SECTION 1: LUNAR HISTORY

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1.1 Introduction

Why understanding events in lunar history is important for engineers and simulant users:

- It explains the motivation for exploration of the Moon.
  - To understand the evolution of our own planet.
- It explains the origin of the operating environment for spacecraft, and ultimately influences the spacecraft design.
- It describes human and spacecraft hazards.
  - Morphology of the landing site.
  - **Micrometeorite** bombardment.
  - Lunar **regolith** (boulders, dust).
- It influences landing site locations.
  - Areas in permanent sunlight and shadow.
  - Regions of interest to scientists.
- It provides the basis for predicting the chemical composition and physical properties of the lunar surface at specific sites.
- It explains the impact history of the moon, which has changed the surface into its present form (creating the regolith).
- It describes the processes that created the size distribution of regolith components, as well as their chemistry.

1.2 Initial Impact

The Earth and Moon have similar chemistries and share the same oxygen isotope signature. This oxygen isotope signature is different from other planets and asteroids. Because of this, the Earth and Moon must have formed at the same distance from the Sun, or from a single chemical reservoir.

The "Giant Impact" theory of lunar origin involves the proto-Earth being struck by a Mars-sized impactor (called Theia). Scientists favor this theory because it explains not only the similarities in composition (and the identical oxygen isotope signature) and the known mass of both the Earth and Moon, but the angular momentum of the Earth-Moon system.

As shown in Figure 1, an oblique impact to the proto-Earth by a Mars-sized body would send a debris ring into orbit. This debris would coalesce to form the Moon. The **accretion** of this debris, by gravity, provided sufficient heat to melt the Moon (and shape it into a sphere).

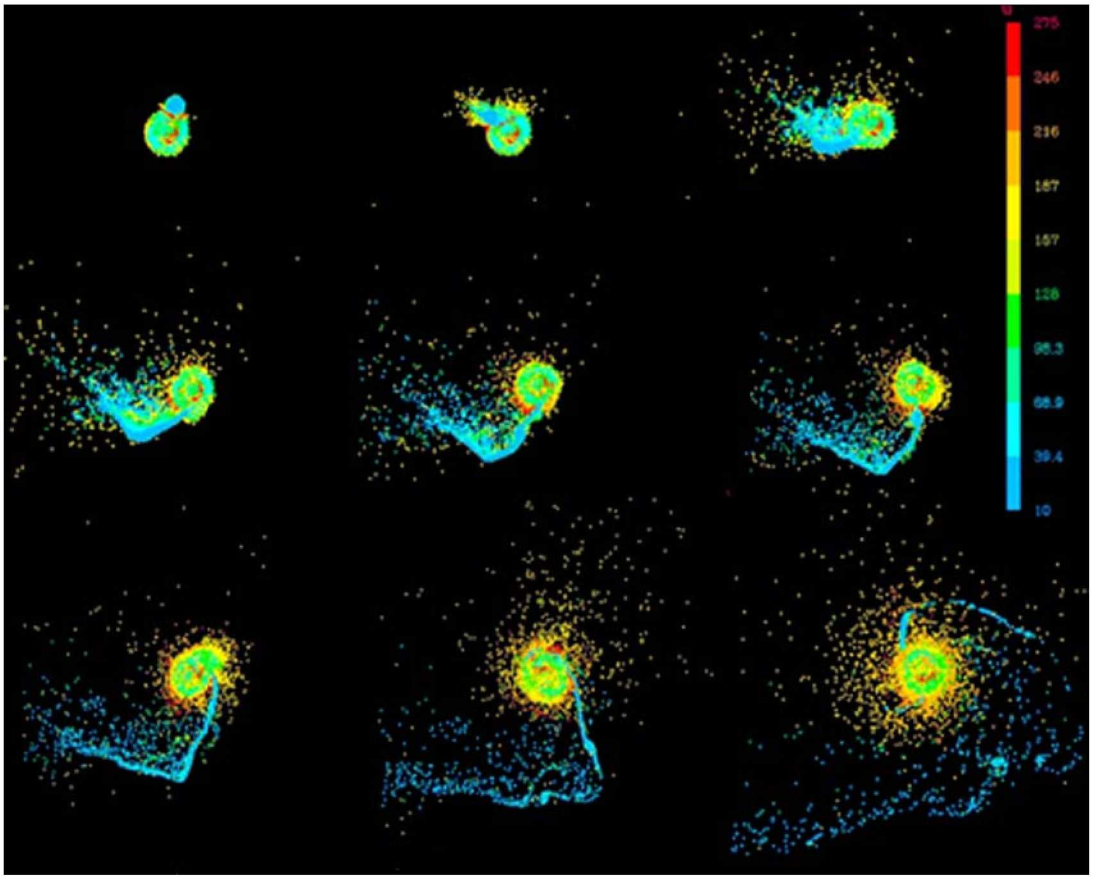


Figure 1: A model following the "Giant Impact" theory for lunar formation. In this scenario, a Mars-sized body (called Theia, in blue) impacted the proto-Earth (green) obliquely. Color indicates temperature. Debris ring around the Earth coalesced to form the Moon. Figure from Canup and Asphaug, 2001.

<u>1.3 Crust Generation</u>

At this stage, the Moon is melted sufficiently to have a **magma ocean** at the surface. There are two models for the formation of the lunar crust (**highlands**) that start at the post-formation magma ocean on the Moon.

The Lunar Magma Ocean Model and the Postmagma Ocean Model

Following the Apollo 11 mission and the return of the first lunar samples, Smith et al. (1970) and Wood et al. (1970) proposed similar models for the formation of the lunar crust. These two proposals have changed over time, with an increasing database of geochemical information, into the Lunar Magma Ocean (LMO) model. The following summarizes the work of Snyder et al. (1992).

This model depends on multiple factors. The crystallization temperature and pressure of specific minerals (**olivine**, **pyroxene**, and **anorthite**; compositions of cumulates dependent on **Bowen's Reaction Series**), the density of those minerals, and the presence of **incompatible elements** all influence the end result of the LMO model. Figure 2 illustrates the sequence of crystallization events in the LMO model.

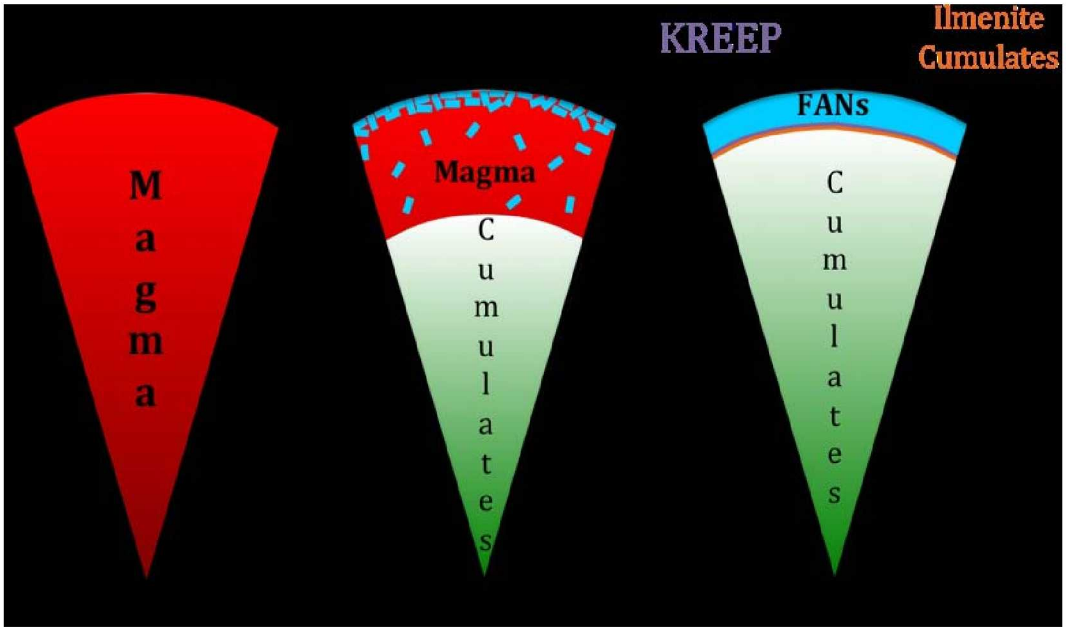


Figure 2: Stages of Lunar Magma Ocean crystallization. PCS = percent crystalline solid. The first **cumulates** to form (green) are composed of olivine and pyroxene minerals, which are more dense than surrounding magma. At 78 PCS, anorthite begins to form. Since anorthite is less dense than the surrounding magma, the anorthite crystals begin to float. These crystals continue to form until the entire lunar surface is composed of anorthosite cumulates, the ferroan anorthosites (FANs). The residual (trapped) magma from the LMO, rich in incompatible elements, forms dense **ilmenite** cumulates, then **KREEP**. This illustration drafted above assumes whole Moon melting, which has not been verified.

