Lunar Sample Compendium

Introduction

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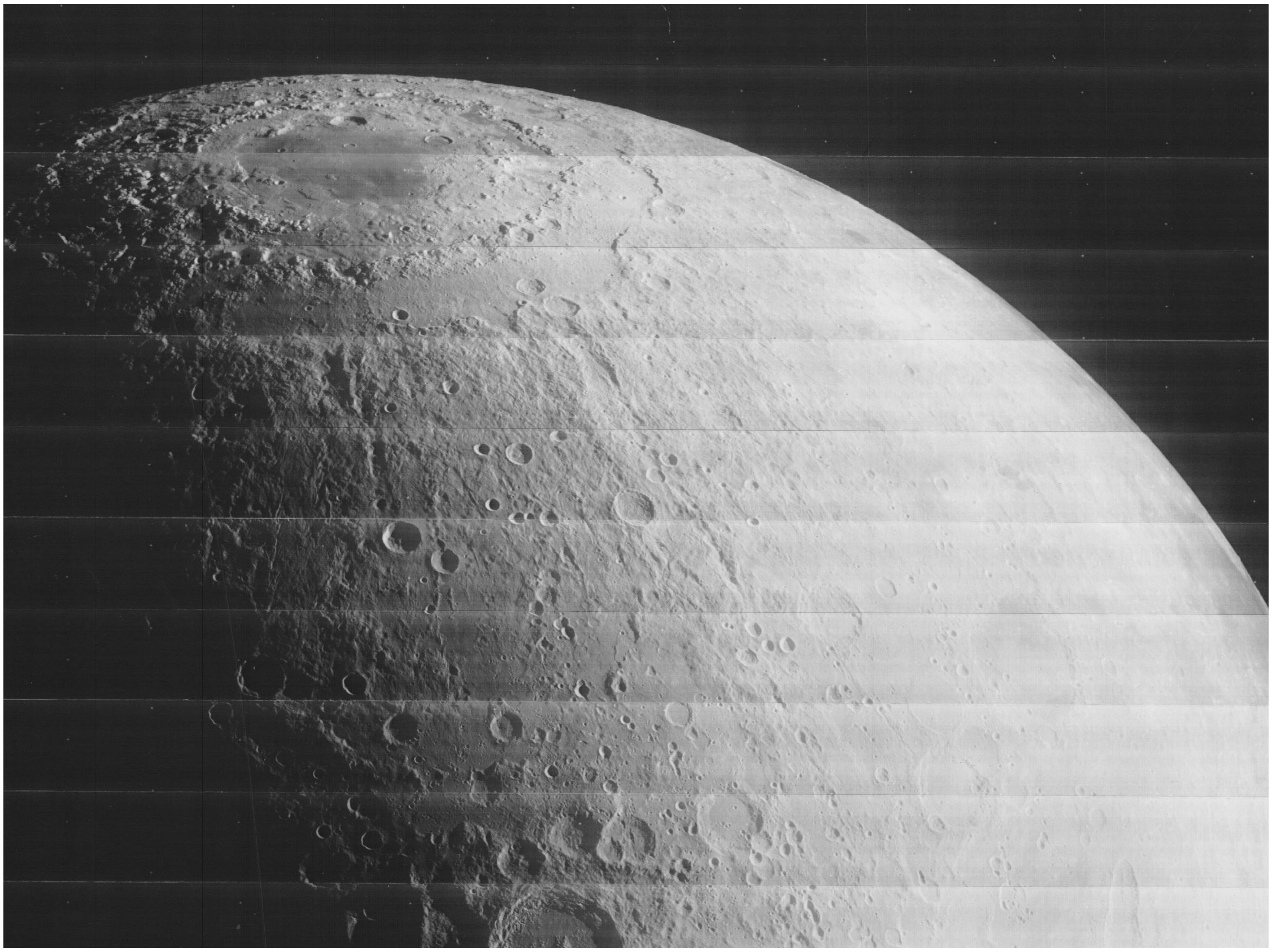

Figure 1: Lunar Orbiter photomozaic of Orientale Basin showing groved ejecta pattern (Hevelius Formation). JPL photo # LO-4-193M

