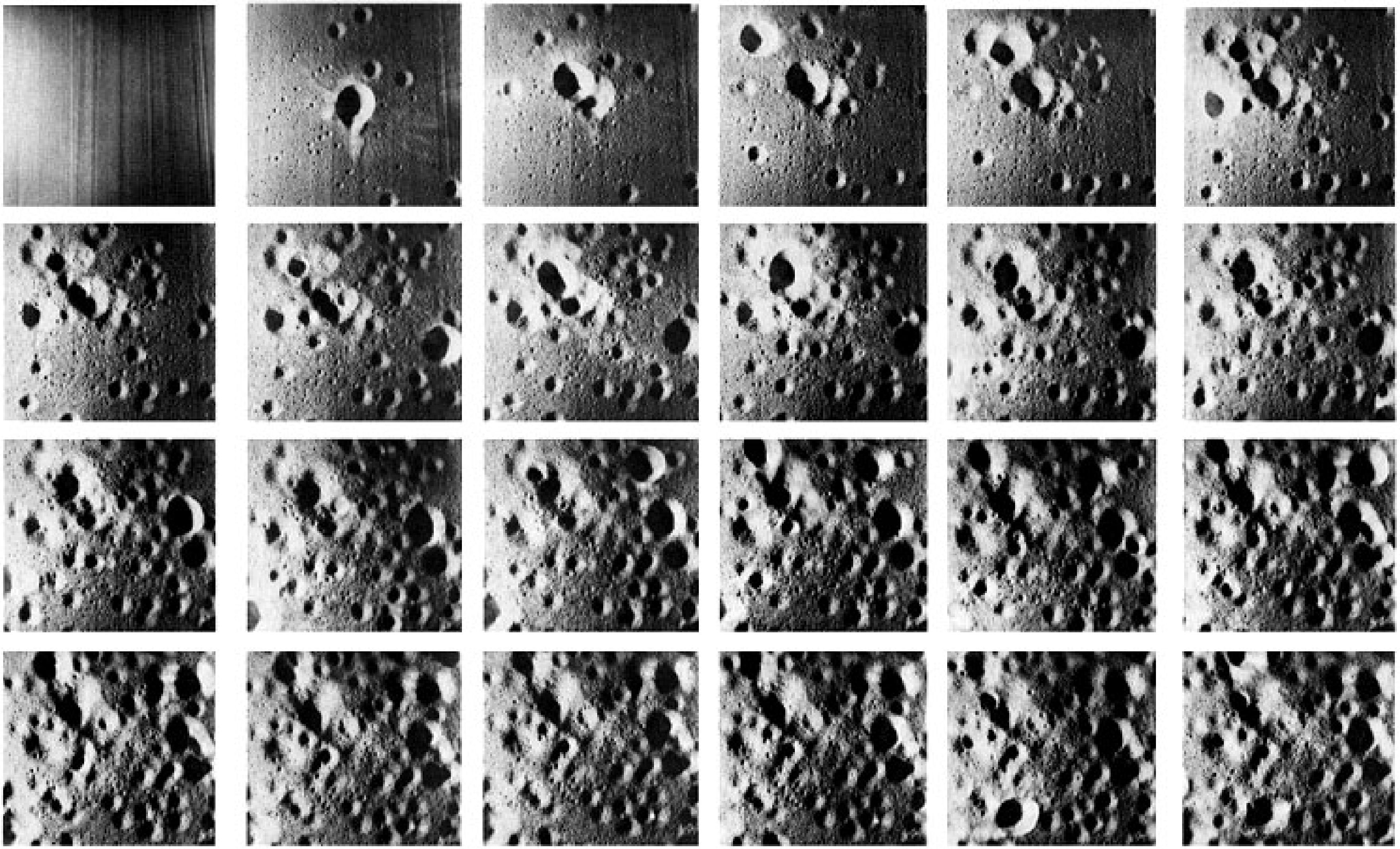
- Impact craters accumulate over time
  - If nothing removes the craters….
    - Like on the Moon
  - And we know the rate they form at…
    - Apollo samples provided the connection between crater counts and age
  - Then we can convert the crater counts to an age.