The LMO model does not explain all highlands lithologies (rock types). **Cumulate overturn** after crystallization of the LMO is required to explain the calculated depth of melting (magma generation depth) and geochemistry of another highland lithology, the magnesium suite (Mg-suite). A magnesium-rich major element composition (typically seen in the first-formed cumulate crystals of the LMO) and a KREEP incompatible element signature (observed in the latest-stage of LMO crystallization) characterize the Mg-suite. Cumulate overturn involves the sinking of the dense ilmenite cumulates into the lunar mantle, entraining "KREEPy" material. Most elements that make up the KREEP signature are radioactive and heat-producing, which may have caused the Mg-suite parent magma to begin rising to the surface. The Mg-suite parent magma would be too dense to erupt on the surface of the Moon, so it is likely that the lunar crust trapped the molten material below the surface. Following the formation of these Mg-suite **plutons**, impact gardening exposed them.

The Postmagma Ocean model was proposed by J. Longhi in 2003 to reconcile the fact that some radiogenic isotope ages determined for FANs and rocks of the Mg-suite overlap. This model also suggests that the core of the Moon did not melt to become part of the original magma ocean, and that **primitive**, **chondritic** material makes up the core of the Moon. Detailed **experimental petrology** studies indicate that Mg-suite rocks can be formed without entire Moon melting, and that FAN magmatism may have led to the concurrent crystallization of Mg-suite rocks.

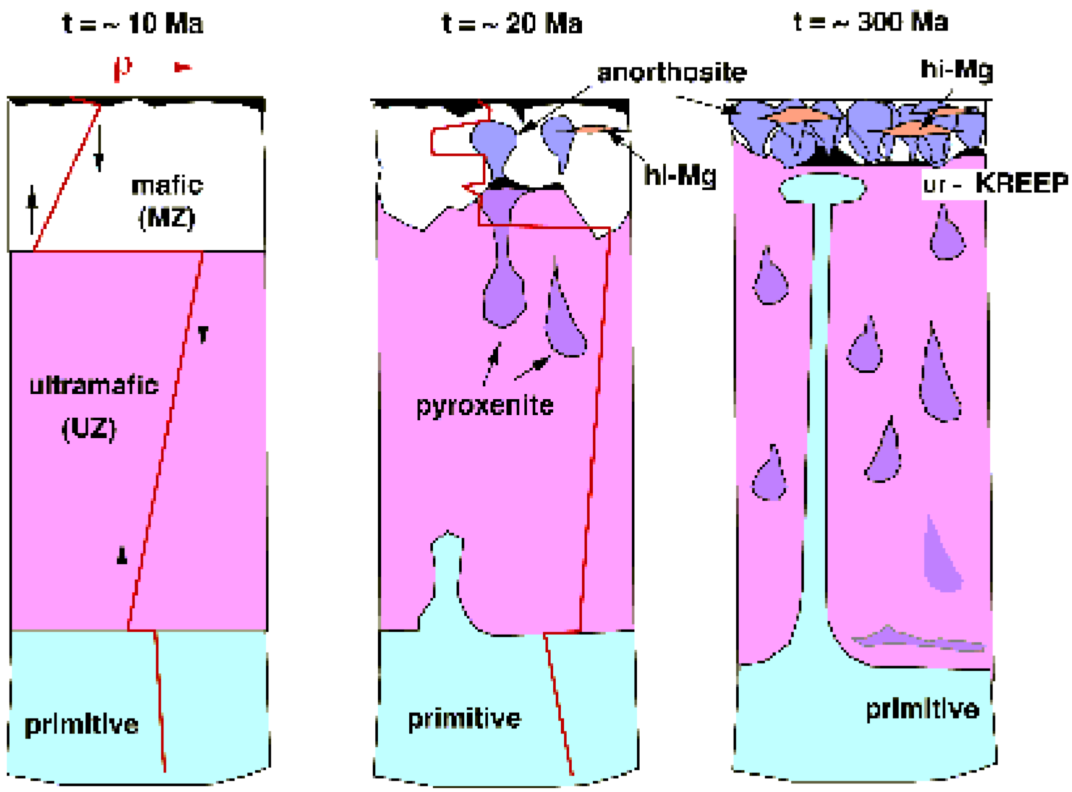


Figure 3: Model for the origin of the lunar crust as suggested by Longhi (2003). T = time, Ma = million years, ρ = density (corresponding red lines indicate density changes in the layers of the Moon, with increasing density towards the right side of the diagram). In this stage, mafic layers include pyroxene and anorthite, and ultramafic layers contain mostly olivine. Convection and density-induced overturn occurs in both layers and is independent of the adjacent layer. This overturn causes a heating of the primitive lunar core. The primitive core begins to melt and rise towards the surface. The density of the melt prevents it from reaching the lunar surface. Thus, Mg-suite plutons (orange) are formed. Meanwhile, heating in the upper layer due to this overturn causes partial melting of cumulates, which separate into a less dense FAN parent liquid (blue, which begins to rise) and a more dense pyroxenite liquid (purple, which begins to sink). The final illustration (right) shows the FAN crust that formed at the same time as the Mg-suite. Ur-KREEP is the name for a physical KREEP material (black).

Comments

Comparative radioisotope studies (^{147}Sm-^{143}Nd) of Mg-suite rocks indicate formation of KREEP at approximately 4518 ± 85 Ma (Edmunson and Nyquist, 2007). Further studies on the accuracy of FAN ages are underway at Marshall Space Flight Center, and a study regarding the petrogenetic links between FANs and the Mg-suite has been proposed.

1.4 Impactors

Craters cover the surface of the Moon (Figure 4). Because of the Apollo missions and the samples returned from their selected landing sites, scientists have been able to determine the relative ages of the craters on the Moon. That is, scientists have determined a **stratigraphy** of the impact craters and their **ejecta** on the Moon, and have calibrated it to represent specific times in lunar history (i.e., the "**crater counting**" method of determining the age of specific areas of the lunar surface).

