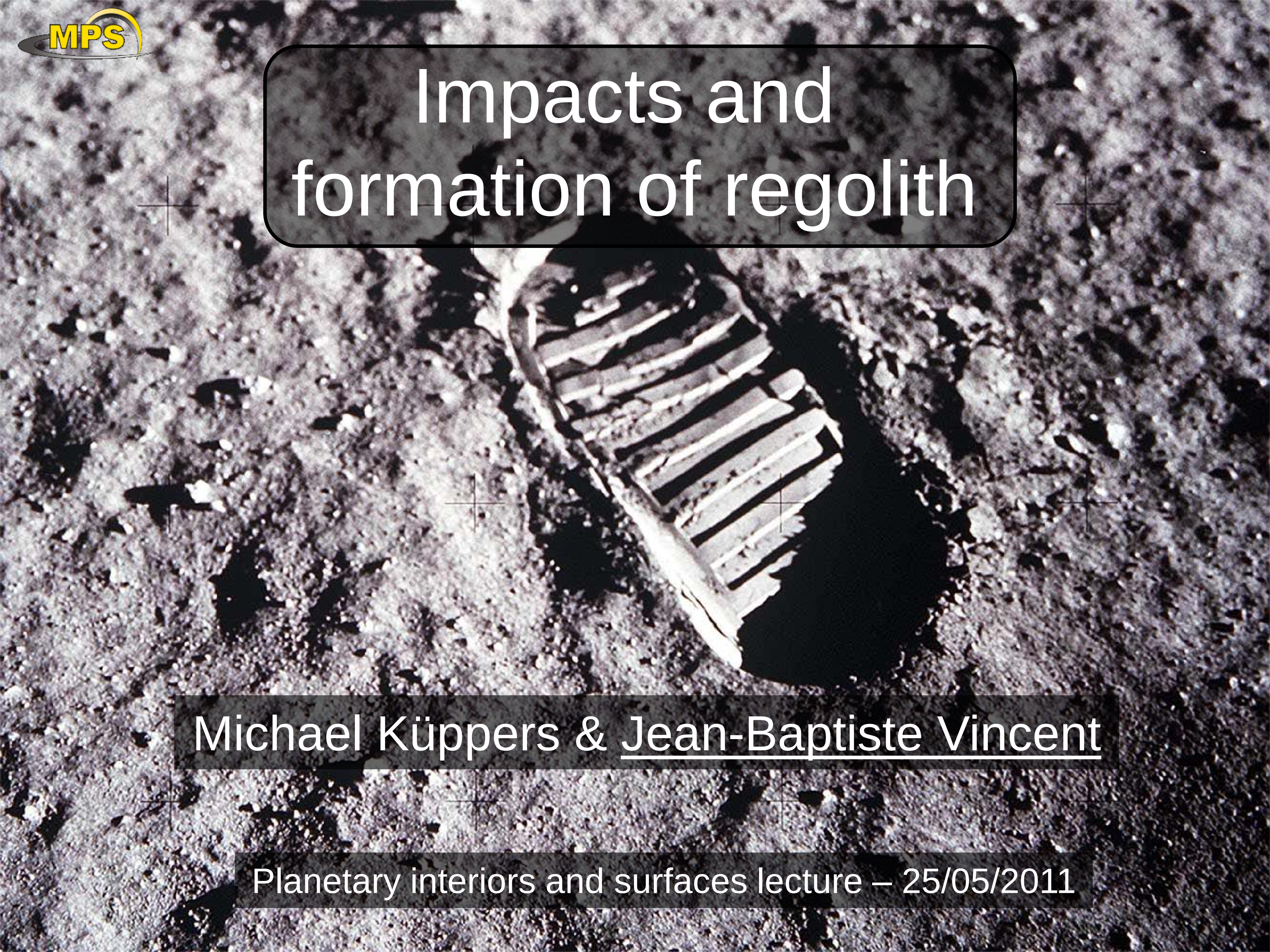
Impacts and formation of regolith



Michael Küppers & Jean-Baptiste Vincent

Planetary interiors and surfaces lecture – 25/05/2011

Contents

- What is regolith and why do we care ?
- Creation of regolith: Large impacts
- Modification of regolith: Small impacts
- Microproperties of regolith: Space weathering
- Issues in planetary science connected to regolith
- Craters and impactors $\Rightarrow$ Laboratory experiments and crater size scaling

What is regolith?

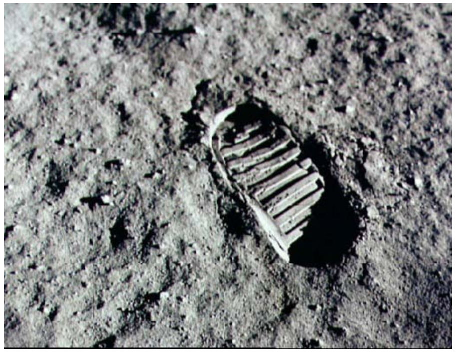
“Superficial layer or blanket of loose particulate rock material found on planet earth or any other hard celestial object” (R. W. Fairbridge, in Encyclopedia of Astronomy and Astrophysics).

Therefore virtually every surface in the solar system consists of regolith.

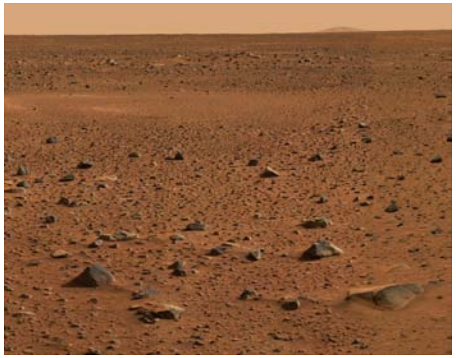
What is regolith?

• On Earth, the origins of regolith are weathering (erosion) and biological processes.

• On bodies without atmosphere like the Moon or asteroids, this regolith has been formed over the last 4.6 billion years by the impact of large and small meteoroids and a continuous bombardment of micrometeoroids and solar and galactic charged particles breaking down surface rocks; + a natural degradation due to huge temperature differences between day and night.

