The Lunar Regolith

Sarah Noble
sarah.k.noble@nasa.gov

Introduction

A thick layer of **regolith**, fragmental and unconsolidated rock material, covers the entire lunar surface. This layer is the result of the continuous impact of meteoroids large and small and the steady bombardment of charged particles from the sun and stars. The regolith is generally about 4-5 m thick in mare regions and 10-15 m in highland areas (McKay et al., 1991) and contains all sizes of material from large boulders to sub-micron dust particles. Below the regolith is a region of large blocks of material, large-scale ejecta and brecciated bedrock, often referred to as the "**megaregolith**". **Lunar soil** is a term often used interchangeably with regolith, however, soil is defined as the subcentimeter fraction of the regolith (in practice though, soil generally refers to the submillimeter fraction of the regolith). **Lunar dust** has been defined in many ways by different researchers, but generally refers to only the very finest fractions of the soil, less than ~10 or 20 microns.

Lunar soil can be a misleading term, as lunar "soil" bears little in common with terrestrial soils. Lunar soil contains no organic matter and is not formed through biologic or chemical means as terrestrial soils are, but strictly through mechanical comminution from meteoroids and interaction with the solar wind and other energetic particles. Lunar soils are also not exposed to the wind and water that shapes the Earth. As a consequence, in contrast to terrestrial soils, lunar soils are not sorted in any way, by size, shape, or chemistry. Finally, without wind and water to wear down the edges, lunar soil grains tend to be sharp with fresh fractured surfaces.

The Components of Lunar Regolith

Lunar regolith is made up of rock chips, mineral fragments, impact and volcanic glasses and a peculiar component only found on the Moon called "agglutinates" (Figure 1). The ratio of these various components varies widely from one soil to the next (Figure 2).

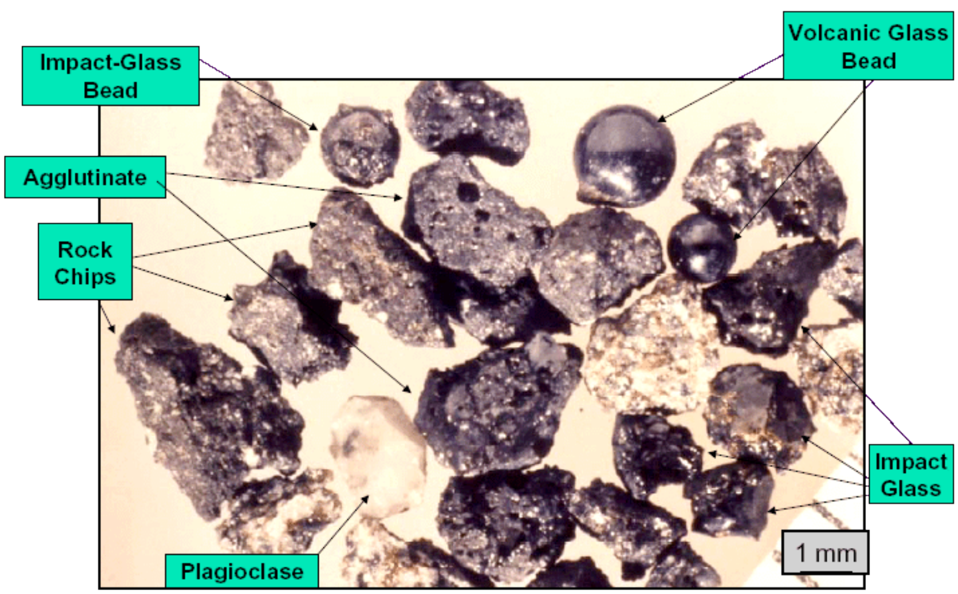

Figure 1. Photograph of a large size fraction of a lunar soil showing the various components that constitute a typical soil (image courtesy Larry Taylor, Univ of TN Knoxville)

