

Lunar Dust 101

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Largely due to rock and soil samples returned during the Apollo program, much has been learned about the composition and properties of lunar regolith. Although, for the most part, the mineral composition resembles terrestrial minerals, the characteristics of the lunar environment have led to very different weathering processes. These result in substantial differences in the particle shapes, particle size distributions, and surface chemistry. These differences lead to non-intuitive adhesion, abrasion, and possible health properties that will pose challenges to future lunar missions. An overview of lunar dust composition and properties will be given with a particular emphasis on possible health effects.



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Lunar Minerals Similar to Terrestrial

- **Silicate/Aluminosilicate** minerals make up **90%** volume of lunar rocks

- Plagioclase feldspar – $(\text{CaNa})(\text{AlSi})_4\text{O}_8$
- Pyroxene - $(\text{CaFeMg})_2\text{Si}_2\text{O}_6$
- Olivine - $(\text{MgFe})_2\text{SiO}_4$

- **Oxide** minerals make up to **20%** volume of lunar rocks

- Ilmenite – $(\text{MgFe})\text{TiO}_3$
- Spinel – FeCr_2O_4 , Fe_2TiO_4 , FeAl_2O_4 , MgTiO_4
- Armalcolite – $(\text{MgFe})\text{Ti}_2\text{O}_5$

- **Minor Constituents**

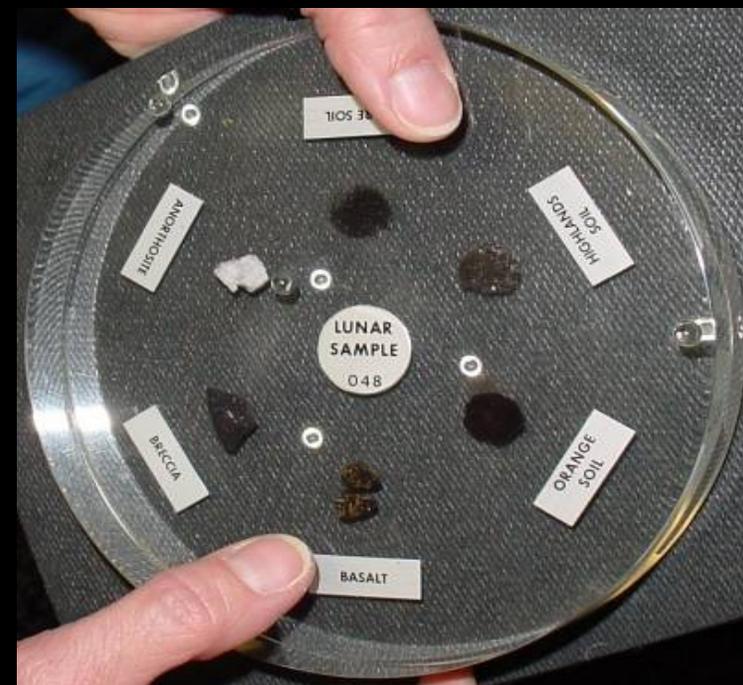
- Low abundance of native metals (Fe, Ni, Co)
- Most sulfur contained in single mineral (Troilite – FeS)
- Traces of many other minerals