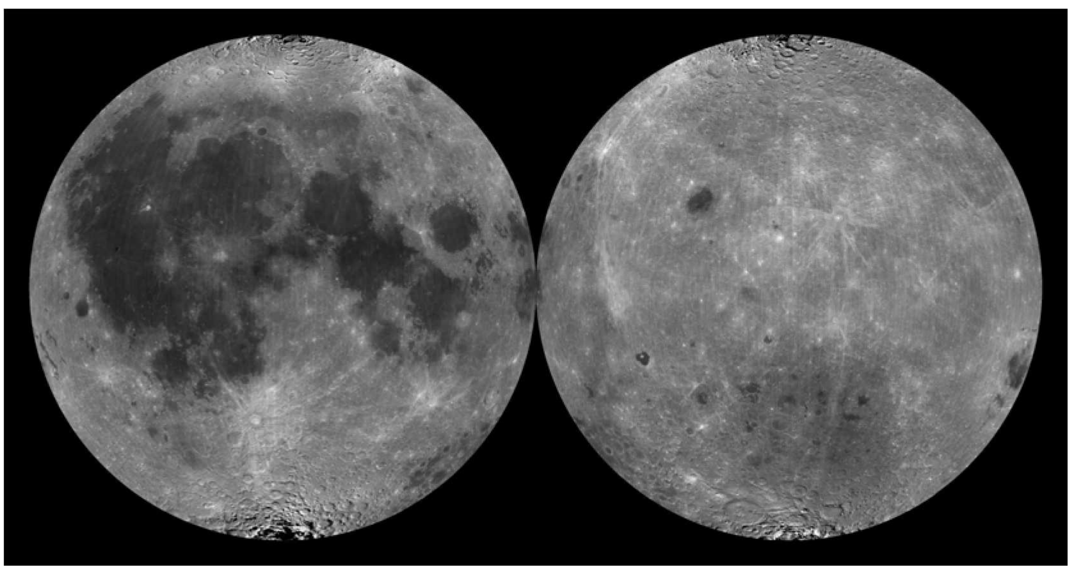


Figure 4: Photomosaic of the lunar surface as seen by the Clementine spacecraft. Image obtained from P. Spudis. Light areas are highlands, dark areas are mare (sea in Latin). Mare lava flows fill crater **basins**, so mare are younger than the highlands rocks and the craters they fill (**superposition**).

1.4.1 Periods

Scientists have designated geologic time periods (similar to those for Earth) based on events in lunar history (Figure 5). The formation age of the Nectaris basin is interpreted to be approximately 3920 Ma and is based on the combined age of brecciated samples (James 1981). Imbrian and Copernican periods start from the formation of the Imbrium basin and Copernicus crater, respectively. The Eratosthenian period, however, begins at the age of the mare lavas on which the Eratosthenes crater ejecta is superimposed.

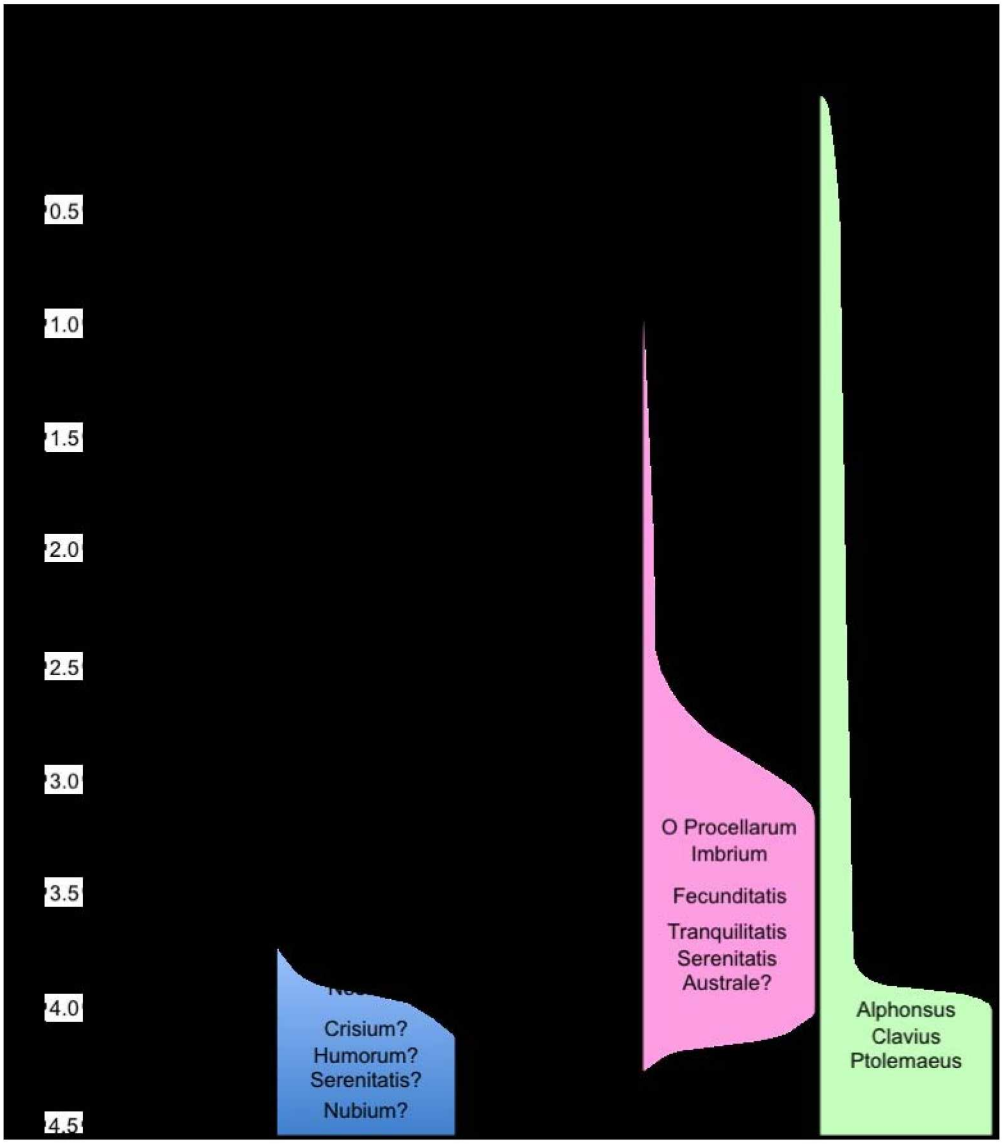


Figure 5: A geologic time scale of events on the Moon. O = Oceanus. Modified from an image obtained from R. L. Nowack. The ages defining specific periods in the history of the Moon are subject to change with new data or further sample return from the Moon.

The Lunar Cataclysm

One can note from Figure 5 that the majority of impacts (basin formation events) occurred very early in lunar history. Indeed, scientists believe that the number of impactors decreased exponentially since the creation of the Solar System. This is likely due to instabilities in the original orbits of the impactors and their consumption by the Sun or by accretion to a larger body. However, around 3900 Ma, a spike can be resolved in the isotopic ages obtained from lunar samples (e.g., Kring, 2000; Kring and Cohen, 2002). This spike is thought to represent a large-scale heating event (**metamorphism**) caused by a relatively short-lived *increase* in the number of impacts on the lunar surface from asteroids or comets (Tera et al., 1974). Some have even hypothesized that life on Earth was affected by this cataclysmic event.