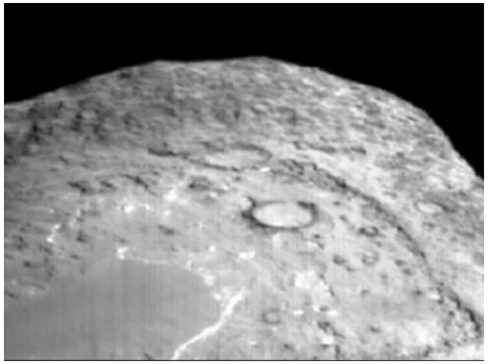


Moon

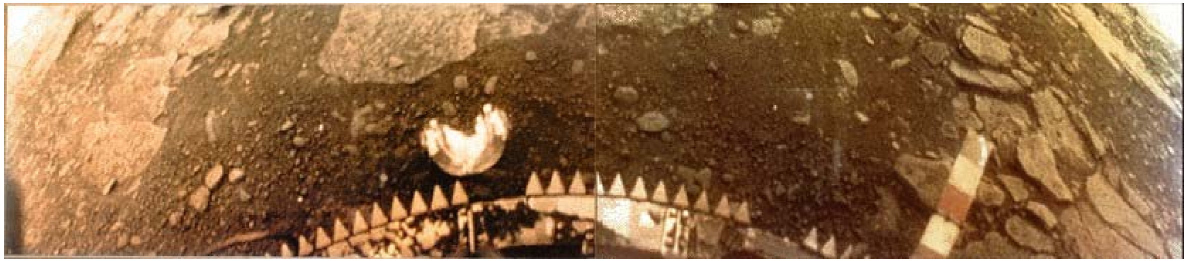


Mars

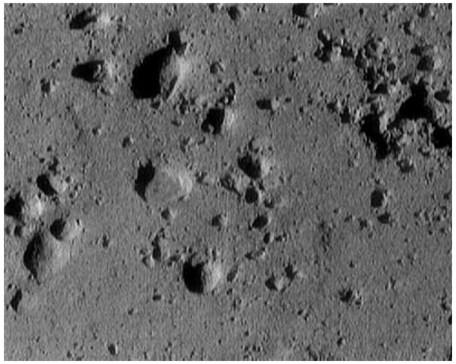
Titan



9P/Tempel 1



Venus



433 Eros

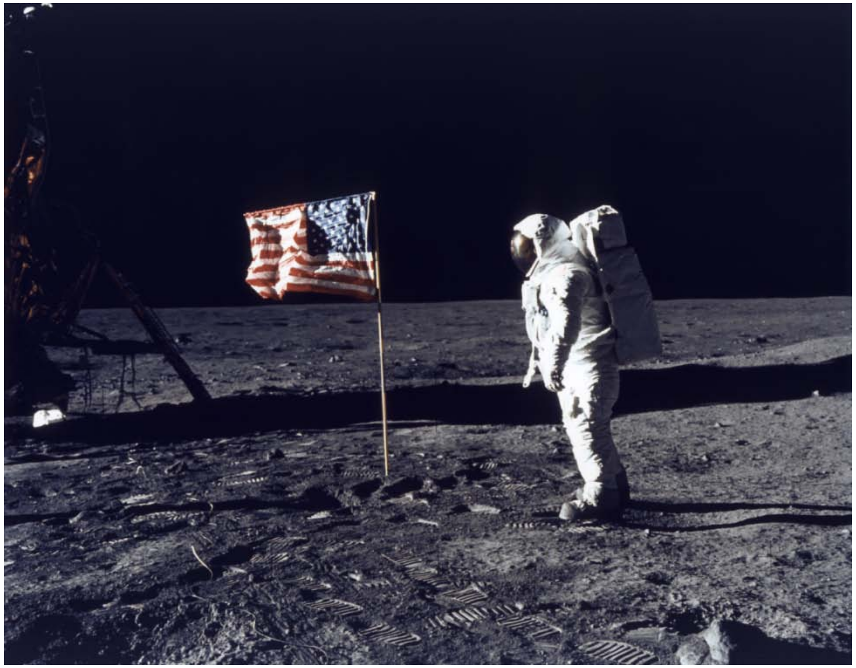
Regolith is everywhere : planets, asteroids, comets...

Examples (1): Earth

Regolith is created from rock by the action of wind and water

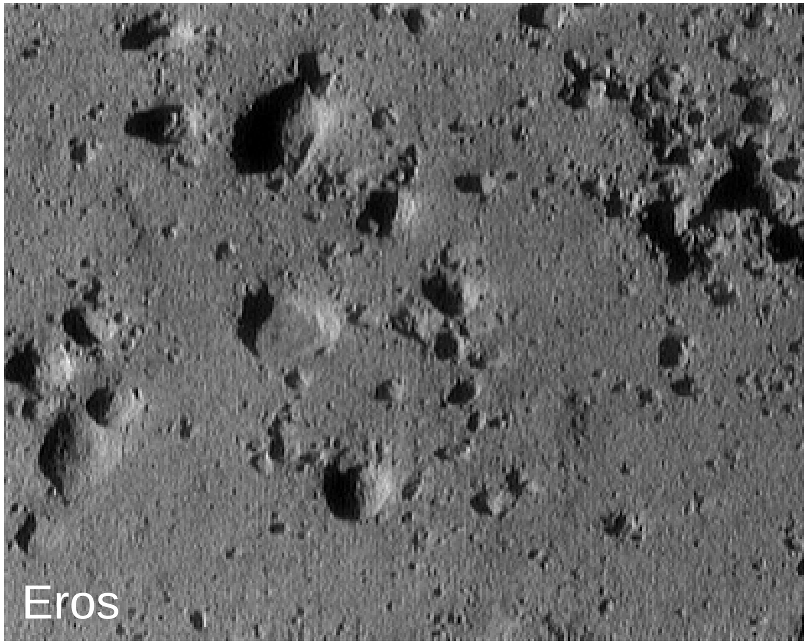
Examples (2): The Moon

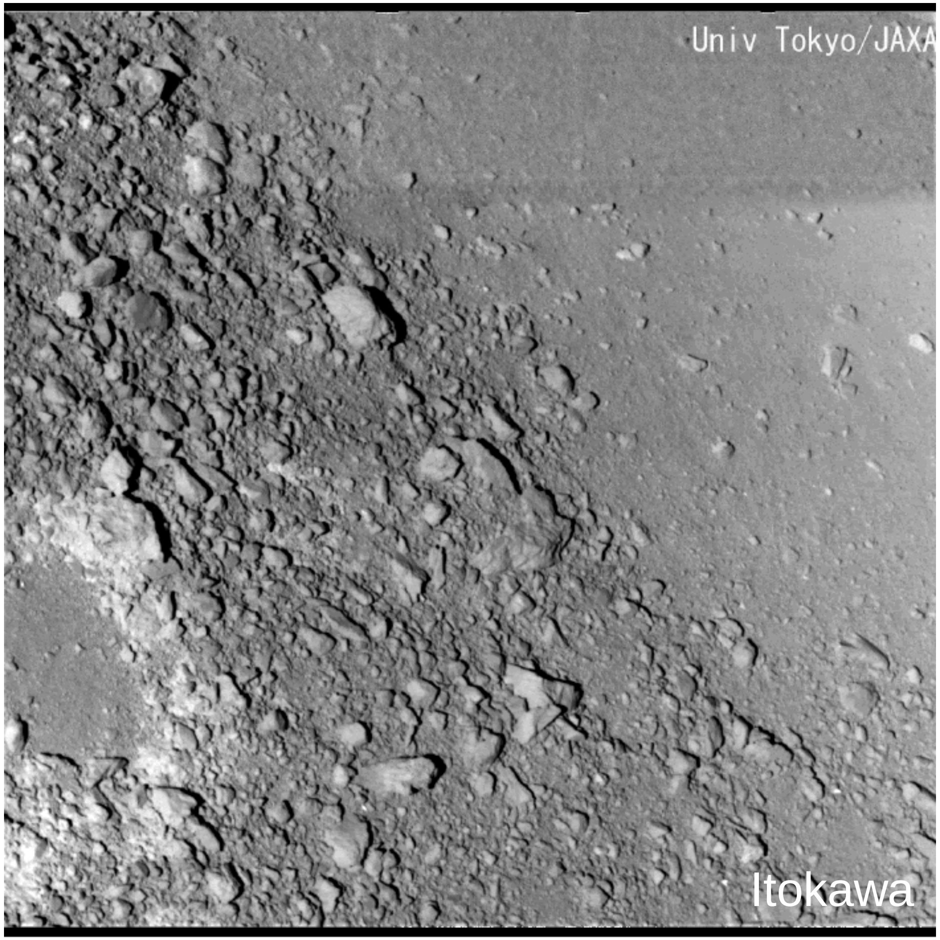
Regolith is created by meteoritic impact



Examples (3): Asteroids

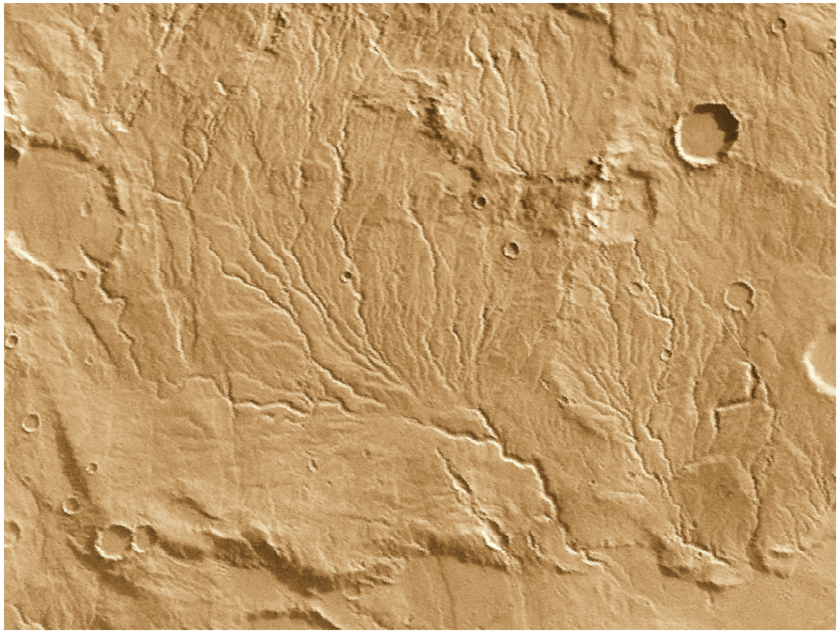
Regolith is created by meteoritic impact