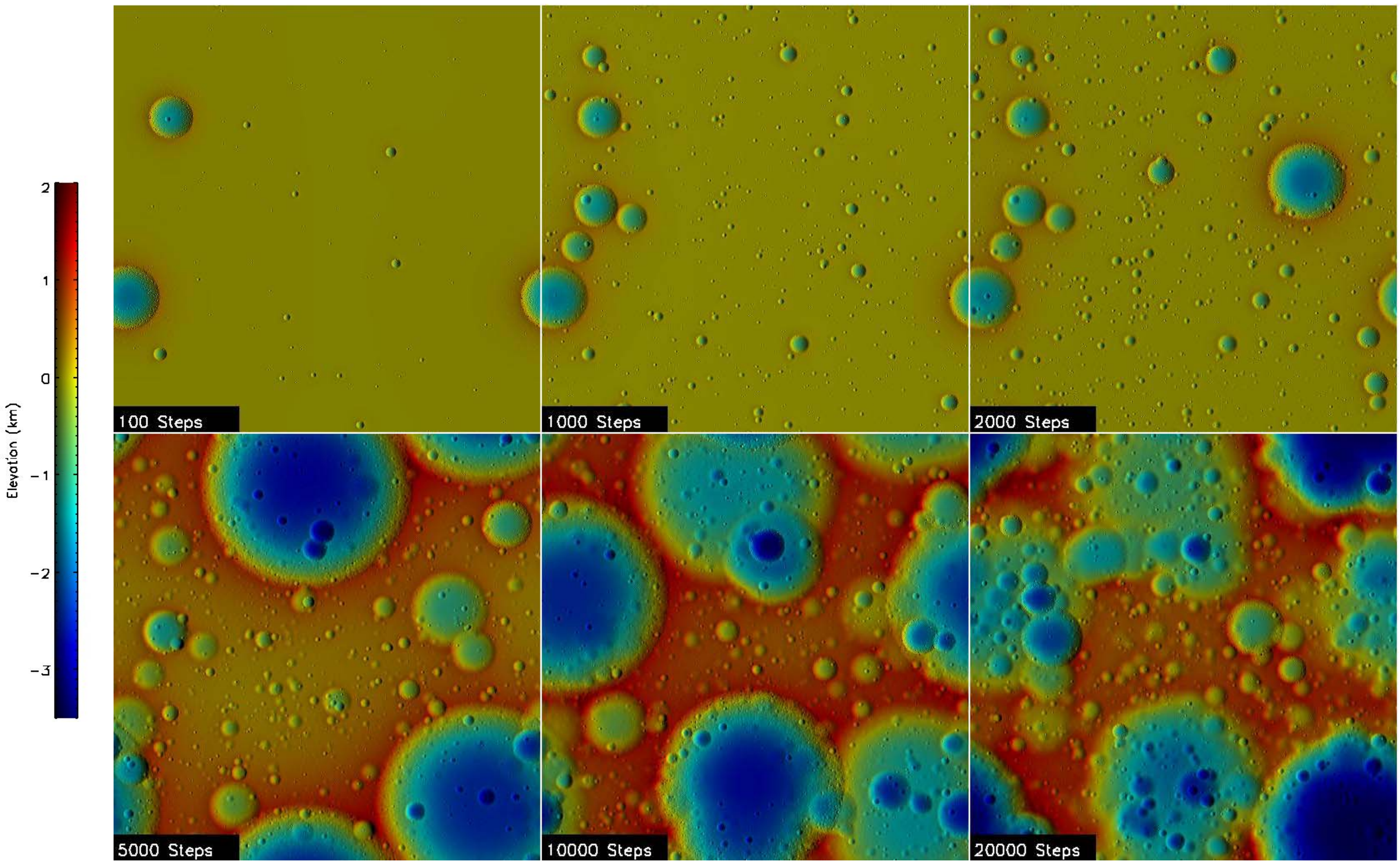




- Calibrating our dating mechanism
  - Apollo samples can be dated in the lab
  - These dates are compared to crater counts
  - We can scale the lunar results to other planets