Disclaimers

Introduction to Compendium

The purpose of the Lunar Sample Compendium will be to inform scientists, astronauts and the public about the various lunar samples that have been returned from the Moon. This Compendium will be organized rock by rock in the manor of a catalog, but will not be as comprehensive, nor as complete, as the various lunar sample catalogs that are available. Likewise, this Compendium will not duplicate the various excellent books and reviews on the subject of lunar samples (Cadogen 1981, Heiken *et al.* 1991, Papike *et al.* 1998, Warren 2003, Eugster 2003). However, it is thought that an *online* Compendium, such as this, will prove useful to scientists proposing to study individual lunar samples and should help provide backup information for lunar sample displays.

This Compendium will allow easy access to the scientific literature by briefly summarizing the significant findings of each rock along with the documentation of where the detailed scientific data are to be found. In general, discussion and interpretation of the results is left to the formal reviews found in the scientific literature. An advantage of this Compendium will be that it can be updated, expanded and corrected

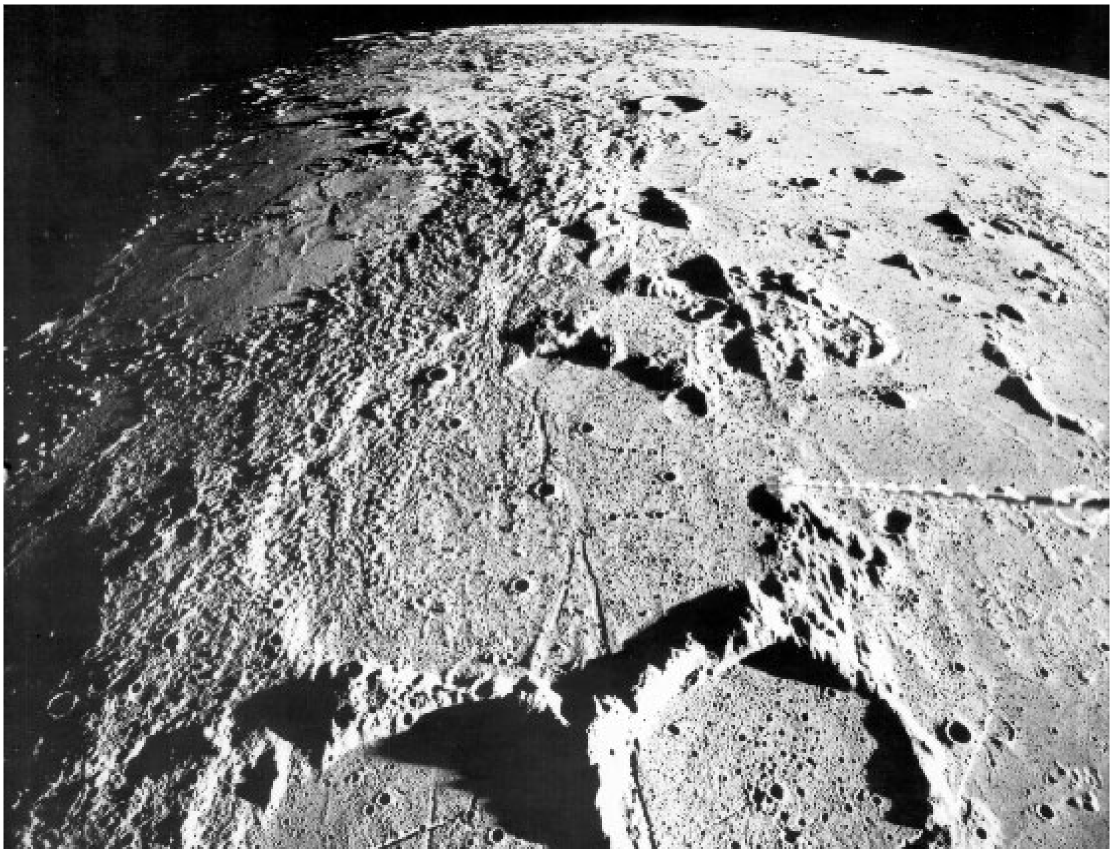

Figure 2: Picture taken at low sun angle by Apollo 16 mapping camera of the Fra Mauro Formation draping over the ancient crater Fra Mauro. NASA photo # AS-16M-1419

as need be. Please send comments, corrections, omissions, suggestions and/or reprints to the author (charles.meyer-1@nasa.gov).