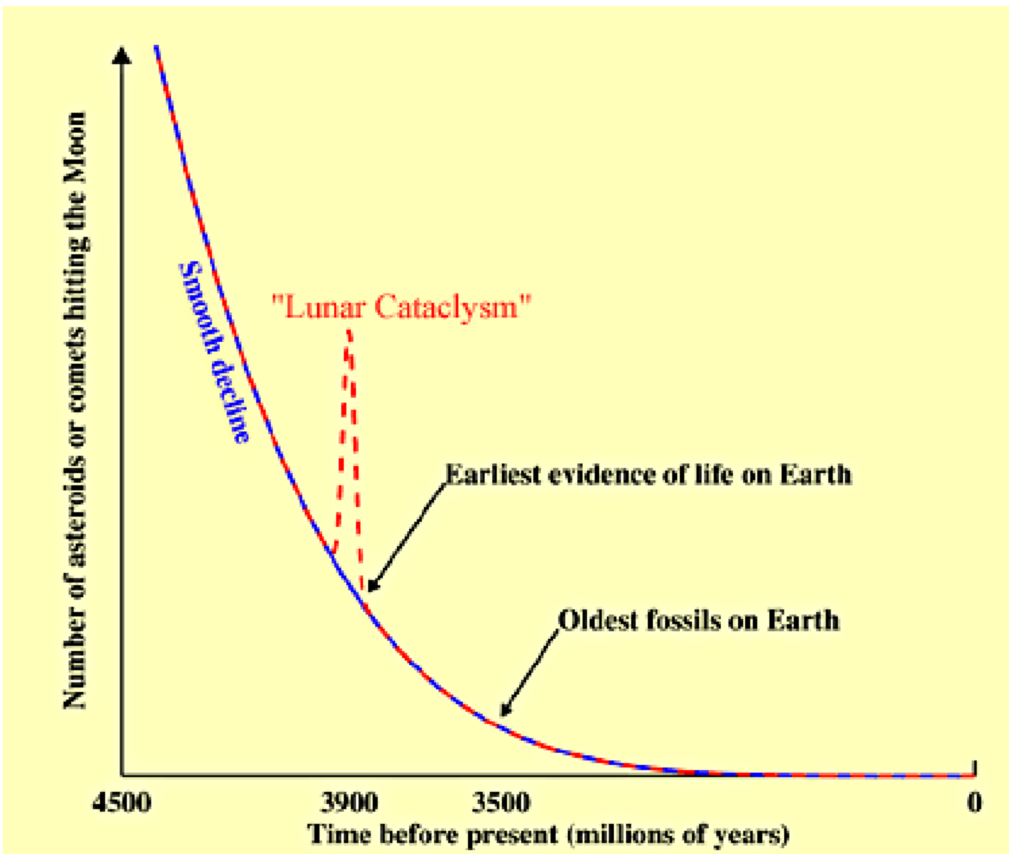


Figure 6: Illustration of the lunar cataclysm (figure by B. A. Cohen).

<u>1.4.2 Size Distribution Versus Time</u>

To further characterize the impact history of the Moon, comparisons were made between the size and frequency of craters for given time periods. Figure 7 shows the diameter of craters versus the number of craters per square kilometer.

This figure shows that Prenectarian craters are larger in size than Nectarian craters, which are in turn larger than Imbrium-period craters. Copernican and Eratosthenian period craters are smaller still in size. This indicates that the largest craters on the Moon were formed during its earliest history, and the size of the impactors has decreased significantly over time.

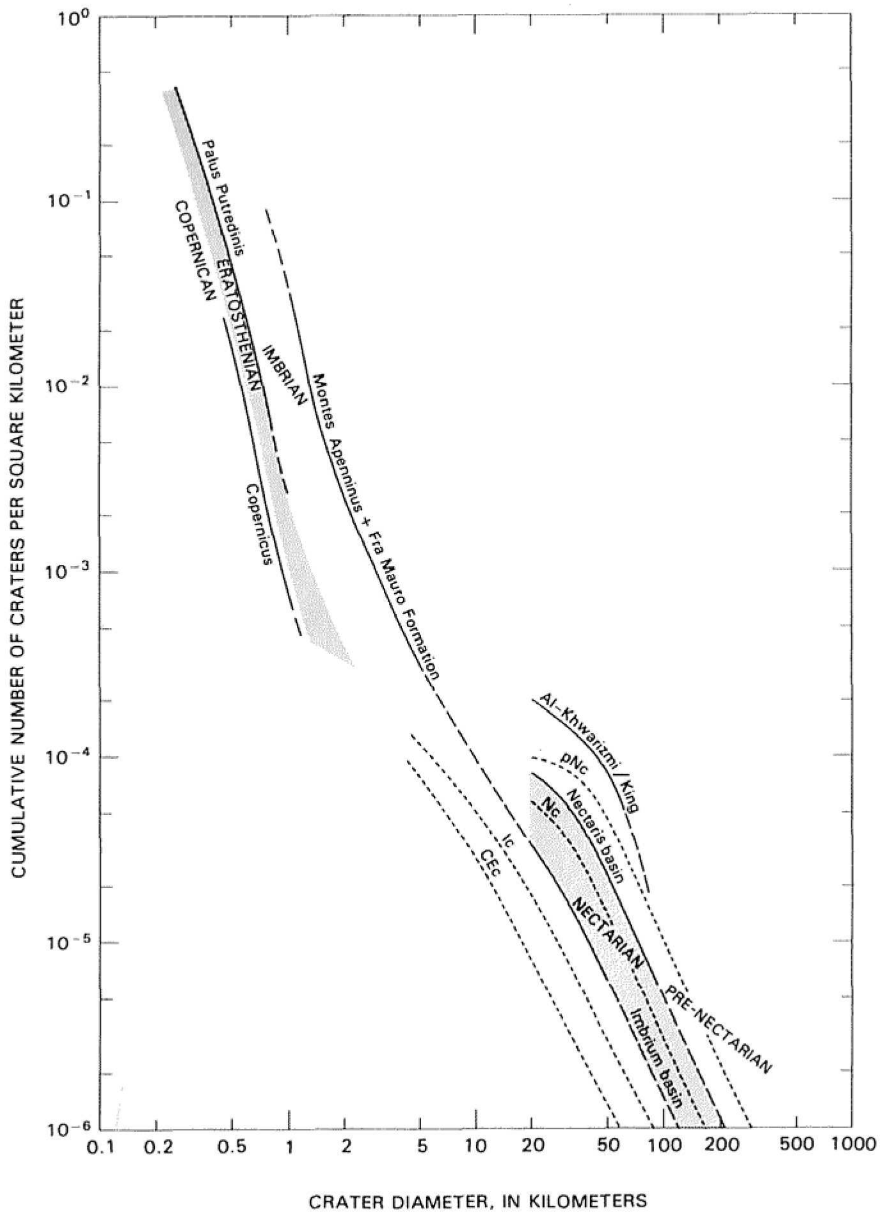


Figure 7: Cumulative crater size vs. frequency for the lunar surface (Wilhelms, 1987). Dashed curves indicate the average frequency of impact craters of Prenectarian (pNc), Nectarian (Nc), Imbrian (Ic) and the Copernican and Eratosthenian (CEc) periods. Please note that this diagram does not imply that smaller craters were not part of the early bombardment of the Moon, but that they were covered by larger crater ejecta.

1.4.3 Nature of an Impact

The following is a chronology of a hypothetical impact on the Moon, and is a modified summary of the work by B. French (1998), with supplemental information from Hörz et al. (1991). Figure 8 illustrates this process.

(1) A body impacts the surface (target) traveling at greater than 3km/s (cosmic impact velocities are 15-20km/s).
(2) Depending on the energy of the impact, vaporization of the impacting body can occur.
(3) The target rock is compressed at the impact site.
(4) A hemispherical shock wave travels outward from the impact site, pushing all surrounding rocks outward, ejecting near-surface material (ejecta), and, in most cases, melting the uppermost impacted rocks (flinging some of this material from the ejection site, giving rise to **tektites**).
(5) The ejecta blankets the surrounding area.
(6) The rocks surrounding the impact site (hemisphere) that are not melted rebound to their original positions (rarefaction wave), but become brecciated in the process (they do not have elastic properties).
(7) Craters are filled with vertically ejected material, portions of melted rock, parts of the crater walls that exceed the angle of repose and collapse into the crater, and the ejecta blanket on top of the collapsing crater walls. **Lithification** occurs by (shock) compaction or welding.
(8) The final (apparent) crater appears shallower than the true crater (where the fractured rock begins).

Simple craters, discussed above, are only less than a few kilometers across. Larger craters, caused by larger impactors, tend to have different characteristics due to the increased rebounding effect on the rocks below the impact site. Like ripples caused by a water droplet falling into a puddle, the rocks below the center of the transient crater are pushed outward by the impact, inward by rarefaction, and upward in response. This upward motion creates a central uplift in complex craters (e.g., Dense, 1968). Note that the central uplift is composed of rocks that were below the surface of the target rocks prior to impact (Figure 9).

1.4.3.1 Crater Morphology

The following set of photos is labeled for ease of reference (Figures 10-13).