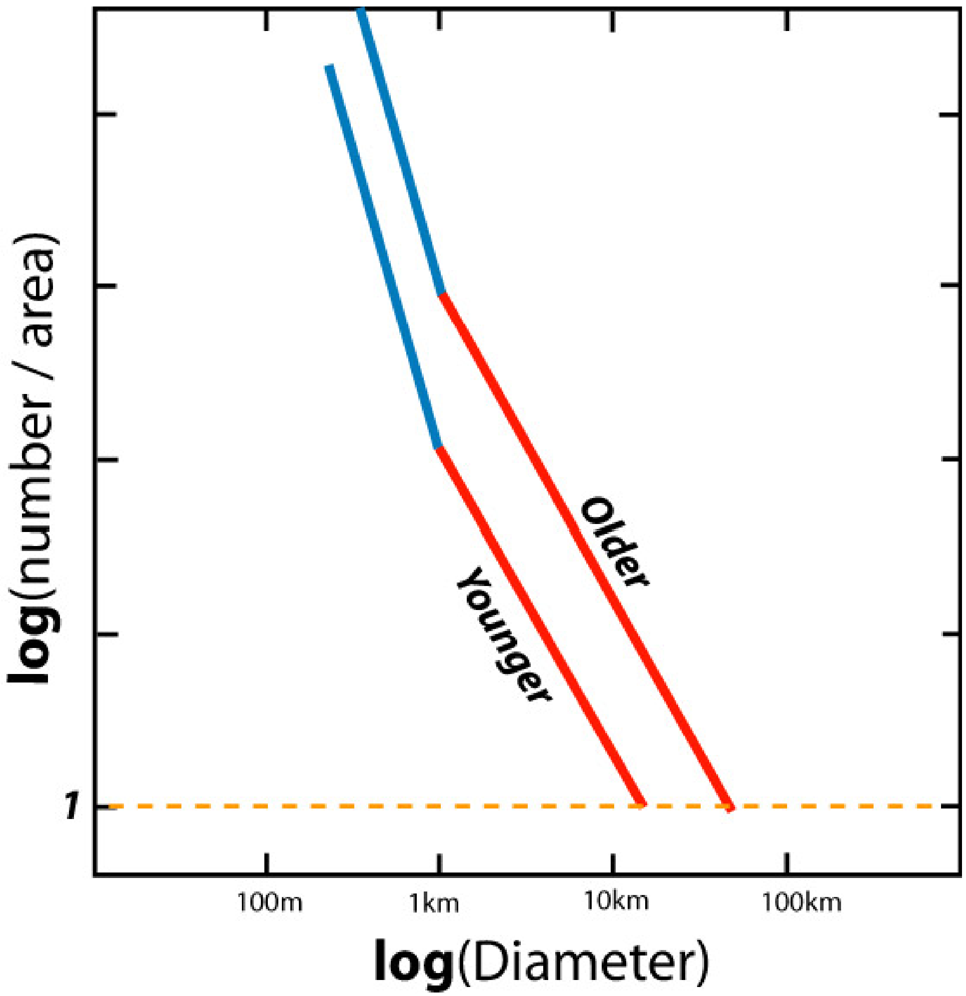
- **This mechanism works only up to a point**
- **When a surface is saturated no more age information is added**
  - **Number of craters stops increasing with age**