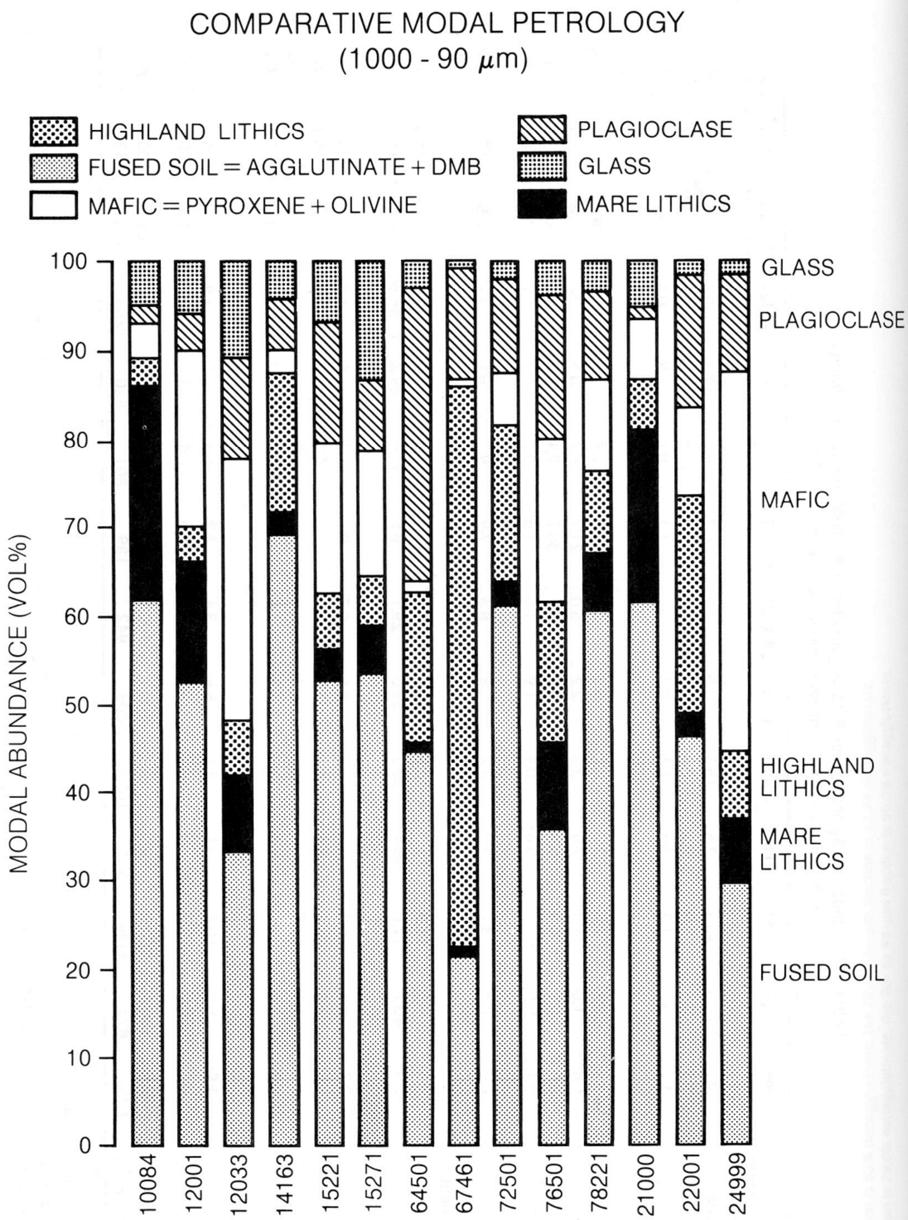

Figure 2. A bar graph of the modal (volume) abundances of various components of several lunar soils from Apollo and Luna missions (Simon et al., 1981).

Agglutinates, aggregates of mineral fragments held together with glass, are a major component of lunar soils, composing up to 60 or 70% of some soils. They are formed when a micrometeorite impact melts a small amount of soil. Several optical, SEM, and TEM images of agglutinates are shown in Figure 3. As can be seen from the images, agglutinates come in a wide range of sizes, from millimeters to sub-micron in diameter. Agglutinitic glass is vesicular (holey) and is full of tiny blebs of metallic iron (Figure 3c).