- **Rare on moon (though common on earth)**

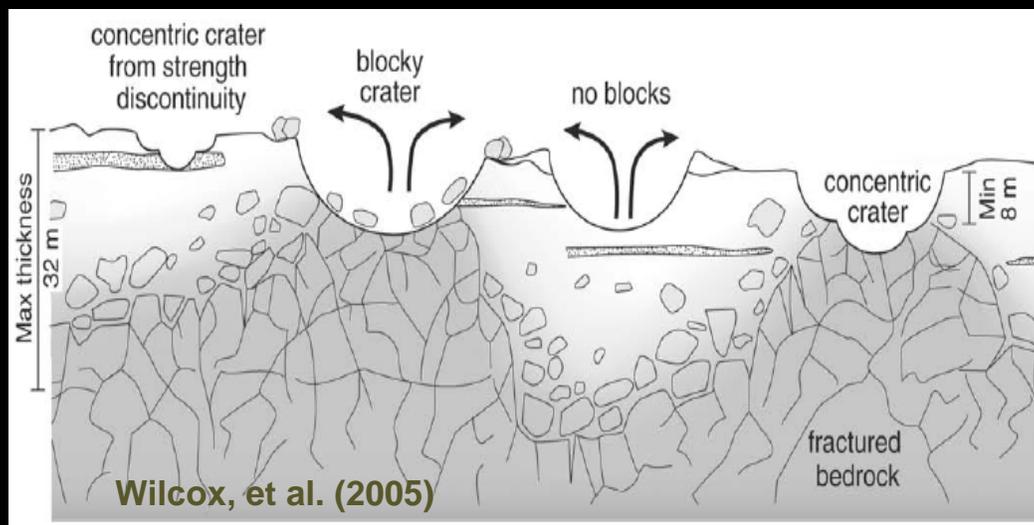
- Potassium feldspar - KAlSi_3O_8
- Silica – SiO_2

- **Absent on moon (because they contain water)**

- Clays, Micas, Amphiboles *



Particle Size Nomenclature



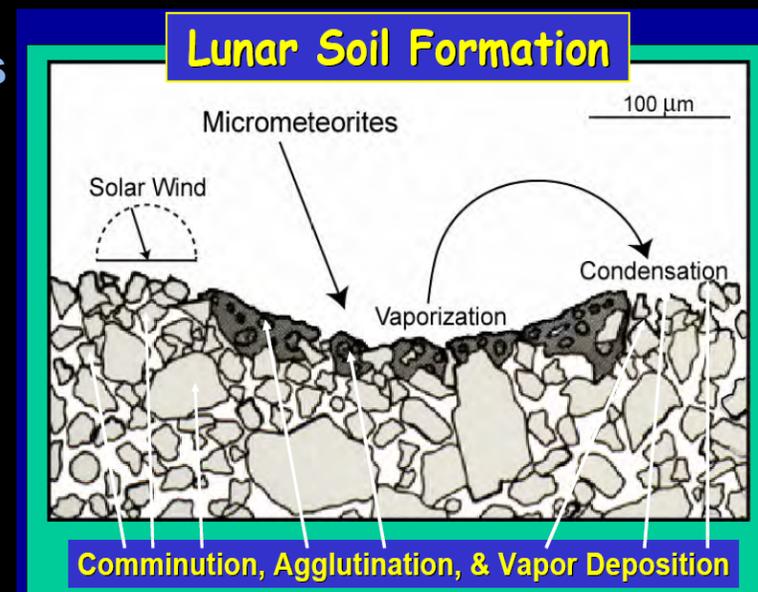
- **Lunar regolith**
 - Crushed up rock fraction that covers coherent bedrock
 - 1 – 40 m deep
- **Lunar soil**
 - Fraction of regolith < 1 cm
 - Does not imply organic component (as do earth soils)
- **Lunar dust**
 - Arbitrarily set at particles < 20 μm diameter
- **Respirable fraction**
 - In 1 g environment < 10 μm diameter
 - In 1/6 g environment may be larger
- **Submicron fraction**
 - Many more submicron particles (down to 4 nm)
 - Agglomeration with water on earth limits submicron fraction



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Formation of the Lunar Regolith

- Regolith formed by **space weathering**
- Energetic solar particles and galactic cosmic rays
 - Constantly bombard surface
 - Implantation of H, He,...
 - Sputtering of atoms off of surface
- **Meteoroid strikes on the surface**
 - Hottest zone underneath impact melts rock together
 - Adsorbed H, He from solar wind escape
 - Oxygen from rock vaporizes and escapes
 - Iron is reduced, vaporizes and re-deposits
 - Mineral grains structure shocked
 - Minerals melted into glass
 - Glass flows down into regolith and glues grains together
 - Forms frothy agglutinates
 - Zone beneath hot zone feels pressure
 - Fractures rock into small, sharp particles (comminution)
- **Volcanic vents spewed molten particles**
 - Green and orange glasses returned by Apollo
 - No active lunar volcanoes known