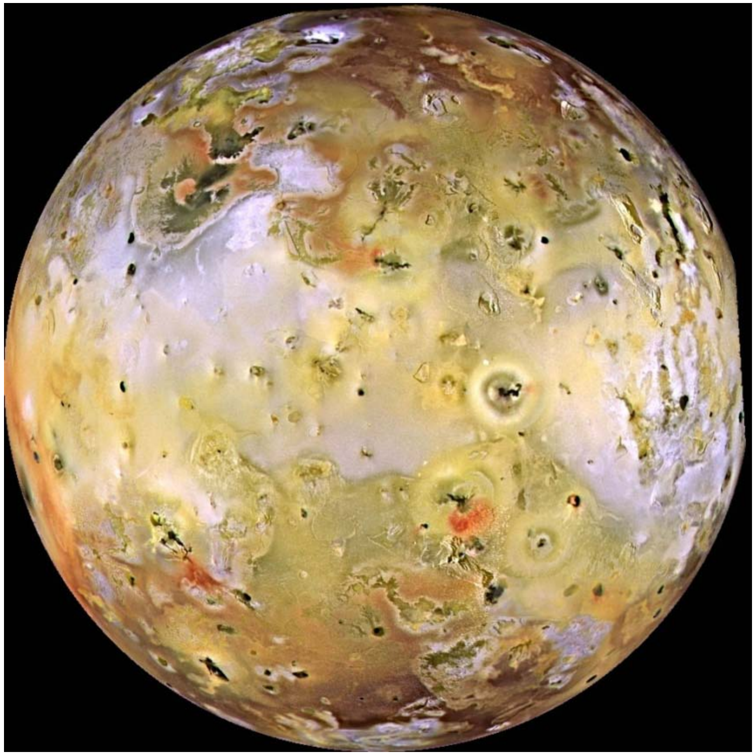
Examples (4): Mars

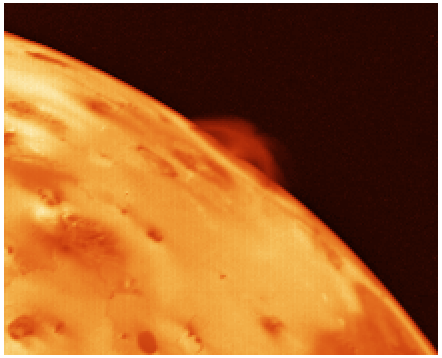
Intermediate case: Cratering + action of wind (and water)



Examples (5): Io

Regolith formation is dominated by volcanism



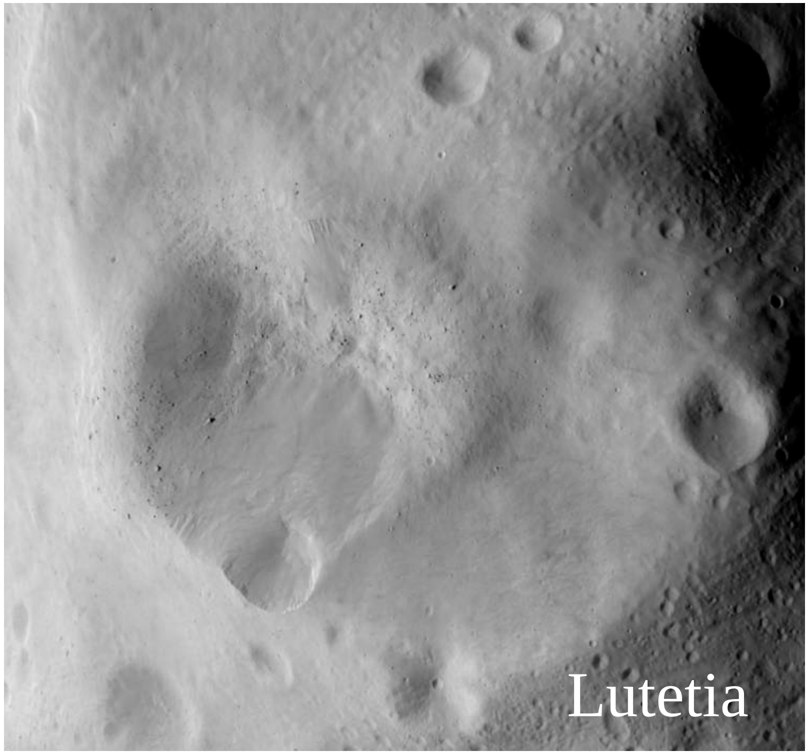


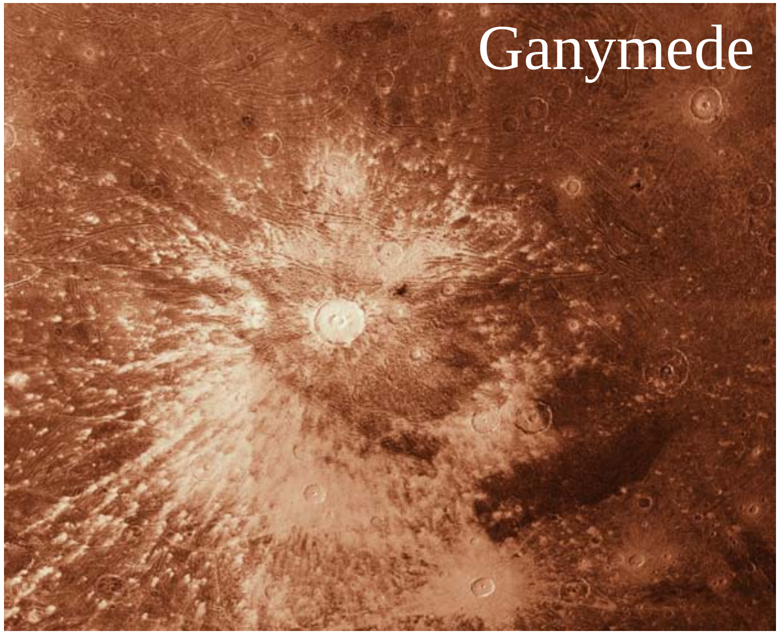
Regolith and remote sensing

- Most investigation of planetary or asteroidal surfaces study the regolith
  - Remote sensing: Depth of µm to meters
  - Landers: Digging into the regolith
- Interpretation of observations requires understanding of formation and evolution of regolith
- Lecture restricted to the case without atmosphere
  - Dominated by impacts
  - Applies to most bodies in the solar system (The Moon, Mercury, satellites of Mars, most satellites of the outer planets, all asteroids)

Creation of regolith (no atmosphere!)

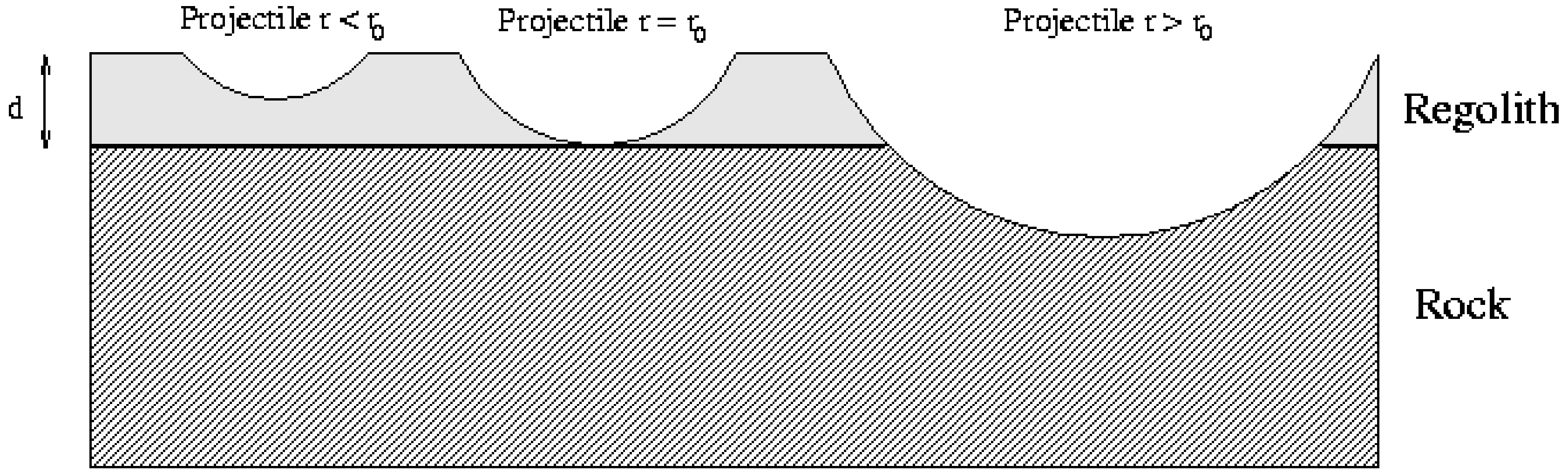
Fresh regolith is created by large impacts





What is a large impact?