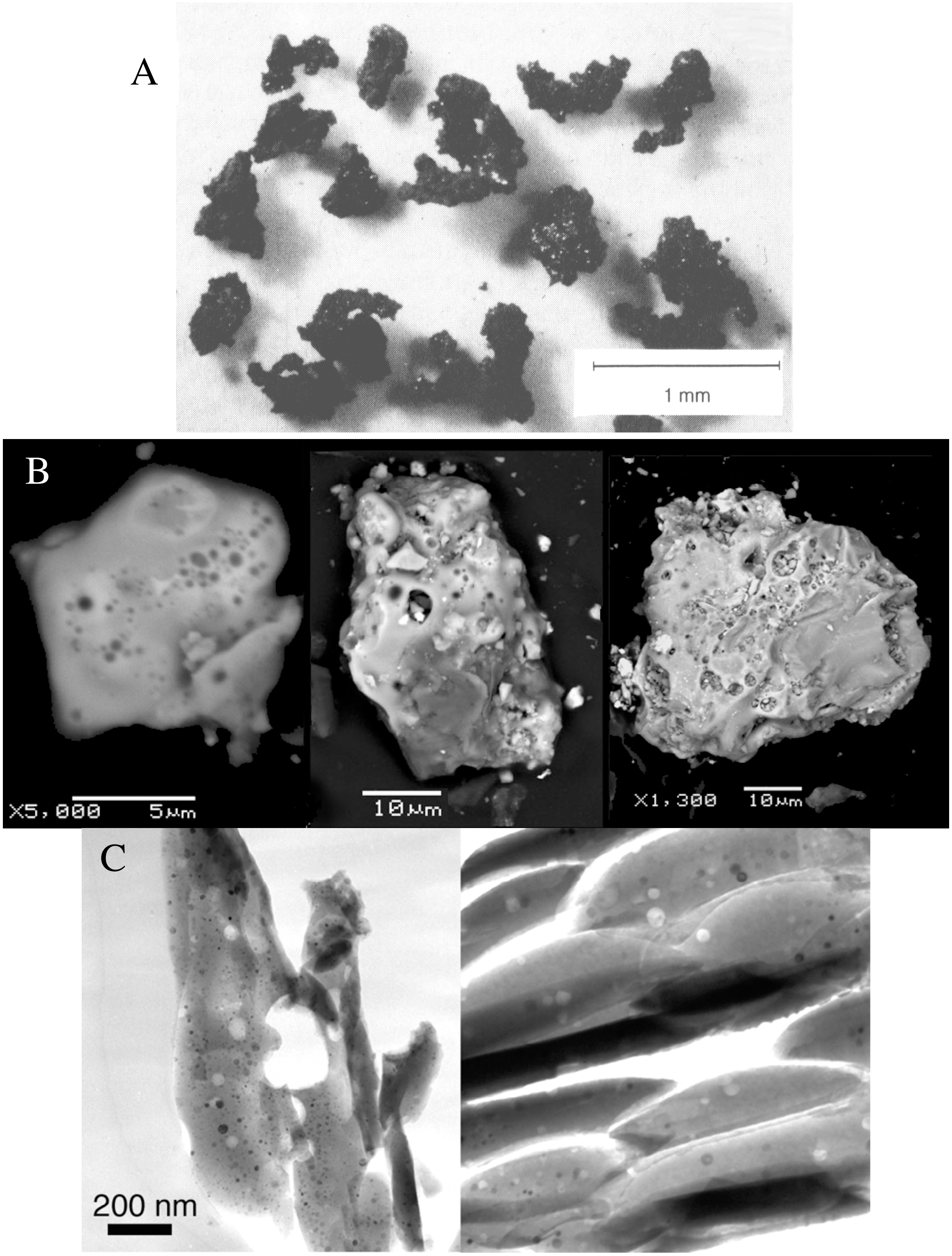

Figure 3. Several images of agglutinates. A) A photo of large agglutinates showing their complex shape (McKay et al., 1991). B) Scanning electron microscope (SEM) backscatter images of agglutinates showing their vesicular nature. C) Transmission electron microscope (TEM) images of cross sections through agglutinates showing vesicles (white spots) and nanophase iron (black spots).

Spherules are also a common component of lunar soils. These typically spherical (hence the name) droplets of glass can be formed volcanically, during "fire fountaining" when lava is thrown up and cools before it hits the ground; the Ap 17 orange glass beads and the Ap15 green glass beads are examples of this process. More commonly though, spherules are formed in impact, when melt is thrown up and cools before it falls back to the ground. Like agglutinates, impact spherules are found in a large array of sizes from sub-micron to several hundred microns (volcanic beads come in a narrower size range, averaging about 40 microns). Both agglutinates and impact spherules come in a wide array of compositions as well, dependent in large part on what material was melted to form them.

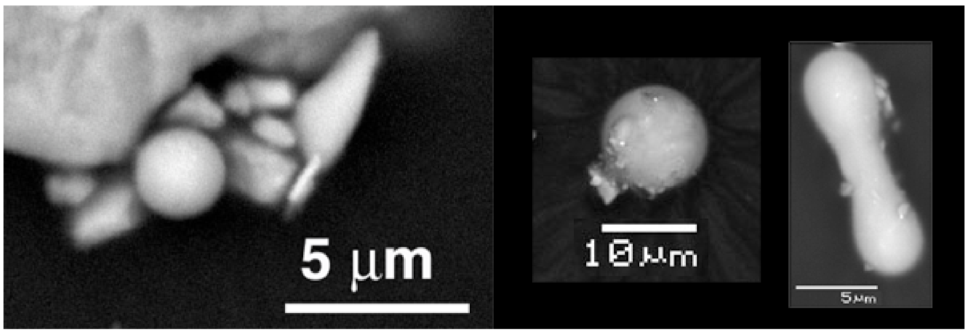

Figure 4. Several SEM backscatter images of spherules.

Larger size fractions of lunar soils commonly contain rock chips, or **lithic** components (Figures 1 and 2), with multiple minerals within a single grain. These are less common in finer size fractions where they have been largely broken down into their individual mineral components.

Nearly all exposed surfaces on the Moon, rocks, pebbles, soil grains, are covered in material from elsewhere: splashes of glass from nearby impacts, very small grains which cling electrostatically or are "glued" on with glass. In Figure 5 are SEM images of two examples of typical surfaces.