An elementary introduction to the petrography of lunar samples is available online at: http://www-curator.jsc.nasa.gov/lunar/letss/contents.htm

The main lunar reference is The Lunar Sourcebook (Heiken et al. 1991) which is now "out of print". But the LPI has made it available in digital format:
http://www.lpi.usra.edu/lunar_sourcebook/

A list of catalogs and other source information for lunar samples can be found at:
http://www-curator.jsc.nasa.gov/lunar/LSCatalogs.doc

Another excellent excellent web site with a broad perspective is:
http://epsc.wustl.edu/admin/resources/moon_meteorites.html

The Apollo Program

The Apollo Program was remarkably successful. Between 1969 and 1972, twelve men walked on the surface of the Moon and carefully collected 2,196 documented samples of soils and rocks during about 80 hours of exploration. Altogether, these samples weigh 382 kilograms. Only a small portion has been consumed during analysis (as described herein). A large number are on public display. The largest portion of each sample is available for future studies.

The lunar samples were collected by the astronauts at great personal risk. Actually, twenty-four astronauts traveled to the moon and back, during nine trips (three astronauts went twice). Some missions, like Apollo 8, did not land. The explosion of the fuel cell during the Apollo 13 mission emphasized the dangers of space travel. There was also the unseen danger of radiation from potentially fatal solar flares (Reedy 1977; Rancitelli et al. 1974a). Today, watching films of the astronauts working on the lunar surface, it is hard to realize that they were working in a complete vacuum, where any tear in the space suit, or micrometeorite