Figures 10, 11, and 12 have one thing in common – the trajectory of the impactor was at a high angle relative to the surface of the Moon. The morphology of oblique (low angle) impacts is slightly different (Figure 13).

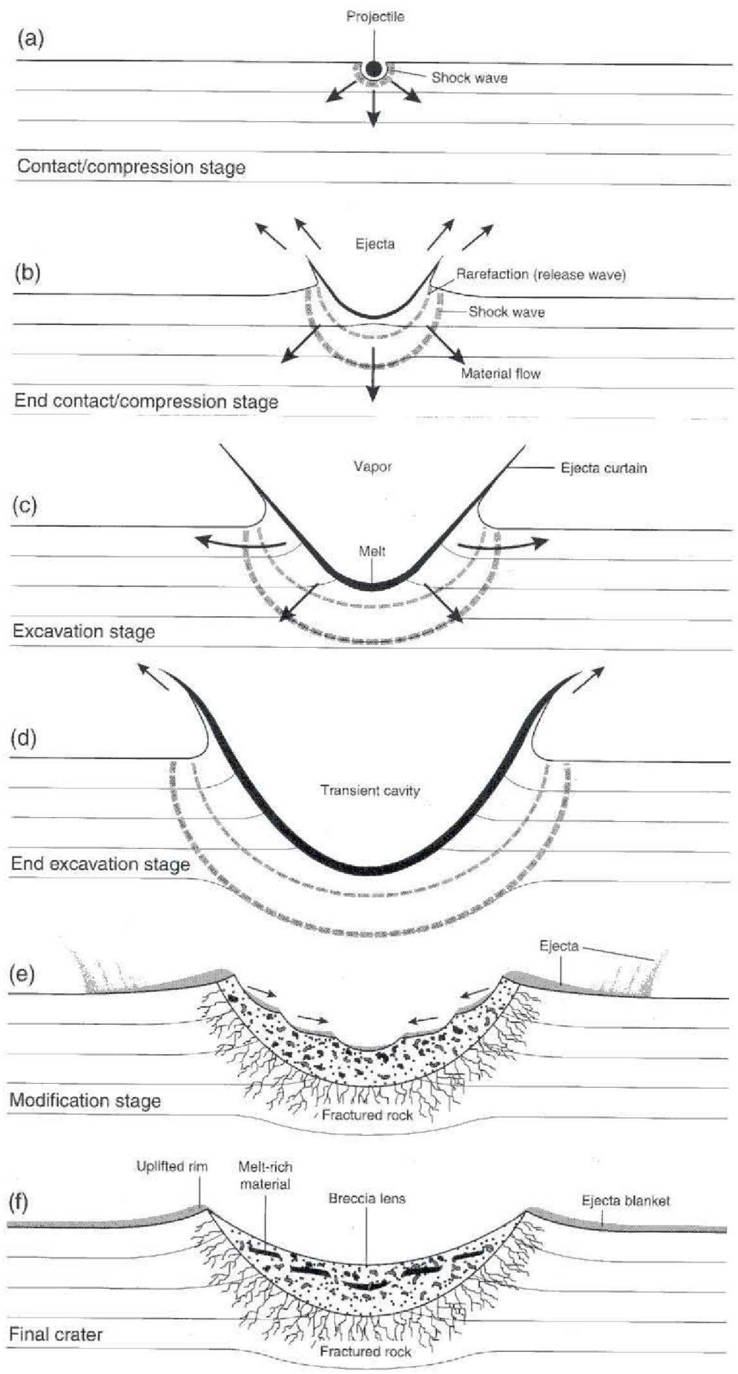


Figure 8: Formation of a simple crater (French, 1998).

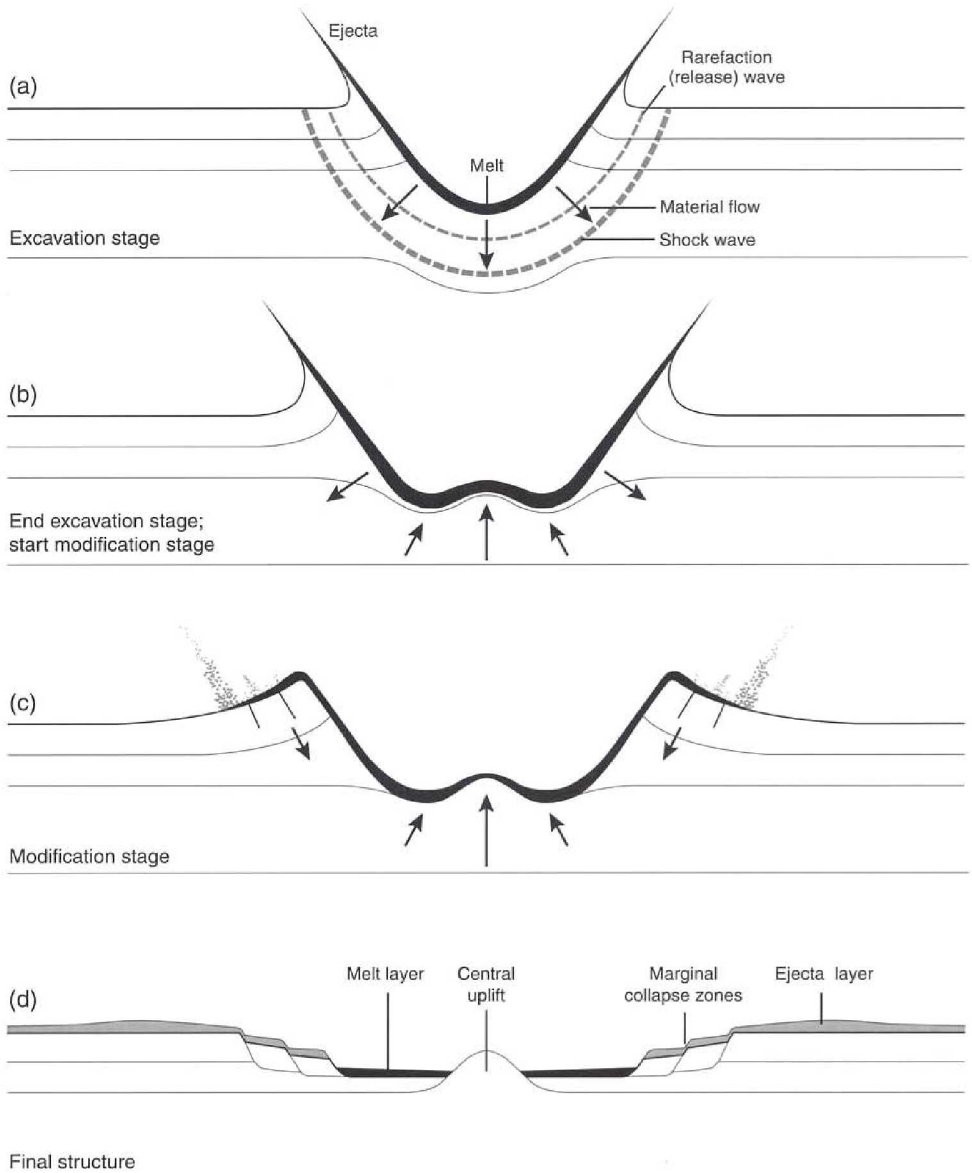


Figure 9: Formation of a complex crater and central uplift (French, 1998).