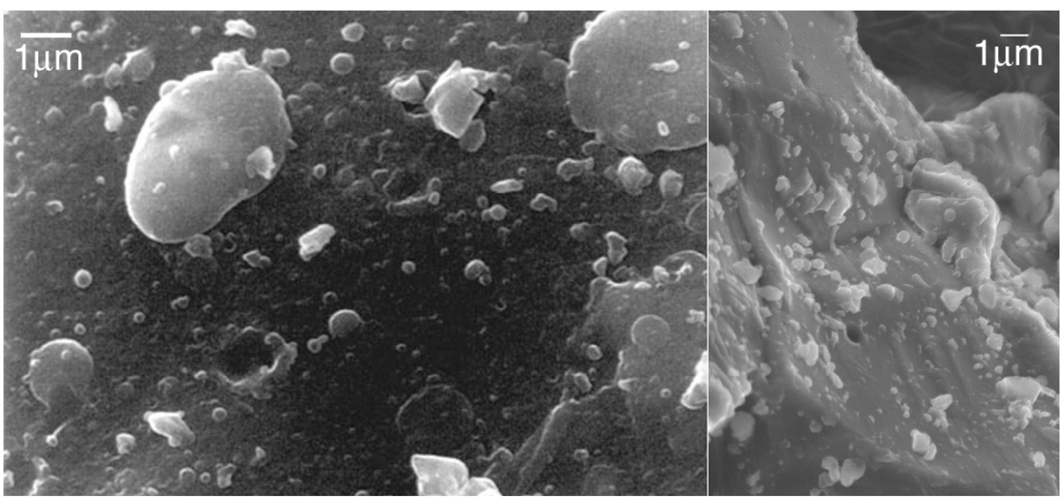

Figure 5. SEM images of the surface of a rock (left) (Wentworth et al, 1999) and a soil grain (right). Glass splashes and "pancakes" are common, as are submicron grains clinging to the surface. Micrometeorite craters can also be seen in both images.

Grain Sizes

The mean grain size of typical lunar soils ranges from 40-800 µm with most falling between 45-100 µm (McKay et al., 1991). In terrestrial terms, most lunar regolith samples would correspond to pebble- or cobble-bearing silty sands, however, it is difficult, and probably dangerous, to apply such terrestrial terminology to lunar soils because their formation mechanisms are so different. Figure 5 is a cumulative size frequency plot for some typical soil samples. As a general rule of thumb, about 10% of lunar soil is greater than 1 mm, about 50% is greater than 100 µm, and about 90% is great than 10 µm. The very finest fractions of the soil (<2 µm) are extremely difficult to measure because those smaller grains tend to stick to larger grains (Figure 6), as well as to the sides of containers.

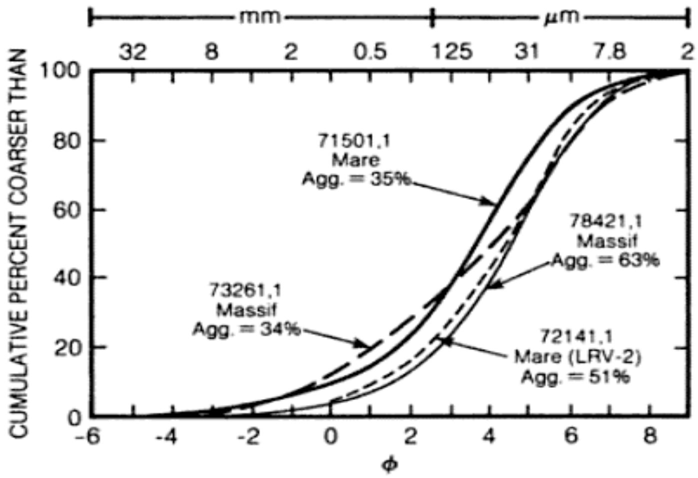

Figure 6. Cumulative size-frequency diagram for typical soils (McKay et al, 1991).

Lunar soil evolves over time as it is exposed to the harsh environment of space. Continuous impacts result in finer grain sizes as a soil "matures" (Figure 7). However, the destructional process of comminution is balanced by the constructional process of agglutinate formation, allowing mature soils to eventually reach a steady state (McKay et al., 1974).