- Crater size ~ 10 x impactor size
- A large impact penetrates the existing regolith layer and creates fresh regolith



Accumulation rate of regolith

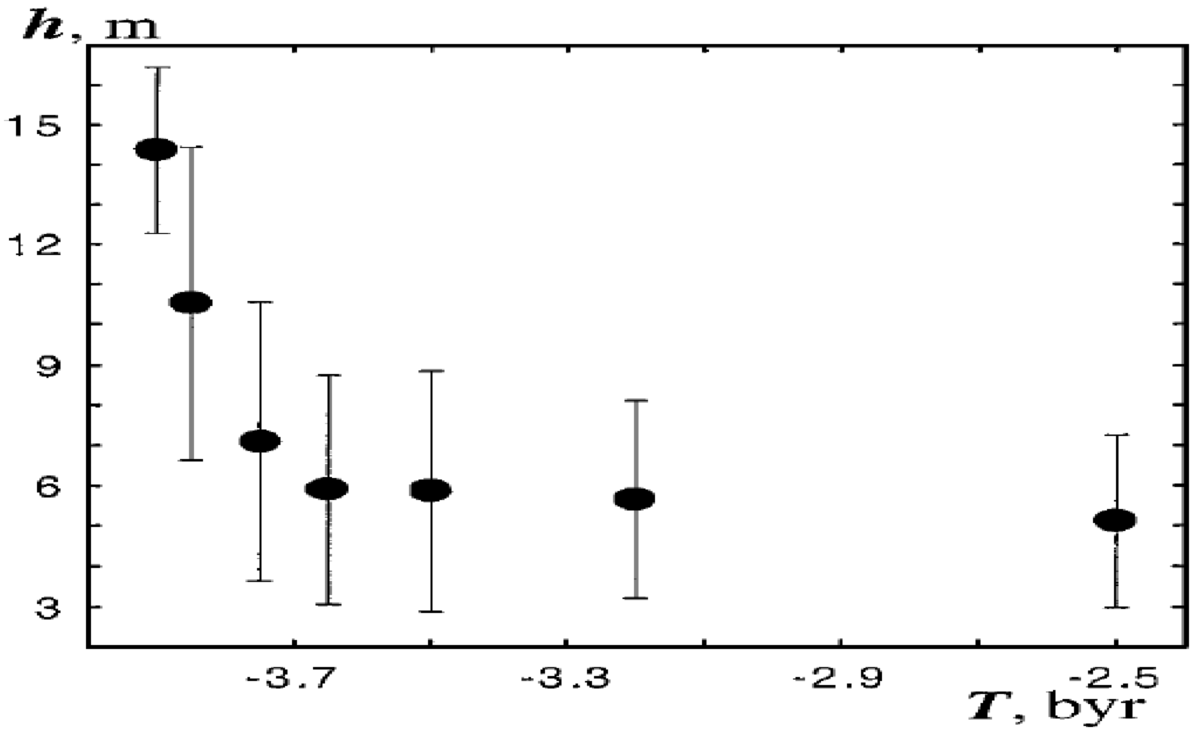
- Accumulation rate was much higher at the beginning
  - More impacts at early times
  - Small layer thickness allows smaller projectiles to penetrate (self-shielding of regolith)

- Current rate on the moon about 1 mm /10^6 years

- Loss of crater ejecta
  - Negligible for the Moon
  - Important for small asteroids (only)

Regolith thickness

Lunar regolith thickness as a function of surface age



From: Shkuratov & Bondarenko, Icarus 149, 329, 2001

Regolith thickness (2)

- Regolith coverage is almost complete
  - Moon
  - Mercury
  - Asteroid Eros

- Bedrock exposure rare
  - Crater slopes most promising

- Lunar regolith thickness is much lower than the total volume of all craters!
  - Ejecta from large basins are physically different from regolith (rock fragments vs. rubble)
  - They are called megaregolith

Regolith thickness (3): Other bodies

- No direct measurements for bodies other than the Moon
- Mercury: Conditions similar to the moon
  - Similar regolith thickness expected
- Asteroid Eros: 10s of meters of regolith coverage
  - Indirect evidence from NEAR mission
  - Is this regolith or megaregolith?
- Asteroid Lutetia: Evidences for a thick layer of ejecta blanket (several 100 meters)

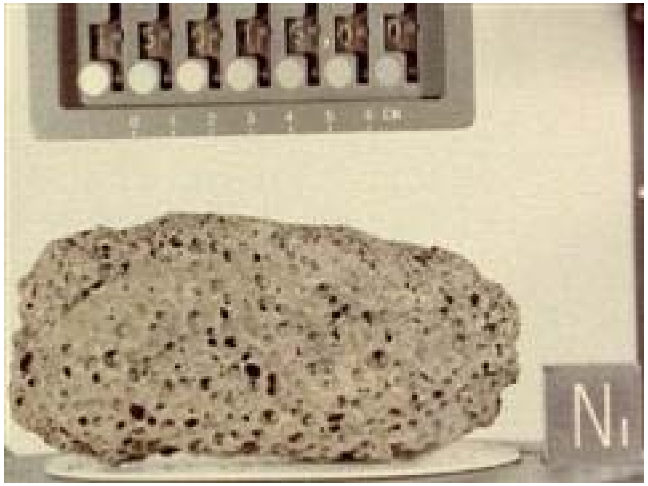
Small impacts: Modification of regolith

- Small impacts do not create new regolith
- Existing regolith is modified
  - Comminution (“grinding”)
  - Modification
    - Melting, formation of glasses
    - Agglutination
    - Size sorting
  - Transport (horizontally and vertically)

Components of the lunar regolith

- Rocks and grains
  - Size limit ~1 cm
- Crystalline and reprocessed components
  - Crystalline components are fragments without further modification
  - Reprocessed rocks are called breccia
  - Reprocessed soils are agglutinates or glasses
- Reprocessed components complicate remote determination of surface properties

Samples of lunar regolith



Basaltic rock: crystalline rock fragment, no strong modification

Breccia: Processed (multiple disruptions and reaccumulations)

Characteristics different from original lunar material

Samples of lunar regolith (2)

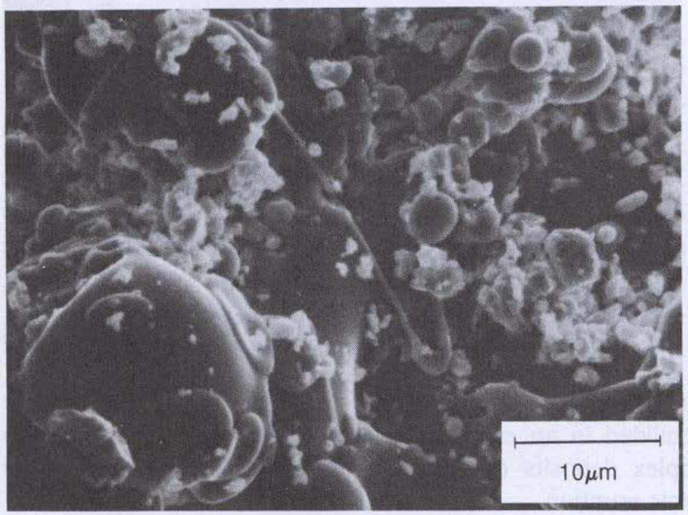
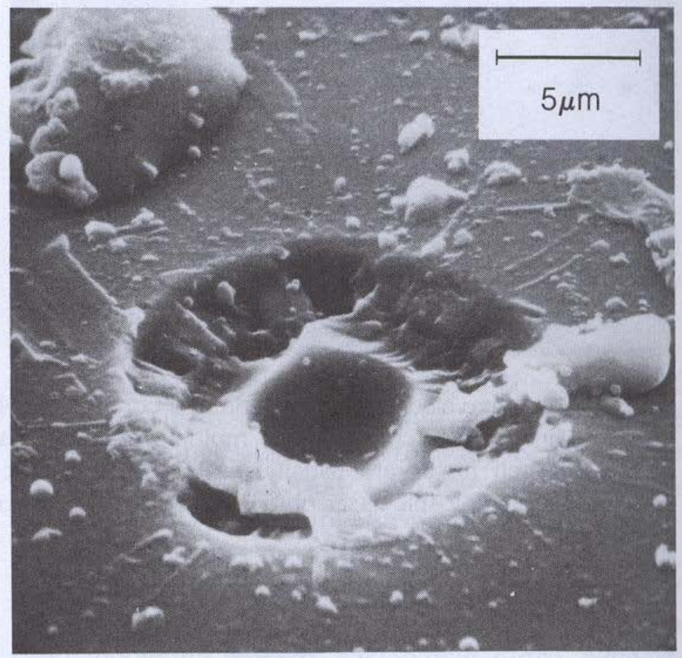