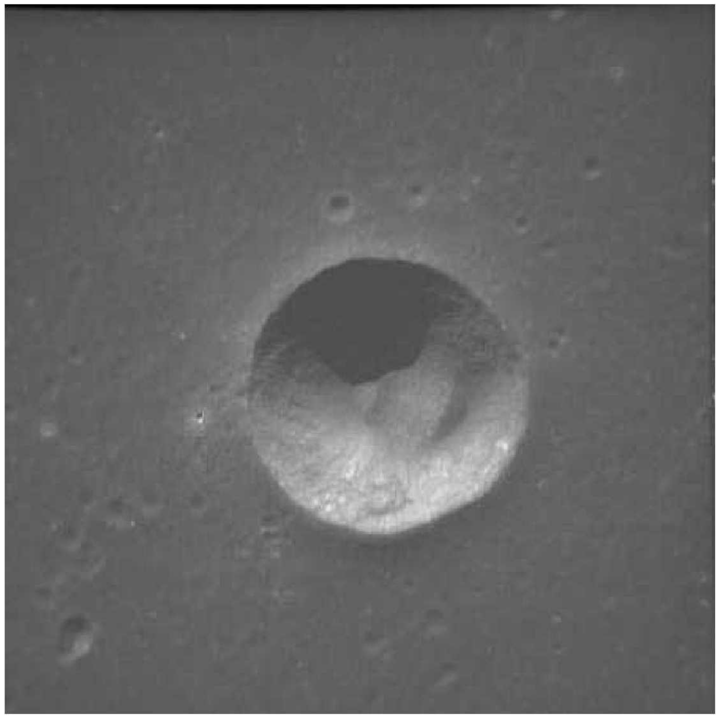


Figure 10: Morphology of a simple crater (Anville). Diameter 11km. Photograph taken during the Apollo 11 mission.

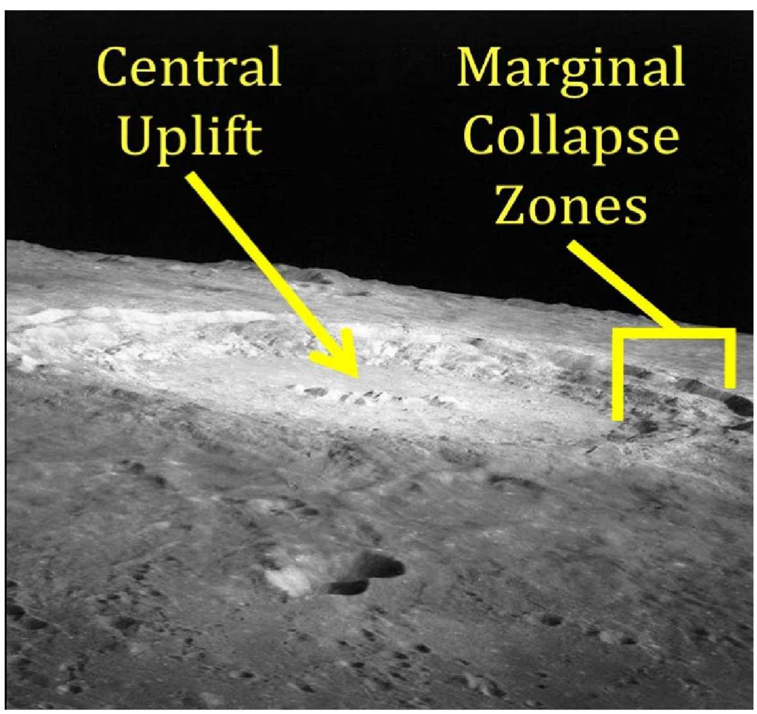


Figure 11: Morphology of a complex crater (Copernicus). Diameter 93km. Photograph taken during the Apollo 12 mission.

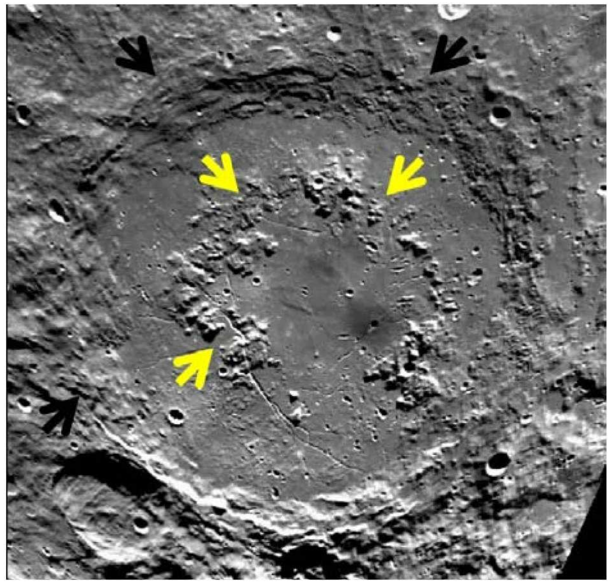


Figure 12: Morphology of a multi-ring basin (Schrödinger). Yellow arrows indicate interior peak ring (150km in diameter), black arrows indicate exterior of the impact structure (320km in diameter). Photograph from the Clementine orbiter.

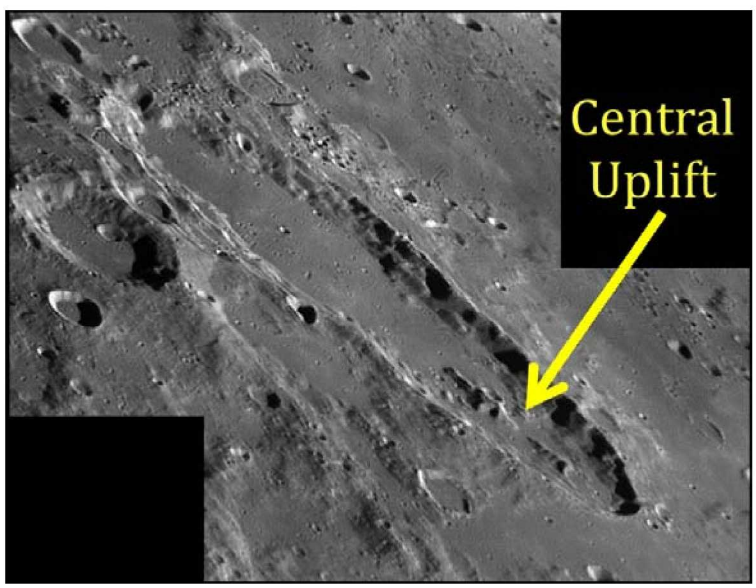


Figure 13: Morphology of an oblique impact. Photomosaic of Schiller crater taken by Damian Peach (from Earth). Crater is 220km in length.

1.4.3.2 Fracturing

Fracturing is the result of the least amount of shock on a sample. Figure 14 shows a thin section (approximately 30um-thick slice of rock) of a lunar lithic breccia. It is called a lithic breccia because it contains no impact melt glass. The samples are pulverized, generally at shock pressures less than 50 kilobars (Maier, 1995). This kind of shock creates compaction, during which the samples become lithified.

Figure 14: Plane-polarized light photomicrograph of lithic breccia 76335, thin section 61. Note large, shattered mineral grains and areas of significant brecciation (forming grains that are too small to be seen on this scale). Section is approximately 1.9cm in length. Photomicrograph by J. Edmunson.

1.4.3.3 Melting

When the temperature and pressure of shock becomes great enough, meting occurs. Minerals tend to melt at grain boundaries first. Figure 15 shows an example of an impact melt breccia.