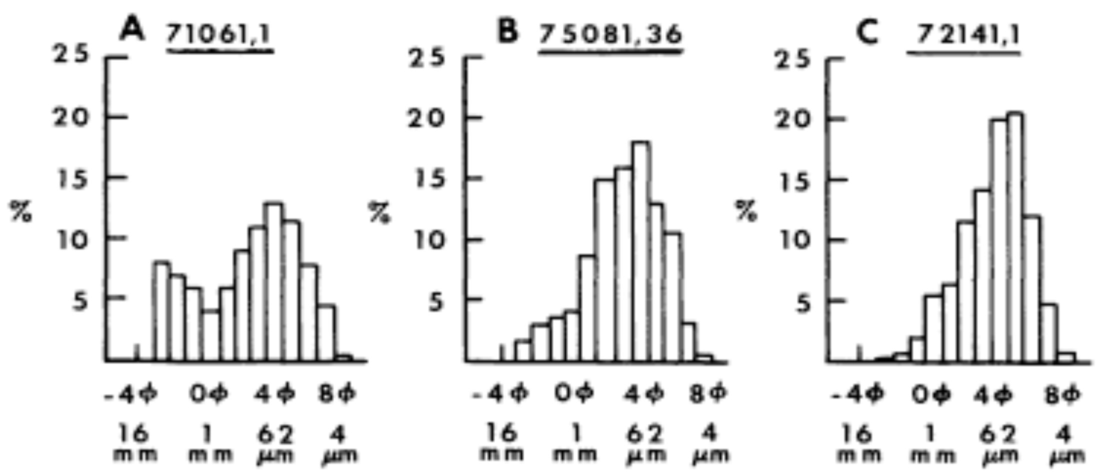

Figure 7. Grain size histograms of an immature soil (A), a submature soil (B), and a mature soil (C) (McKay et al, 1974).

Space Weathering

"**Space weathering**" is a blanket term used for a number of processes that act on any body exposed to the harsh space environment. Lunar soils incur galactic and solar cosmic rays; irradiation, implantation and sputtering from solar wind particles; as well as bombardment by all sizes of meteorites (Figure 8).

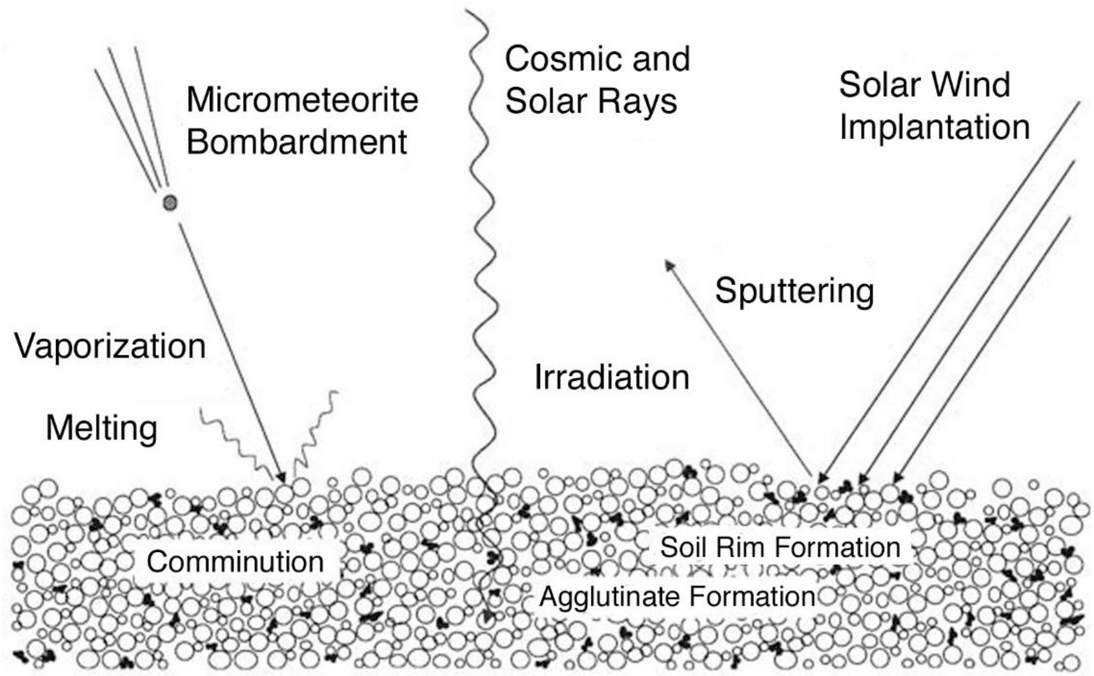

Figure 8. Cartoon showing the various components of space weathering.

Cosmic rays, high energy electrons, positrons, and other subatomic particles traveling at near light speed, leave behind tracks in soil grains. These tracks are sometimes used by scientists as a crude estimate of how old a grain is, i.e. the older the grain, the more tracks it has accumulated. Moderate shock and/or heating (to ~650-850°C - Fraundorf et al, 1980) can anneal, or erase, these tracks. Tracks are identified in a grain of Apollo 11 soil (10084) in Figure 9.

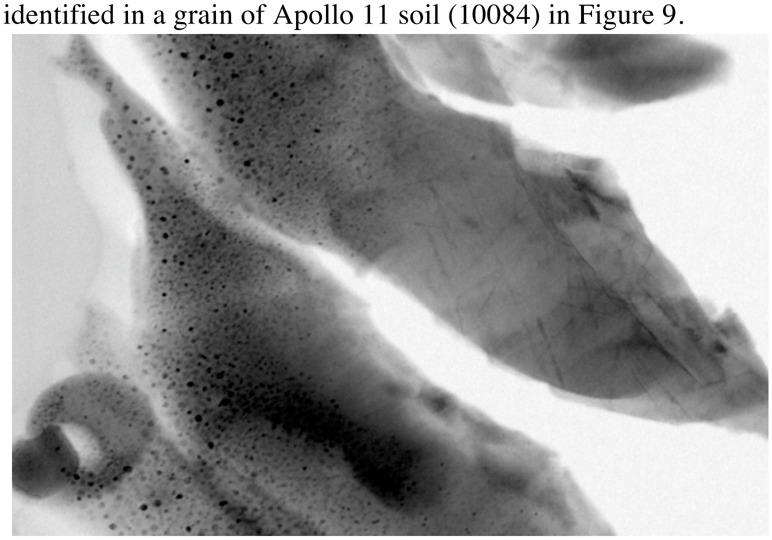

Figure 9. A TEM image of a lunar grain with tracks left behind by galactic and solar cosmic rays (in TEM images, tracks appear as criss-crossing lines of various lengths).