Fig. 7.7. Scanning electron micrograph of a plagioclase grain from lunar soil sample 10084, showing a variety of complex depositional features on the surface of the grain.



From:

Heiken et al.,

Lunar Sourcebook,

1989.

Crystalline grain with depositions on the surface (left) and a microcrater (right)

Samples of lunar regolith (3)

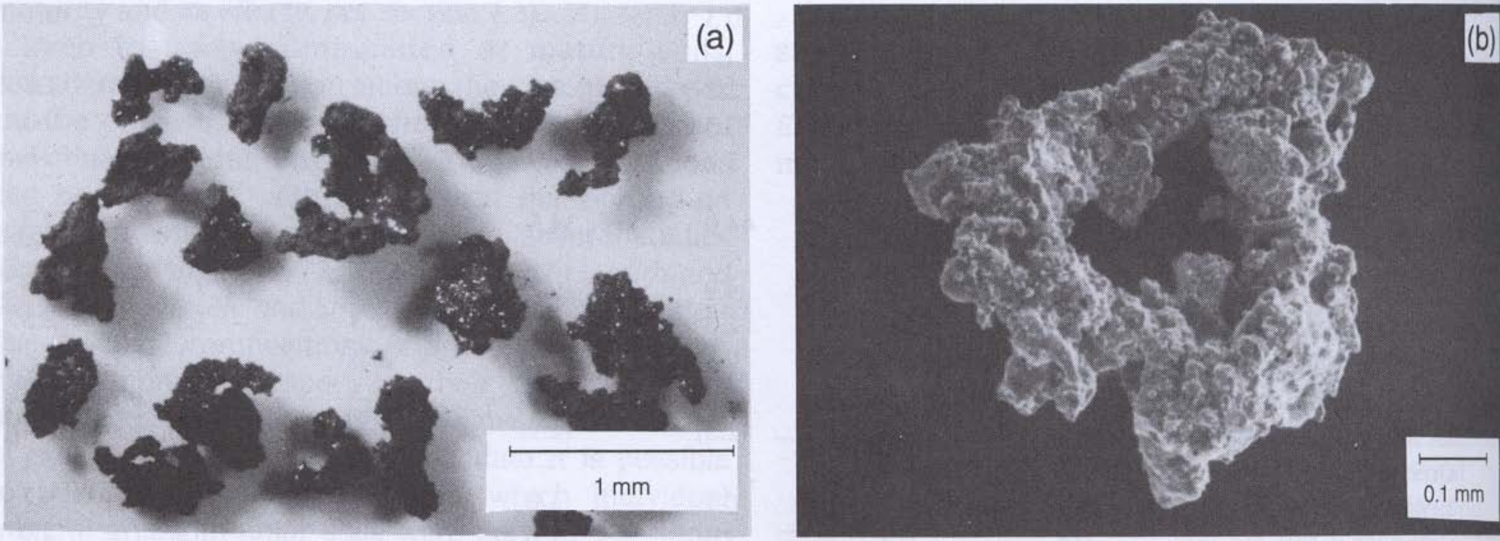
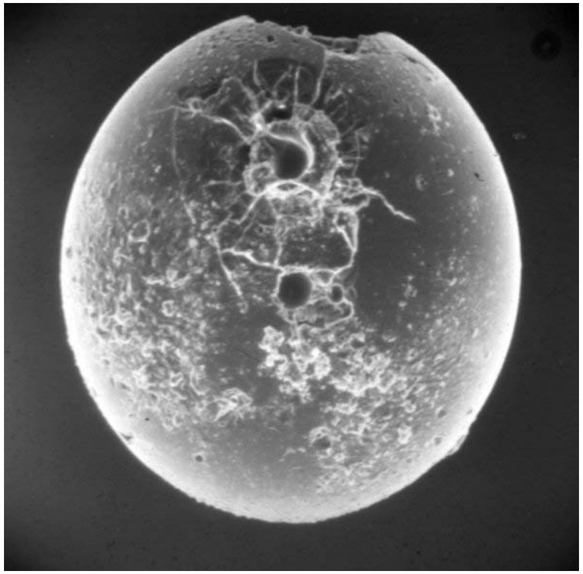


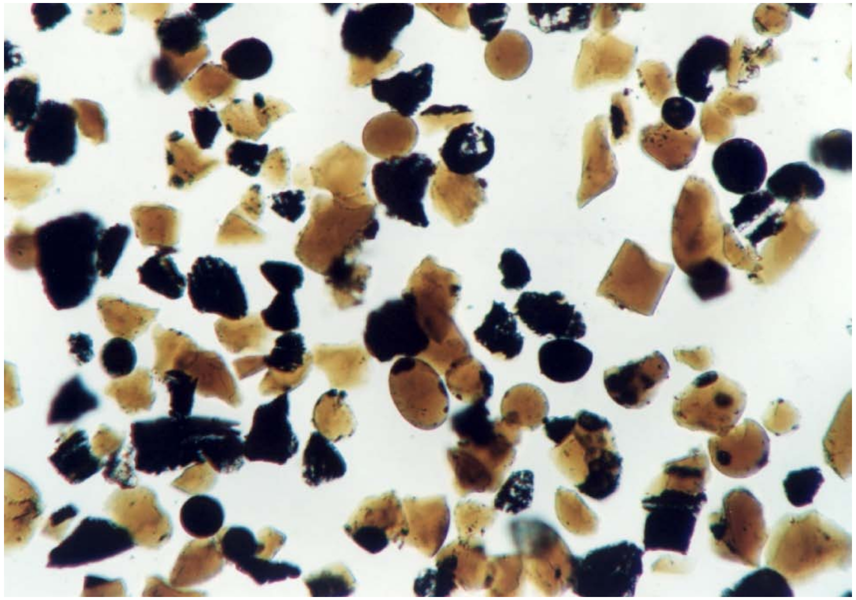
Fig. 7.2. Typical lunar soil agglutinates. **(a)** Optical microscope photograph of a number of agglutinates separated from Apollo 11 soil sample 10084, showing a variety of irregular agglutinate shapes (NASA Photo S69-54827). **(b)** Scanning electron photomicrograph of a doughnut-shaped agglutinate. This agglutinate, removed from soil 10084, has a glassy surface that is extensively coated with small soil fragments. A few larger vesicles are also visible (NASA Photo S87-38812).