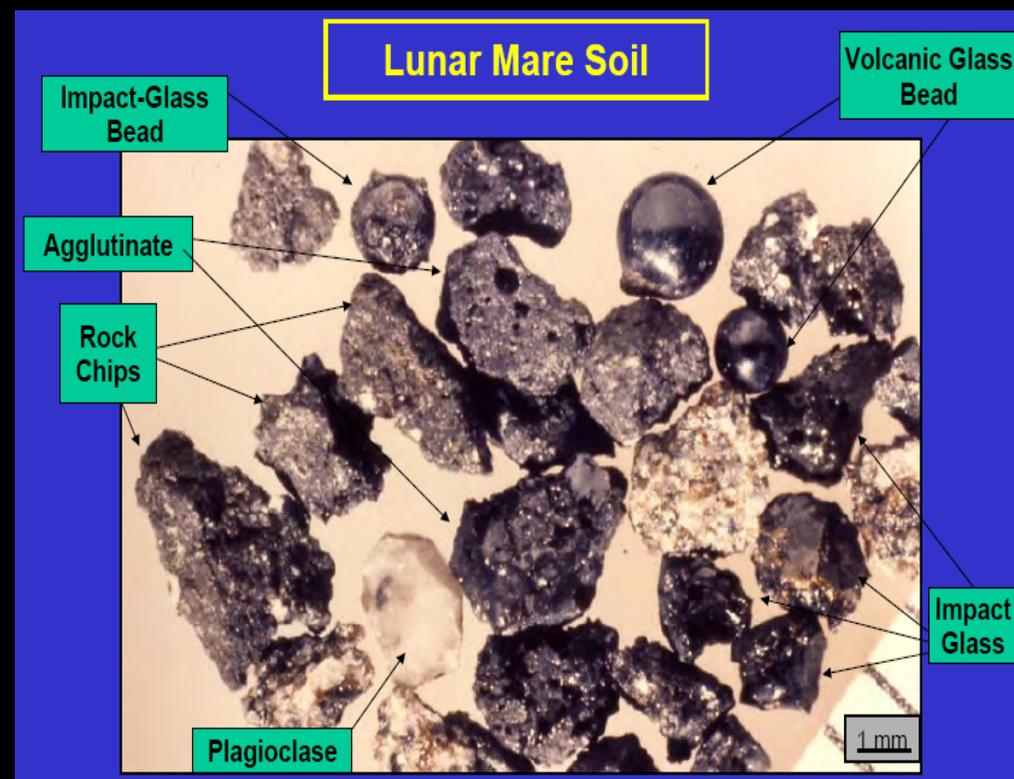
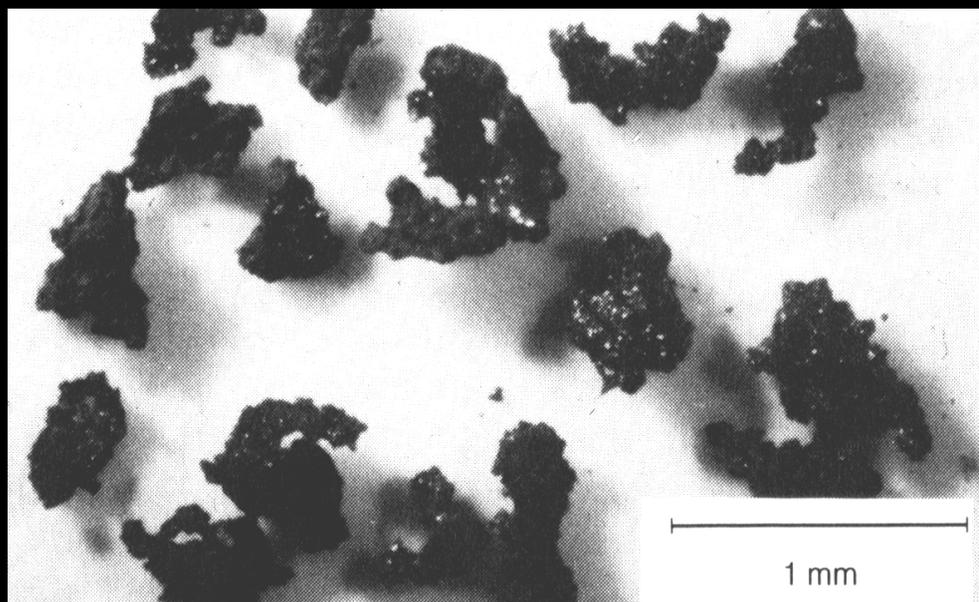
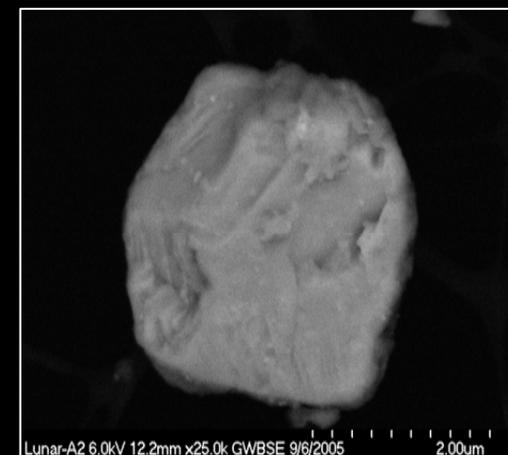