Solar wind, the plasma of charged particles flowing from the Sun, can irradiate the outer ~50-100 nm of a grain, causing the mineral to breakdown to an amorphous state, like the irradiated rim in Figure 10. Solar wind particles, largely composed of hydrogen and helium, but also heavier elements, can become imbedded in the soil particles. The time scale for saturation with hydrogen is on the order of 100 Kyrs. Solar wind ions can also knock individual atoms out of place in a process called "**sputtering**." Those atoms will either be lost to space or re-deposited on nearby grains.

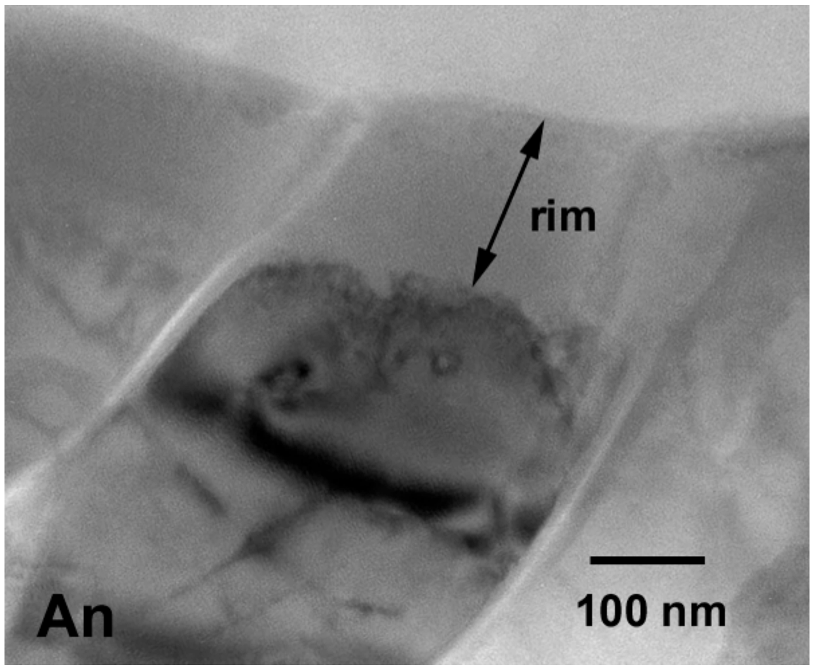

Figure 10. Plagioclase grain with an irradiated rim. Such rims retain the chemical heritage of their host grain, but the crystal structure has been destroyed.

On the Earth, we have meteorites which impact on a regular basis, but smaller particles burn up in the atmosphere (shooting stars). On the Moon, everything impacts, down to the smallest micro and nanometer particles. When these micrometeorites impact, they melt and vaporize small amounts of material that can then be re-deposited on nearby grains.

Both sputtering and the melting and vaporization associated with micrometeorite bombardment create **nanophase iron (npFe^0)**, also sometimes called **submicroscopic-iron (SMFe)**, nanometer-scale blebs of metallic iron embedded in a glass matrix. In lunar soils, npFe^0 is found in two places, throughout **agglutinitic glass**, glass created from the melting of soil in micrometeorite impacts, and in vapor/sputter deposited rims on individual soil grains, **npFe^0-bearing rims**.

The ubiquitous iron particles in agglutinates come in a wide range of sizes from a few nanometers up to several hundred nanometers (James *et al.*, 2002). They are thought to be created when hydrogen-saturated soil is melted, causing a reduction reaction where the FeO in the minerals is reduced to Fe^0+OH or Fe^0+H_20. A study using energy election-loss spectroscopy (EELS) found that in the majority of analyzed agglutinitic glass grains, Fe^{2+} had not been completely reduced to iron metal during space weathering (Keller and Clement, 2001).