Agglutinates: particle fragments molten together

Samples of lunar regolith (4)

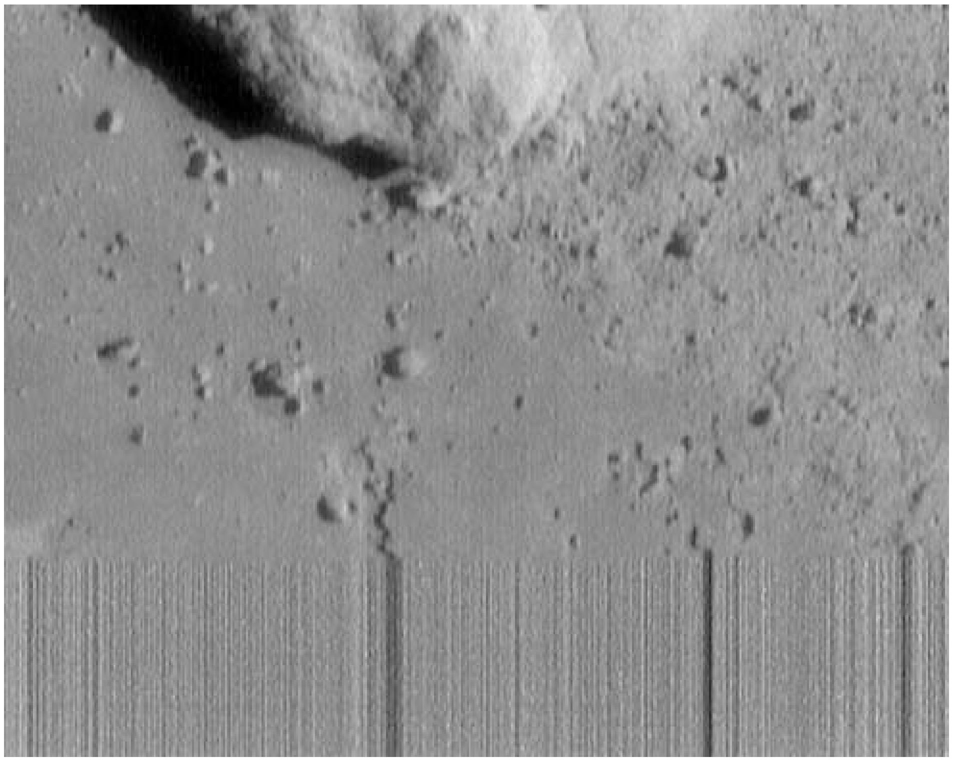


Impact glass



Volcanic glass

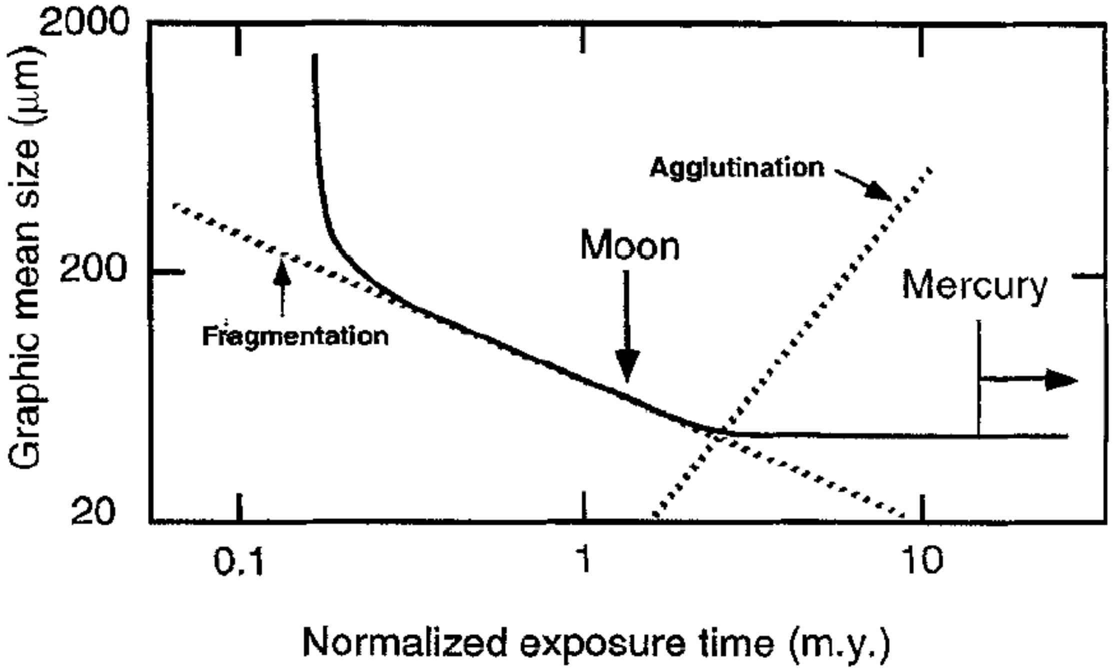
Regolith of asteroid Eros



- Last image taken by the NEAR-Shoemaker spacecraft
- Distance from surface: 120 m
- Field of view: ~6m
- Resolution: ~2cm
- Note combination of stones and unresolved fine-grained material
- Note borderline between different “landscapes” (on cm-scale!). Similar borders seen on Itokawa.

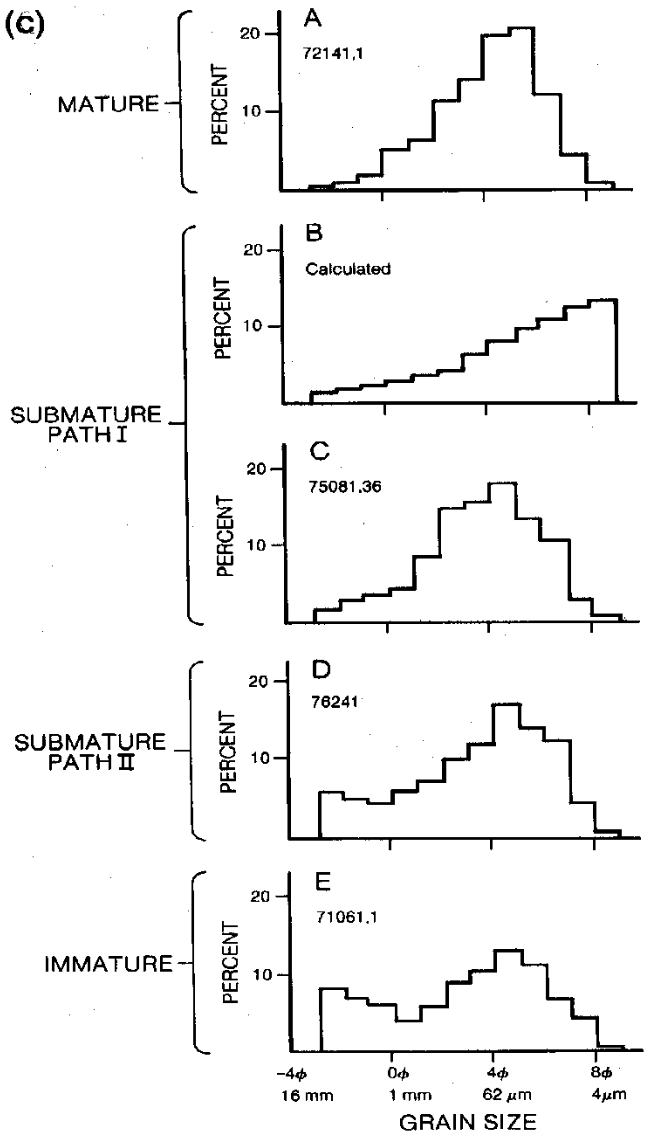
Size distribution of the grain component

- Competition between fragmentation and agglutination
- Equilibrium mean size not reached on the moon



From: Langevin, Planet. Space Sc. 45, 31, 1997.