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Figure from L. Taylor presentation at Lunar Simulant Materials Workshop, Jan 2005.

Lunar Particles Have Complex Shapes

- **Hot zone under impact melts and vaporizes rock**
 - Some spewed from the surface as droplets → frozen droplets
 - Volcanic vents also spew molten rock → spheroids
 - Volume fraction < 0.2 percent
- **Molten rock flows and glues grains together**
 - Complex agglutinate shapes for particles > 100 μm
- **Impacts cause brittle fracture beneath**
 - Rock chips
 - Irregular agglutinate chips ~ 1 mm
 - Smallest particles regular in shape *



Lunar Particle Surfaces in Excited States

- **Constantly streaming solar wind impact lunar surface**
 - H^+ , He^{2+} , e^- , small number of heavier ions
 - Solar particle events greatly increase number and energy
 - Constant output of hard UV, x-rays, and γ -rays
- **Galactic cosmic rays**
 - H^+ , He^{2+} , e^- , small number of heavier ions
 - Very high energies
 - Come from all directions
- **Constant bombardment from meteoroids**
 - Most smaller than 1 mm in size
 - High kinetic energy (11-72 km/s velocity)
- **Large thermal cycles**
 - Equatorial regions range 100 – 400 K (-280 to 260 °F)
 - Polar range 210 – 230 K (permanently shadowed craters 40 K?)
- **Ultra-high vacuum (10^{-12} – 10^{-14} Torr)**
 - Each surface atom hit once a day by a gaseous atom
 - On earth each surface atom hit 10^8 times per second
 - Passivation of dangling bonds and defects is *very* slow