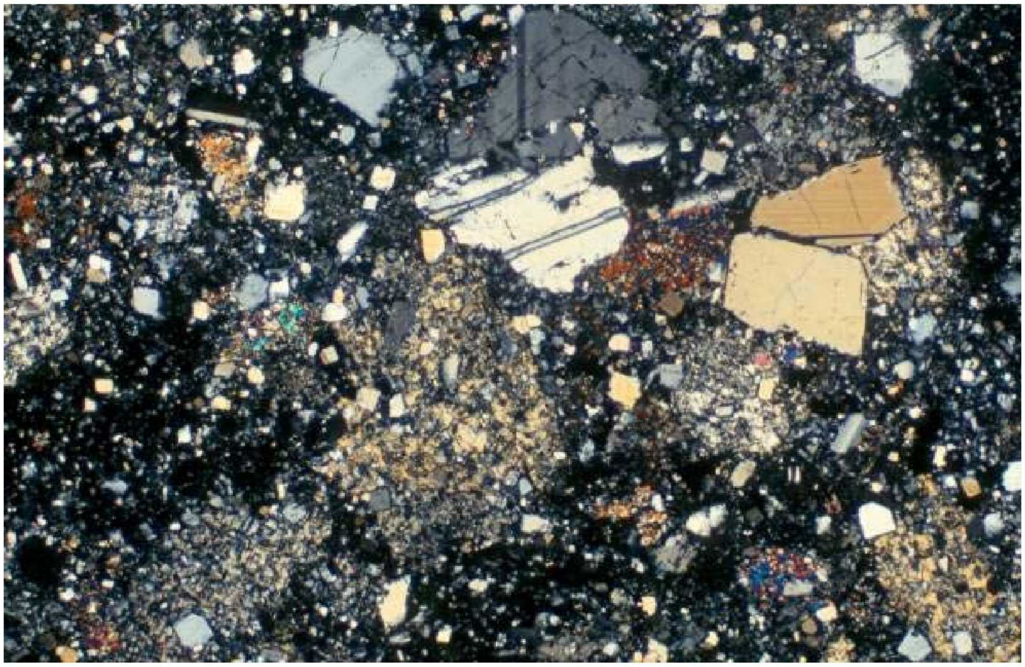


Figure 15: Impact melt breccia 65015. Crossed polarized light, showing impact melt glass (black) amid areas of both large and small mineral grains. Colors are the result of mineral type and the ability of the crystal to bend transmitted light. Photomicrograph by B. Jolliff.

1.4.3.4 Shock Welding

Experiments indicate that shock welding can occur in loose lunar soil at pressures as low as 160 kilobars. (Schaal and Hörz, 1980). Shock welding involves heating by the shearing of grains, creating melts in between the grains and ultimate lithification during cooling of the glass (melt). This shock glass represented between 5 and 30% of the total sample in the experimental study.

1.5 "Recent" Processes

Figures 5, 6, and 7 all show that the frequency of impacts, and the size of the impact craters generated, has decreased over time. Thus, other processes have become dominant mechanisms in altering the surface of the Moon. The following is a brief summary of these processes. More detailed analysis will be presented in following chapters.

1.5.1 Micrometeorites

Micrometeorites are small meteorites (less than 1mm in diameter) that vaporize on impact with the lunar surface, imparting approximately 1 Joule of energy. This method of surface erosion is akin to sandblasting, and is estimated to occur at a rate of 1mm/10^6 years for kilogram-sized rocks on the lunar surface (Ashworth, 1977). Micrometeorites create agglutinates on the lunar surface, as well as reduce oxidized (crystal structure) iron into iron metal in the agglutinates (McKay et al., 1991). Figure 16 shows the damage to a lunar sample by micrometeorite impact. Micrometeorites are also capable of penetrating manmade materials, so spacesuits are built with several layers of Kevlar and Dacron to prevent penetration and decompression of the suit. The estimated amount of material delivered as micrometeorites on Earth (Love and Brownlee, 1993) can be applied to the Moon. An estimated annual micrometeorite mass of 80g/km^2 is added to the lunar surface. This equates to an approximate 5-10 micrometeorite impacts per year on every square meter of the lunar surface.

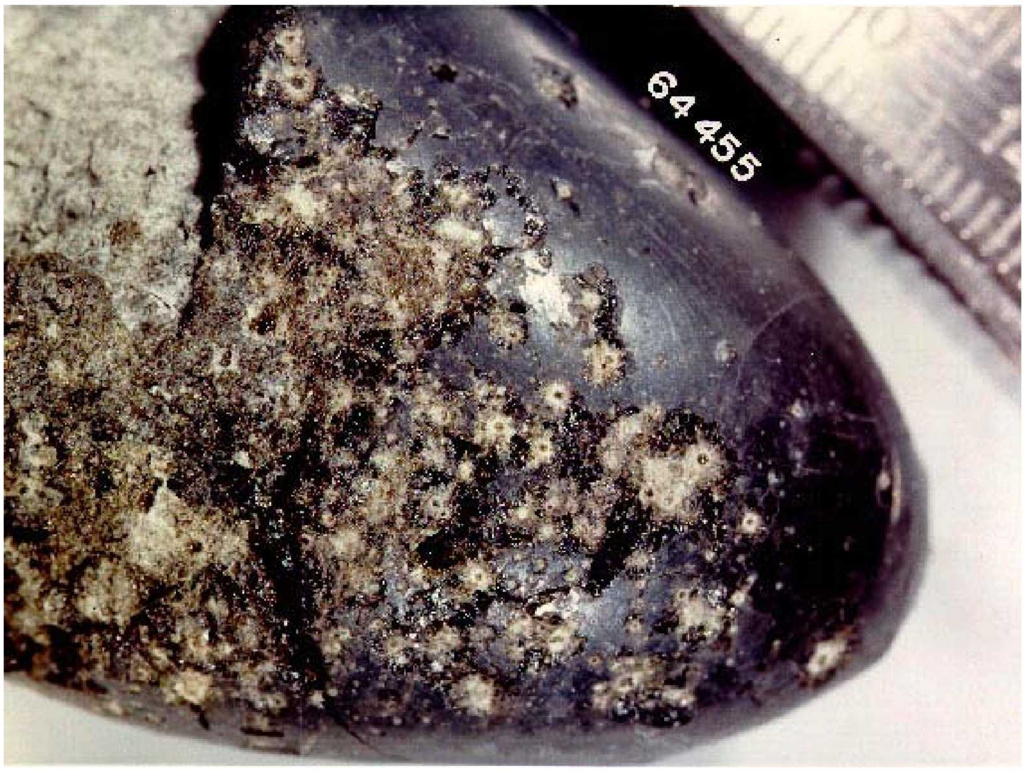


Figure 16: Photograph of the surface of Apollo 16 sample 64455, revealing the erosion of the surface from exposure to micrometeorites. NASA photograph 5-78-22656.

1.5.2 Solar Wind

"Solar wind" is used to describe the abundant, low-energy (1KeV) particles (i.e., protons, electrons, and alpha particles to a lesser extent, as well as light volatile elements) being emitted by the Sun and implanted, typically to a depth of a few tens of nanometers, into the lunar surface (e.g., Lucey et al., 2006 and references therein). Some of the implanted material is able to diffuse out of the rock, but much of it remains implanted. This bombardment ultimately causes a decrease in the **albedo** of the lunar surface. The Moon's lack of an atmosphere allows very concise study of solar wind particles and their implantation. Solar energetic particles, those accelerated to 1-100MeV, can be implanted up to approximately 1cm in depth.

1.5.3 Radiation

Radiation of the lunar surface by galactic cosmic rays (those particles with energies of 100MeV to 10GeV) can change the chemistry of the surface. Neutron capture reactions can create higher concentrations of specific isotopes (e.g., ^{150}Sm from ^{149}Sm), and this effect decreases with depth from the lunar surface. Scientists have used this technique to determine the depth at which the sample was exposed to cosmic rays. The cosmic ray particles can also produce lighter elements and isotopes (such as ^{15}N, used to calculate the rate of spallation at the lunar surface by Mathew and Marti, 2001). Galactic cosmic rays are composed of approximately 87% protons, 12% alpha particles, and 1% heaver ions. They can penetrate meters into the lunar surface. (Lucey et al., 2006).

1.5.4 Generation of Agglutinates

Agglutinates are aggregates of other regolith particles on the lunar surface, including other agglutinates (e.g., Duke et al., 1970). They are cemented together by **vesicular** impact melt glass, indicating their formation by micrometeorite impact. Agglutinates are typically less than 1mm in size, and can constitute approximately 60% of mature lunar soils by volume (Papike et al., 1998).