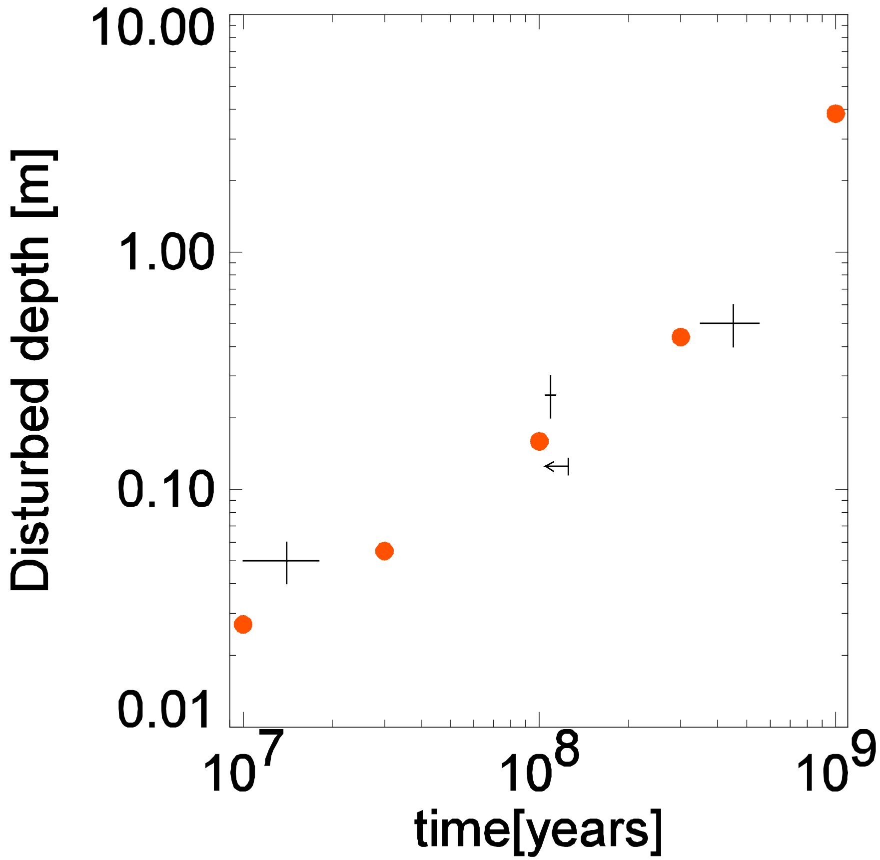
Size distribution of lunar regolith



- Sizes smaller with increasing maturation (with time)
- Maturation from
  1. Agglutinate content
  2. Tracks of solar and galactic cosmic rays
- Equilibrium between fractionation and agglutination not reached
  - ❑ Replenishment with fresh impact ejecta

From: Lunar Sourcebook

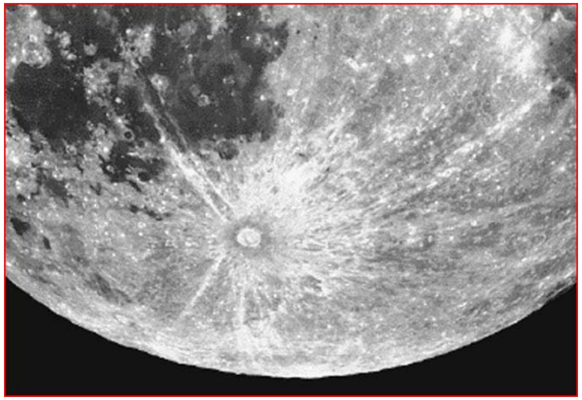
Vertical motion of lunar regolith



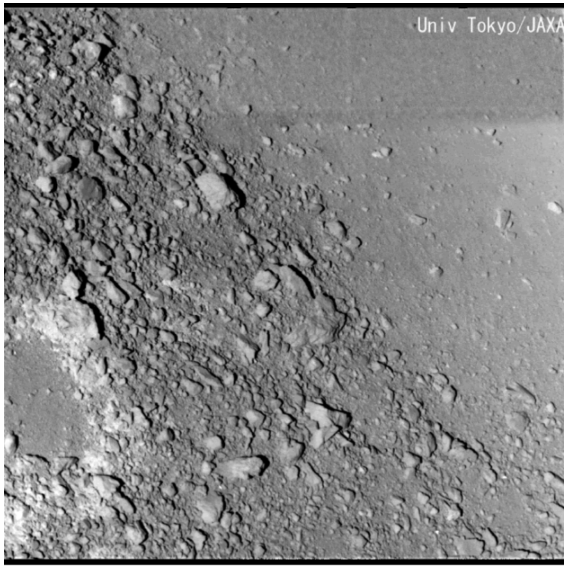
- Discrete ejecta layers are visible in Apollo drill cores
- Age estimate through particle tracks
- Plot shows depth vs. age
  - ❑ crosses are measurements
  - ❑ Orange dots are model results
- Upper mm continuously turned around and homogenized
  - ❑ “Lunar skin”

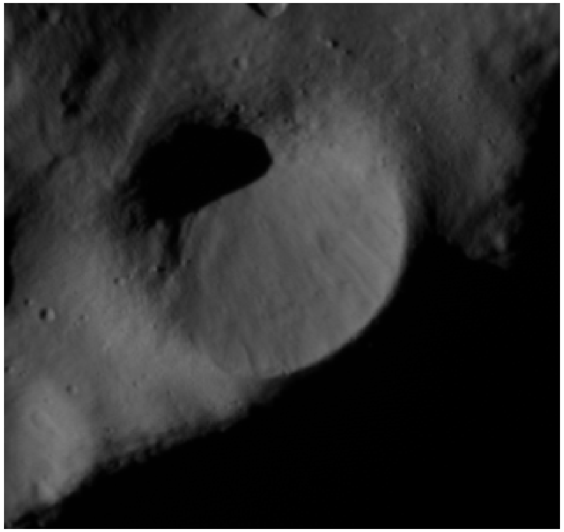
Horizontal motion of lunar regolith

- Ejecta are distributed around the crater
  - Ejecta typically up to 6-8 crater radii visible
  - A very small fraction of grains and rocks is distributed globally (see lunar meteorites!)
- Grain/rock motion in multiple impact events is a random walk
- Regolith is locally distributed
  - Typically within a few kilometers from place of origin
  - Otherwise the lunar surface would look completely homogeneous!