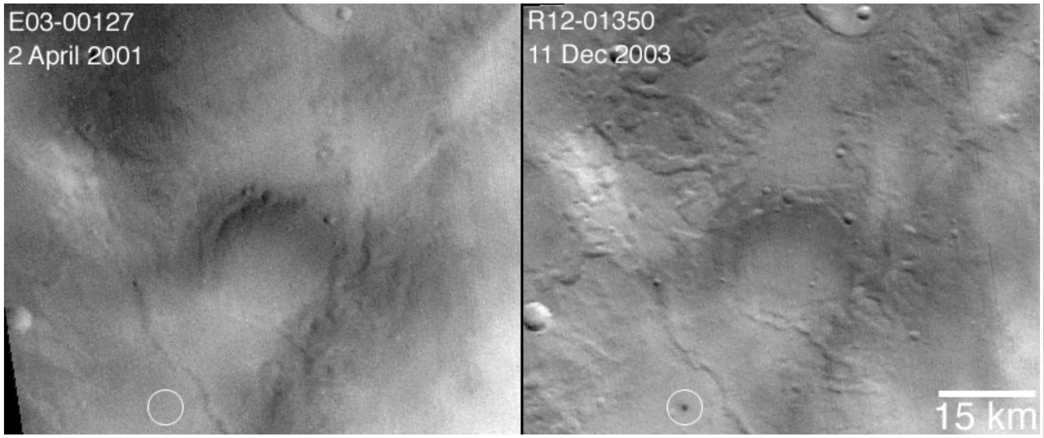


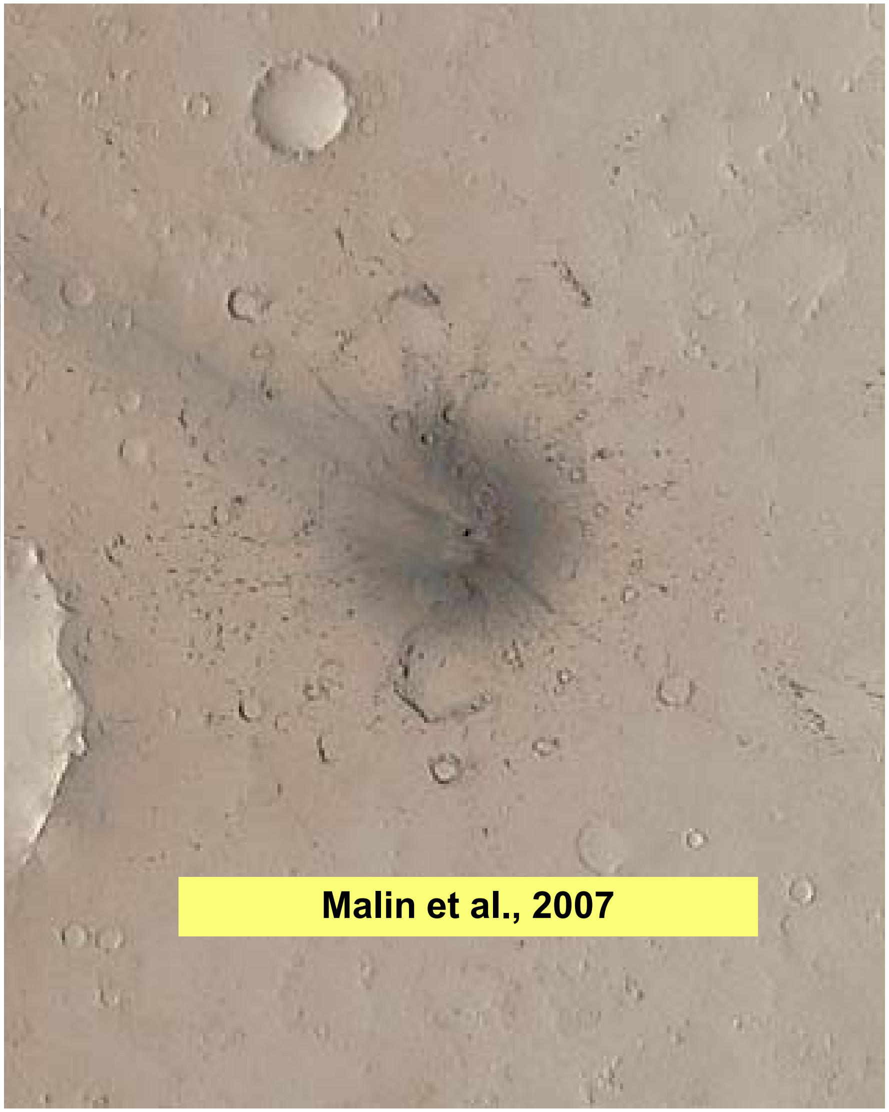
Elevation (km)
2
1
0
−1
−2
−3
100 Steps
1000 Steps
2000 Steps
5000 Steps
10000 Steps
20000 Steps

- Big craters are rarer than small craters
- Number of craters plotted against size looks like this
  - Uses a log-log plot
  - Straight lines are isochrons
- Red lines are 'primary craters'
- Blue lines are primary and secondary craters
  - i.e. more than you'd expect
  - Secondaries dominate the small crater population



- **Impacts continue today**





Malin et al., 2007

In this lecture…

- Characteristics of craters
  - Bowls, rims and ejecta blankets
  - Nuclear test results
  - Simple vs. complex craters
- Crater formation
  - Contact, Excavation, Relaxation
  - e.g. Meteor crater, Chicxulub
- Atmospheric effects
  - E.g. Tunguska
- Crater populations
  - Dating a planetary surface

Next: Craters

- Reading
  - Chapter 7.6 to revise this lecture
  - Chapter 9.2 for next lecture