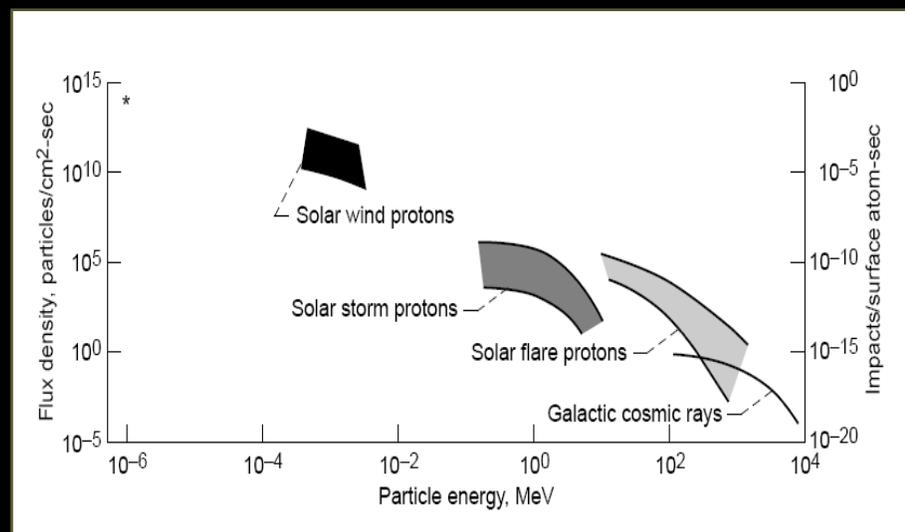


Figure derived from Wilson, et al., NASA Ref. Pub 1257 (1991).

Dust Degrades Capabilities

- Apollo astronauts cited multiple problems caused by lunar dust
- Dust degradation effects can be sorted into categories*
 - Vision obscuration
 - False instrument readings
 - Loss of foot traction
 - Dust coating and contamination
 - Seal failures
 - Clogging of mechanisms
 - Abrasion of materials
 - Thermal control problems
 - Inhalation and irritation risks



J.R. Gaier, "The Effects of Lunar Dust on EVA Systems During the Apollo Missions", NASA/TM-2005-213610/Rev1

Inhalation and Irritation Risks

- *Dust could compromise astronaut health*
- **Apollo 11 reported dust gave off distinctive, pungent odor**
 - Suggests small particle sizes were suspended in spacecraft
 - May have reactive volatiles on the surface of the dust
 - Dust irritated eyes, but was easily removed
 - Dust under fingernails was persistent
- **Apollo 12 reported eye and lung irritation on return trip**
 - Contaminated the CM after docking with LM
- **Apollo 12 crew reported dust got in everywhere**
 - Conrad and Bean covered with dust when they removed space suits
- **Harrison Schmitt reported hay fever-like symptoms from dust**
 - Lasted much of the return trip
- **No astronaut has had recurring problems attributed to dust exposure**

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Activated Dust and Human Health

- **Conclusions of Biological Effects of Lunar Dust Workshop (2005)**
- “Lunar dust has some striking similarities to terrestrial silica, which has cause the deaths of thousands of people (respirable size, metals, chemically reactive). But lunar dust has unique properties that we don’t understand from a toxicological perspective (ultrafines, shape, **unique reactive surfaces**).”
- “Initial toxicological studies can be conducted with existing lunar samples. These finding needs to be validated via in situ lunar measurements because the **lunar samples have changed during transport and storage.**”



CONCLUSIONS

- **Lunar dust is unlike any substance on Earth**
 - Result of space weathering, energetic environment
 - Sharp particles
 - Small particle sizes
 - Chemically active surfaces
- **Apollo experience with dust mixed**
 - Dust was an acute irritant
 - No long-term effects for any astronaut
- **Unknowns for long-term dust exposure**
 - Effects of exposure of more than several hours
 - Will “hay fever” symptoms get better or worse?
 - Toxicity of clean fracture surfaces

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Additional Information

Hawk's Nest Incident

- **Tunnel built while constructing hydroelectric dam in West Virginia in early 1930's**
 - Discovered silica in tunnel
 - Silica was mined for steel making
 - Lots of silica dust, no personal protection
- **Worst industrial accident recorded**
 - Perhaps **700 of 2000 workers died of silicoses within 1 year**
 - Freshly ground silica has enhanced toxicity
 - **Do all activated rock surfaces have enhanced toxicity? ***