Other motion of regolith

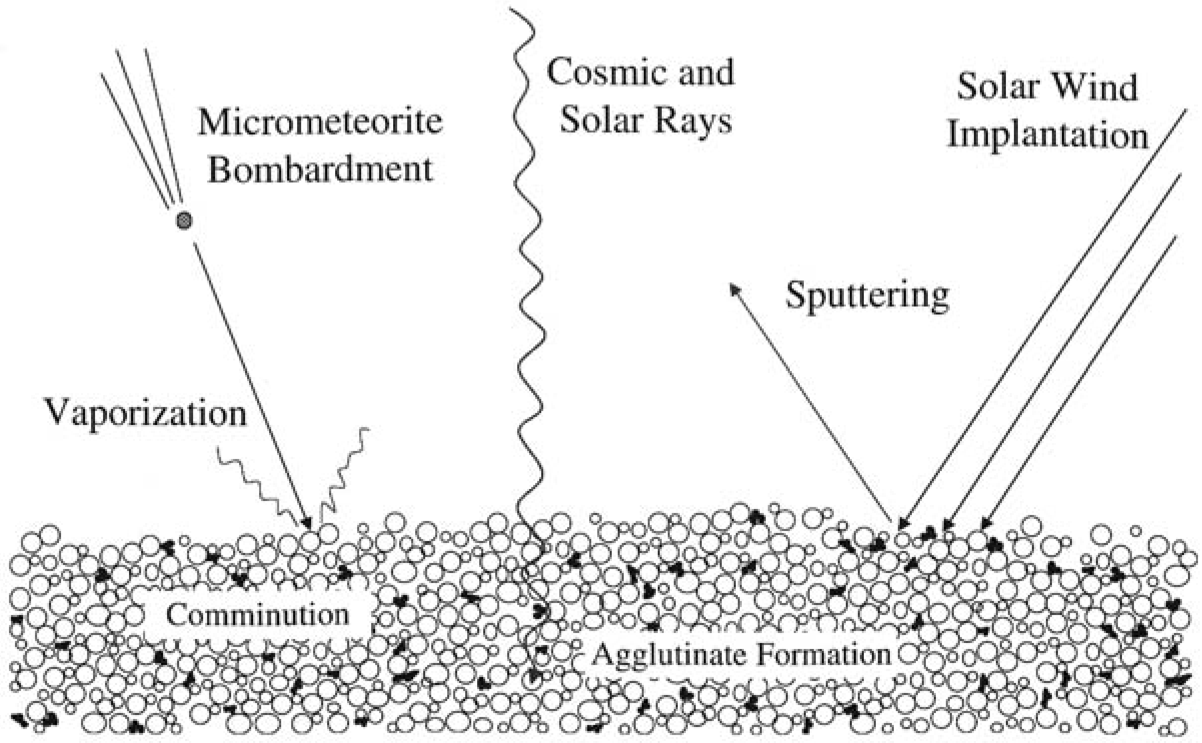




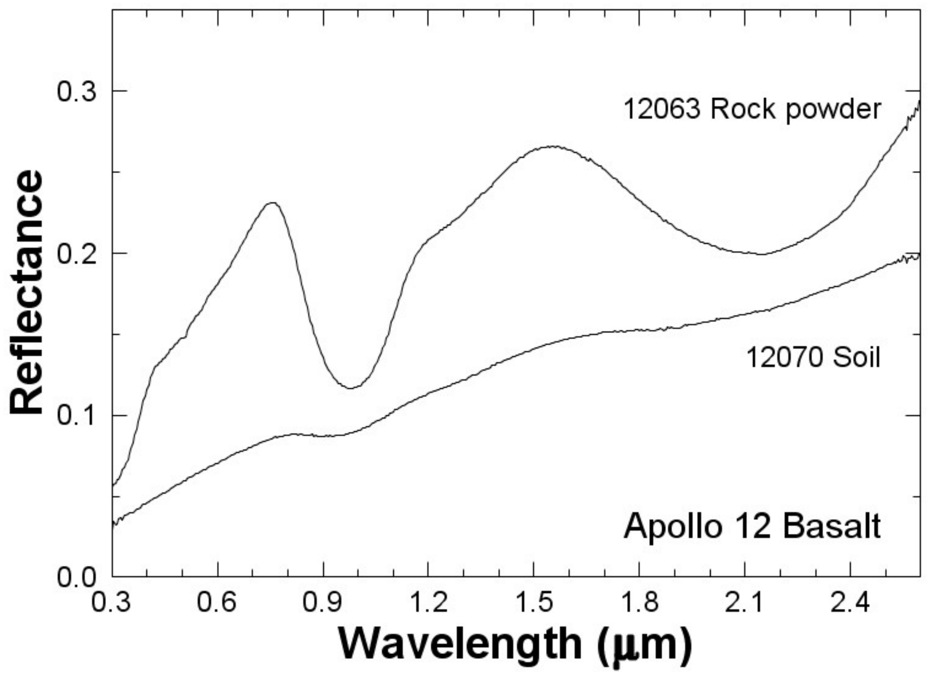
- Vibrations, seismic shaking can lead to horizontal or vertical motion of grains ("brazil-nut effect")

- Avalanches are observed, even in low gravity environment.

Microscopic regolith properties and space weathering



Effects of space weathering



- Suppression of absorption lines
- Reddening of the spectrum
- Reduction of overall albedo (darkening)
- Study of space weathering effects of known surface provides surface exposure age (in principal)

Cause of space weathering

- Immediate cause: Impact of micrometeorides and solar and interstellar radiation (cosmic rays)

- Process: Reduction of iron ($FeO \Rightarrow Fe + O$) and deposition of submicron iron particles on the surface during impact or sputtering process

- Reduction of iron happens either in the liquid or in the vapour phase

Foreign material in the regolith

- Crater scaling:
  - Crater diameter ~ 10 x projectile diameter
  - Crater volume ~ 1000 x projectile volume
- Modification due to small impacts
  - Add foreign material to the regolith
- In practical situation at most a few % of foreign material
  - Not important for most studies of planetary surfaces
  - Exception: High accuracy composition investigations

Craters and impactors $\Rightarrow$ Laboratory experiments and crater size scaling

- Crater scaling: Size of the crater produced by a projectile

- Needed for
  - Derivation of impactor population from crater counts $\Rightarrow$ Asteroid and comet populations in the solar system
  - Amount of “foreign” (asteroidal or cometary) material in a regolith

Method I: Laboratory experiments

D=1.9 cm D=3.2 cm D=17.0 cm D=34.4 cm

From: Housen & Holsapple, Icarus 142, 21, 1999.

- Example: 4 experiments aluminium impacting on granite
    - ❑ Same impact velocity and specific energy (kinetic energy of the projectile per unit mass of the target)
    - ❑ Result: Specific strength of the target decreases with increasing size

Power and limitations of experiments

- Easy to isolate specific parameters
- Can be performed with a large number of materials
- Results are direct (no modelling necessary)

Limitation:

- Experiments cannot be performed at planetary scales

Method II: Scaling laws

Possibility to apply laboratory scale results to planetary events

Method: Use non-dimensional expressions

$$V_c = f(a, \rho, v, Y, g, \delta)$$

V_c : Volume of the crater

a : Radius of the impactor

ρ : Density of the impactor

v : Velocity of the impactor

Y : Strength of the surface material (pressure needed to destroy it)

g : Surface gravity

δ : Surface density

Non-dimensionalization

- 7 quantities, 3 dimensions (length, time, mass) $\Rightarrow$ can be expressed as equation between 4 non-dimensional quantities:

$$\frac{V_c}{a^3} = f\left(\frac{\rho}{\delta}, \frac{ga}{v^2}, \frac{Y}{\rho v^2}\right)$$

$$\rho g a : \quad \text{Lithostatic pressure}$$

$$\rho v^2 : \quad \text{Dynamic pressure}$$

Distinguish small and large impactors

$$\text{Small impactors}: \frac{V_c}{V_p} = f\left(\frac{Y}{\rho v^2}\right)$$

$$\text{Large impactors}: \frac{V_c}{V_p} = f\left(\frac{ga}{v^2}\right)$$

- Advantage: Same non-dimensional values can be used on laboratory scale and planetary scale

Power and limitations of scaling laws:

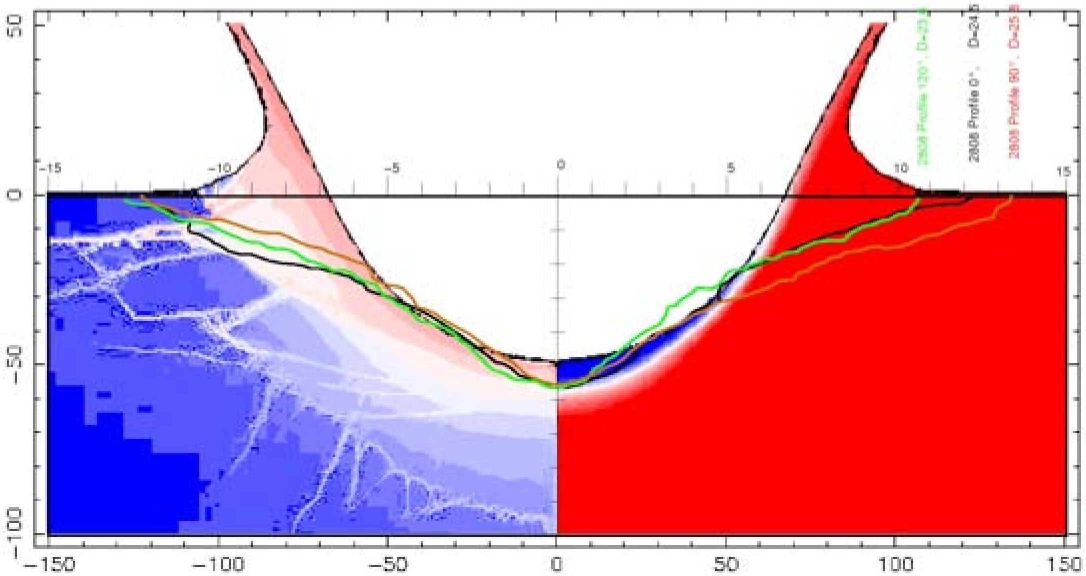
- Connect laboratory scale experiments with planetary scale events
- Computationally inexpensive

Limitations

- Need experiments to establish functional form
- What exactly is Y?

Method III: Numerical modelling

- Numerically model the stress and pressure waves in the target material caused by the impactor
- Directly model disruption and ejection of target material
- Provides not only crater size but also ejecta sizes (and velocities)



Power and limitations of numerical modelling

- Only method which treats the physical processes involved
- Provides many different parameters in a single model

Limitations:

- Parametrization of material properties difficult
- Computationally expensive

Litterature

- Lunar Regolith
  - Lunar Sourcebook, Heiken et al., eds., Cambridge Univ. Press, 1991
- Impact Cratering
  - Impact Cratering, Melosh, Oxford Univ. Press, 1989 (2nd ed. 1996)
- Impact scaling
  - The Scaling of Impact Processes in Planetary Science, Ann. Rev. Earth Planet. Sc. 21, 333, 1993