1.6 Lack of Sorting Relative to Terrestrial Rocks

In geology, sorting refers to the proportion of grains of a particular size range in a given sample. Geologists refer to samples, such as the lunar regolith, as poorly sorted when they contain multiple-sized grains. Most terrestrial samples, because of their formation by **weathering** and deposition by water or wind – such as beach sand, are considered well sorted. Water and wind are capable of suspending very specific grain sizes at specific velocities. Impacts, on the other hand, break up target material into multiple sizes and transport it via projectile motion. The surface of the Moon is covered with the results of 4567 Ma of impact, volcanism, solar wind bombardment, cosmic ray-induced reactions, and agglutinate generation. These processes have led to the formation of a lunar regolith with very poorly sorted grains.

1.7 Vocabulary

Modified and annotated from the Dictionary of Geological Terms, 3rd edition.

Accretion: Any hypothesis of the origin of a planetary body which assumes that it has grown from a small nucleus by the gradual addition of solid bodies, such as meteorites, asteroids, or planetesimals, formerly revolving about the Sun (or planet) in independent orbits, but eventually drawn by gravitiation to the forming planetary body and incorporated with it.

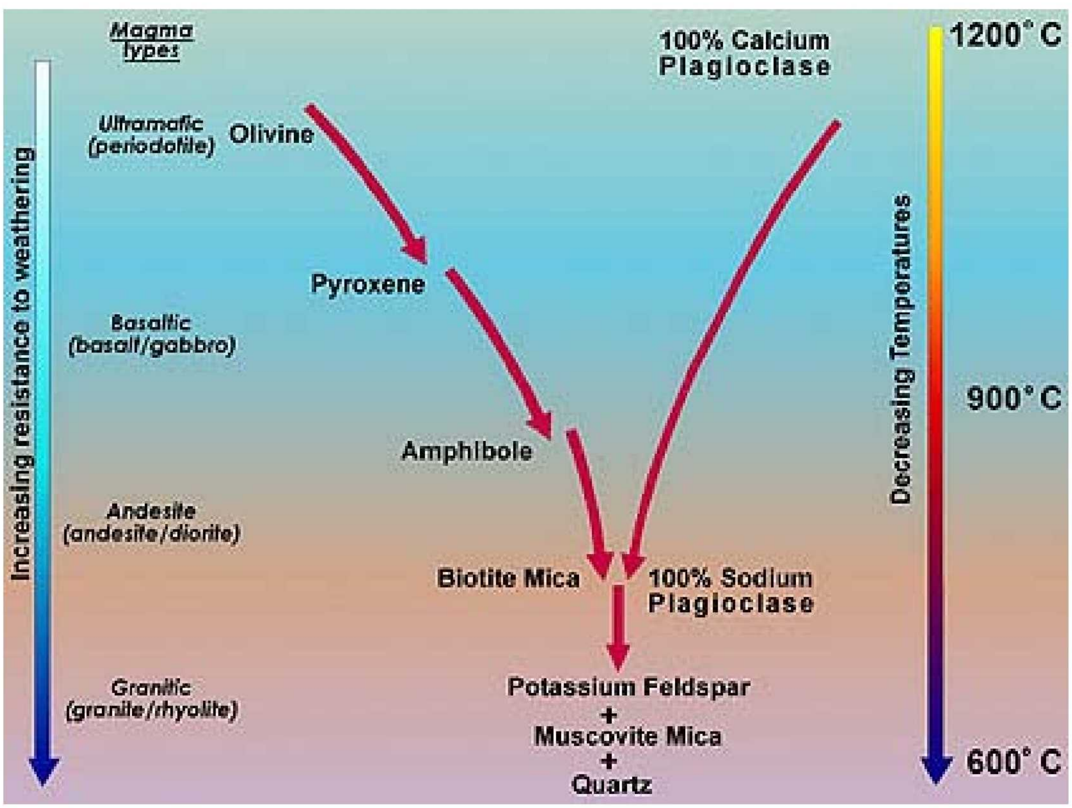
Albedo: The percentage of the incoming radiation (light) that is reflected by a natural surface.

Anorthite: A white or gray mineral of the feldspar (plagioclase) group: $CaAl_2Si_2O_8$.

Anorthosite: A rock composed almost wholly of plagioclase (anorthite).

Basin: A depressed area with no surface outlet (e.g., crater).

Bowen's Reaction Series: A series of minerals in which any early-formed mineral phase tends to react with the melt, later in the differentiation, to yield a new mineral further down in the series. This series shows which minerals form first, and which form later during the crystallization process. Thus, each mineral in this series has different properties – temperature and pressure of formation, chemistry, and reactivity. Figure describing Bowen's reaction series from Idaho State University.



Chondritic: A composition resembling that of the earliest solar system material, as observed in un-differentiated stony meteorites. Chondritic meteorites contain both metals and silicate minerals.

Crater Counting: A method of determining the age of a specific area based on the number of craters within that area. This number is correlated to both the impactor flux and, in the case of lunar samples, with radioisotope ages.

Cumulate Overturn: A density-driven movement of crystals. More dense minerals will sink, while less dense minerals will rise.

Cumulates: Crystals that settle out from a magma by the action of gravity.

Ejecta: Glass, rock fragments, and other material thrown out of an explosion or impact crater during formation.

Experimental Petrology: The science that involves using known chemical constituents (e.g., certain metal oxides), melting them, and observing what crystals or melt compositions form at specific temperature and pressure conditions.

FAN (ferroan anorthosite): Specific to the Moon, ferroan anorthosites are anorthosites that have higher than terrestrial (Earth) Fe abundances.

Highlands: The heavily cratered, white portion of the Moon. Ferroan anorthosites and Mg-suite rocks are considered highland rock types.

Ilmenite: An iron-black opaque mineral, $FeTiO_3$. It is the principal ore of titanium.

Incompatible element: An element that does not fit readily into the structure of a mineral due to ionic radius or charge.

KREEP: The latest-stage of differentiation of the Moon, a concentration of incompatible elements. The acronym KREEP stands for potassium (K), rare earth elements (REE) and phosphorous (P).

Lithification: The conversion of deposited sediment into a solid rock, involving such processes as cementation, compaction, and crystallization.

Magma Ocean: Molten rock that covers the surface of a planet. The (likely) original state of a planet prior to the formation of a core, mantle, and crust (differentiation). The depths of magma oceans are unknown, and may in fact involve the entire planet.

Metamorphism: The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions imposed at depth below the surface zones of weathering and cementation (or temperature and pressure changes during impact), which differ from the conditions under which the rocks originated.

Micrometeorite: A meteorite particle with a diameter generally less than a millimeter, so small that it undergoes atmospheric entry (on Earth) without vaporizing or becoming intensely heated and hence without disintegration.

Olivine: A green or brown mineral, $(Mg,Fe)_2SiO_4$. It is a common rock-forming mineral, crystallizes easily from magma, and weathers readily under terrestrial surface conditions.

Pluton: An igneous intrusion (that is, a magma body that is emplaced below the surface and solidifies).

Pyroxene: A group of common rock-forming minerals with the general formula $(Mg,Fe,Ca,Na)(Mg,Fe,Al)Si_2O_6$.

Regolith: The fragmental and unconsolidated rock material, whether residual or transported, that nearly everywhere forms the surface of the land and overlies the bedrock. It includes rock debris of all kinds.

Stratigraphy: The arrangement of strata (geologic layers), especially as to geographic position and chronologic order of sequence. Chronology is dominated by the Principal of Superposition.

Superposition: The order in which rocks occur in strata one above the other, the highest being the youngest (older rocks must underlie younger rock strata).

Tektites: A rounded pitted jet-black to greenish or yellowish body of silicate glass of non-volcanic origin (products of large hypervelocity meteorite impacts).

Vesicular: Containing small cavities in glassy igneous rock, formed by the expansion of a bubble of gas during solidification.

Weathering: The destructive processes by which rocks are changed on exposure to atmospheric agents at or near the Earth's surface, with little or no transport of the loosened or altered material; specific to the physical disintegration and chemical decomposition of a rock.

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