NpFe^0-bearing rims were first identified in the transmission election microscope (TEM) by Keller and McKay (1993), who followed up with a study which classifies the different types of rims observed to date (Keller and McKay, 1999); also see Wentworth et al. (1999) who studied coatings on rocks, rather than individual grains, for some detailed scanning election microscope (SEM) images. Several examples of $npFe^0$-bearing rims can be found in Figure 11. Unlike the agglutinates, it appears that hydrogen isn't necessary to reduce the Fe here; the temperatures reached in vaporization are so high that the Fe^0 will separate without the presence of a reducing agent. Soil rims are quite common in mature lunar soils, with up to 90% of grains bearing rims (Keller *et al.*, 2000). The size of iron blebs in $npFe^0$-bearing rims is, on average, considerably smaller than is found in agglutinates and confined to a much narrower size range. Averaging about 3 nm in diameter, they range from roughly 1 to 15 nm in rims (Keller and Clement, 2001), compared to the tens to hundreds of nm diameter of grains found in agglutinates. By volume, the majority of the metallic iron in lunar soils can be found in the agglutinates; however, because the iron in the rims is surface correlated, it can often have a bigger impact on the physical and optical properties than the volume correlated iron in the agglutinates.

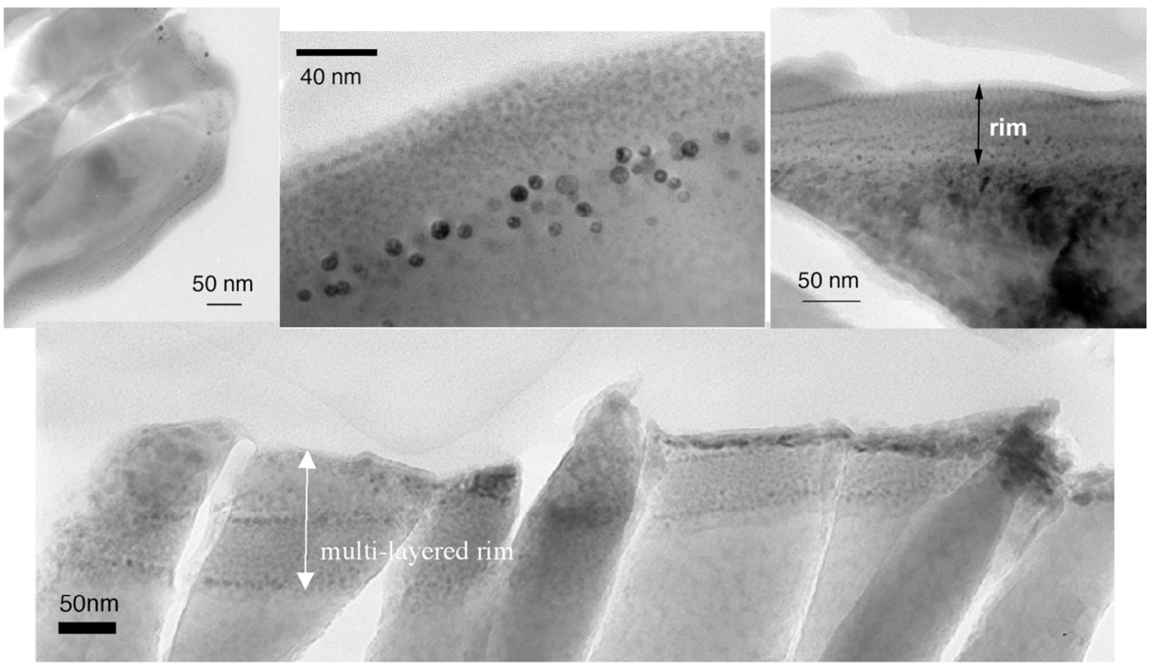

Figure 11. Several TEM images of nanophase iron-bearing rims on lunar soil grains (images a and c courtesy Lindsay Keller, NASA JSC).

Maturity

The concept of **maturity**, how long a grain has been exposed at the surface, is important to understanding lunar soils. The maturity of any given sample can be defined in several ways (e.g. the percentage of agglutinates, the density of cosmic ray tracks, etc), but in recent years, the standard definition has become its **I_s/FeO** value (Morris, 1978). **I_s** is the measure of the intensity of ferromagnetic resonance (FMR) resulting from the presence of iron particles in the 4 to 33 nm range. It is then typically normalized by the iron content (FeO) of a soil, since soils that have more iron available to reduce are going to create $npFe^0$ more quickly (i.e. it is easier for a mare soil to produce nanophase iron than for a highland soil). An I_s/FeO value of less than 30 is considered **immature**. This roughly corresponds to soils that are composed of 5-20% agglutinates. An I_s/FeO of 30-60 is considered **submature**, these tend to contain ~15-50% agglutinates. Anything with an I_s/FeO over 60 is considered **mature**. Mature soils are often composed of 40-60% agglutinates. Figure 12 plots several maturity indices vs I_s/FeO for a variety of lunar soils.

