Impacts and formation of regolith

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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.
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

Eros

Itokawa
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

Lutetia

Ganymede
What is a large impact?

• Crater size \( \sim 10 \times \) 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)

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

From:
Heiken et al.,
Lunar Sourcebook,
1989.
Samples of lunar regolith (3)

Agglutinates: particle fragments molten together

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).
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

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
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

- Micrometeorite Bombardment
- Cosmic and Solar Rays
- Solar Wind Implantation
- Vaporization
- Sputtering
- Comminution
- Agglutinate Formation
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 micrometeorites and solar and interstellar radiation (cosmic rays)

- Process: Reduction of iron ($\text{FeO} \rightarrow \text{Fe} + \text{O}$) 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 ⇒ 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 ⇒ Asteroid and comet populations in the solar system
  – Amount of “foreign” (asteroidal or cometary) material in a regolith
Method I: Laboratory experiments


• 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
- \( \rho \): Density of the impactor
- \( v \): Velocity of the impactor
- \( Y \): Strength of the surface material (pressure needed to destroy it)
- \( g \): Surface gravity
- \( \delta \): Surface density
Non-dimensionalization

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

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

\(\rho ga\) : Lithostatic pressure

\(\rho v^2\) : Dynamic pressure
Distinguish small and large impactors

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

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 scaling