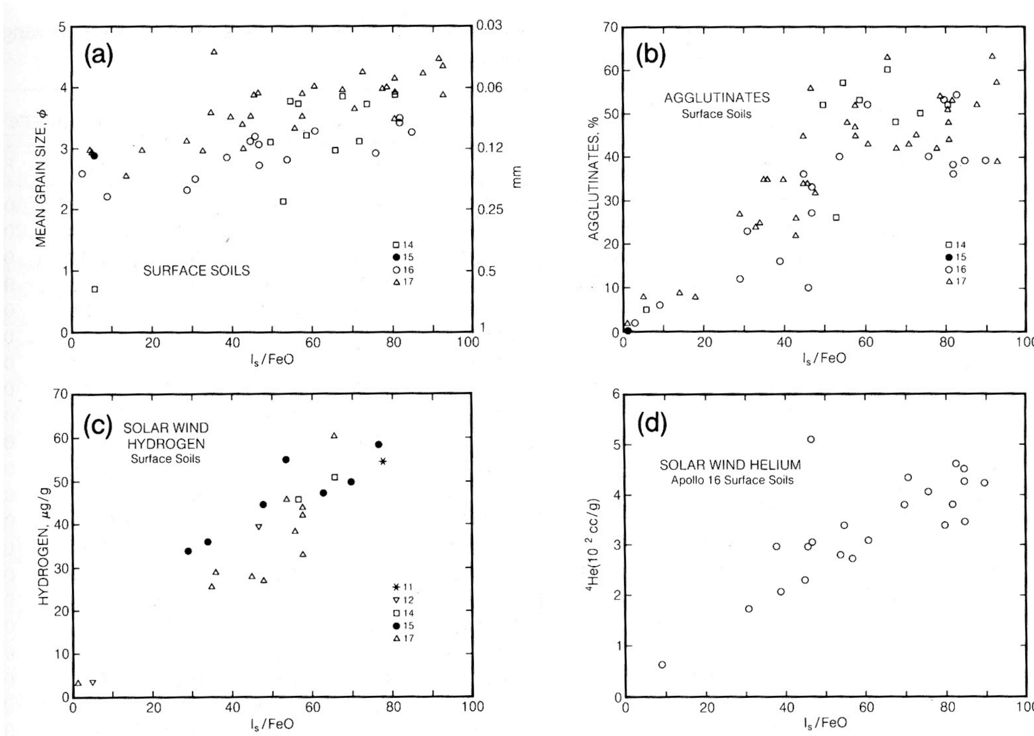

Figure 12. Nanophase iron content (Is/FeO) versus several other maturity indices; (a) mean grain size, (b) agglutinate content, (c) and (d) solar wind components (McKay et al., 1991).

The finest fractions of lunar soil contain more nanophase iron than the larger fractions, i.e. it appears more mature (Figure 13). There are two reasons for this: first, finer grains have a higher ratio of rim material to grain material (surface to volume), and since the iron is concentrated in the rims, nanophase iron increases in the finest fractions, secondly, nanophase iron-rich agglutinitic glass is fragile and tends to break down into small grain sizes more quickly than many of the other lunar minerals, again resulting in an enrichment in the finest fractions.

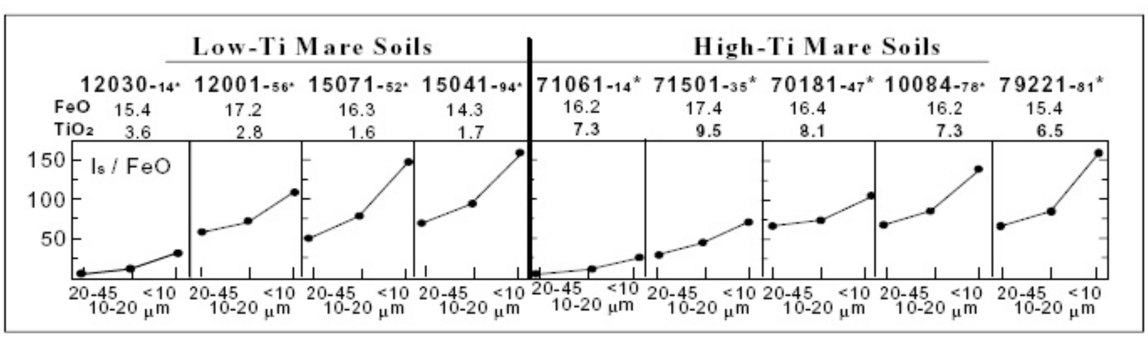

Figure 13. Is/FeO for the 20-45, 10-20, and <10 µm grain size fractions of several lunar soils (adapted from Taylor et al, 2000).

In addition to being enriched in agglutinitic glass compared to larger size fractions, the finest fractions of lunar soil are also enriched in plagioclase. This is because the mineral plagioclase, like the glass, breaks down easier than the other common lunar minerals (e.g. pyroxene, olivine, ilmenite, and cristobalite) (Hörz and Cintala, 1997).

The so-called "F^3" model – fusion of the finest fraction (Papike et al., 1981) posits that agglutinates are largely formed by the melting of the finest fraction of soil because of the higher surface to volume ratios of those grains. Since the finest fractions are enriched in glass and plagioclase, the average chemical composition of agglutinitic glass is skewed away from the bulk composition toward the composition of the less than 10 µm fraction.

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