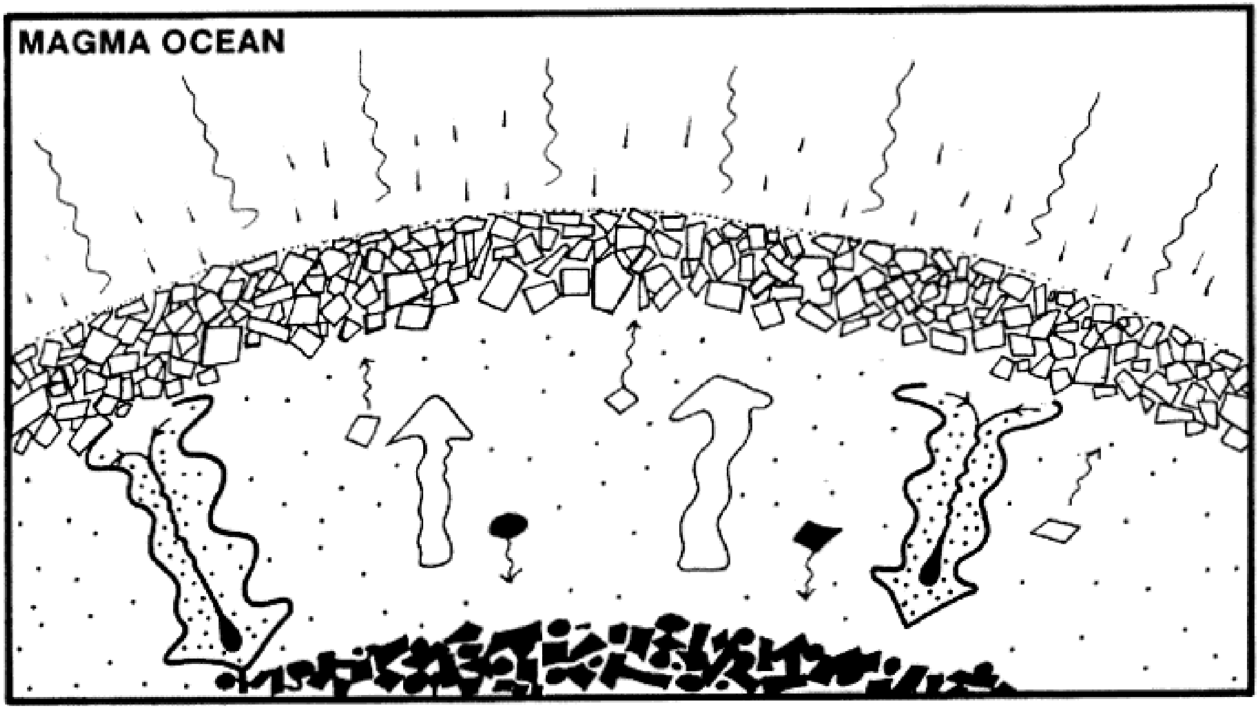

Figure 3: Schematic of supposed early magma ocean on the moon (from Walker 1983). This cartoon, illustrates plagioclase floatation as a possible mechanism leading to a thick anorthositic crust.

impact, would have been catastrophic. Some of the tasks, such as the withdrawal of the Apollo 15 core, were extremely difficult to accomplish. On the last three missions, there was the potential need for a long walk back to the Lunar Module in case the rover broke down. For geoscientists, the legacy of Apollo is a complicated task to unravel the secrets hidden in the collection of samples obtained during this extraordinary adventure.

Samples from the early missions were returned in sealed rock boxes; however, other samples were exposed to the atmosphere of the Lunar Module, the Command Module and even (briefly) the atmosphere of the equatorial Pacific Ocean. However, once the samples reached the curatorial laboratory in Houston, they were stored and processed in pure nitrogen. Originally they were quarantined to make sure there were no extraterrestrial life forms, and oriented by means of artificial lighting to match shadow patterns on the documentation photos taken by the astronauts. Indeed, no life forms, organic molecules nor water was found; so the quarantine was discontinued.

Immediately after each of the six Apollo mission, the samples were examined by an international team of investigators in what was call PET (for preliminary examination team):
http://www.curator.jsc.nasa.gov/lunar/PETScience.doc

This led to the set of initial lunar sample information catalogs. Some samples were immediately sent to the radiation counting laboratory to determine the effects of cosmic ray and solar flare exposure. As the years have gone by, this collection has been re-catalogued in various publications; but the lunar sample literature is the best source of information. Most of this literature is published, in peer-review manner, in the Proceedings of the Lunar and Planetary Science Conferences (1970-1992). However, some of this literature is spread out in various scientific journals; some of it is only published in abstracts which are getting harder and harder to access.

The Luna Program

The USSR was successful in returning lunar samples automatically and operating a large Lunakod. The Luna samples were collected as core tubes and returned by wrapping the core liners around a drum. They were also studied intensively by international efforts and it was learned that modern analytical techniques could extract a lot of information from small samples. Luna

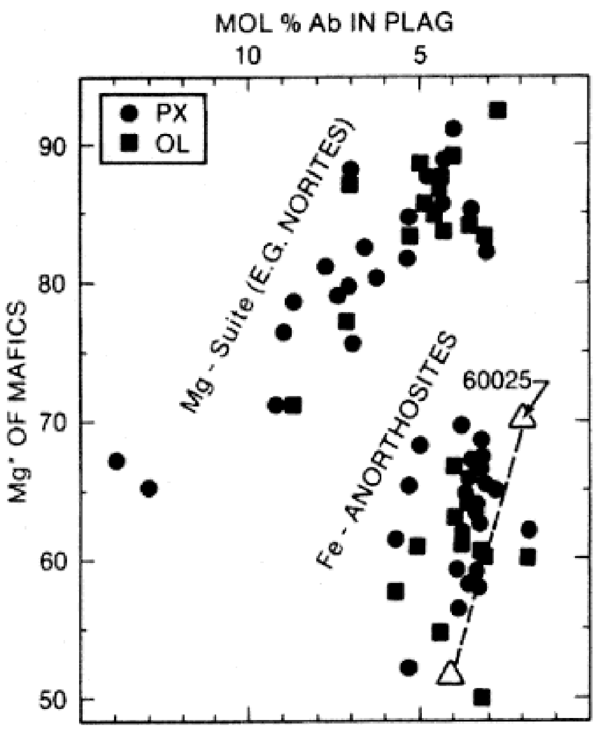

Figure 4: Chemical composition of co-existing plagioclase and mafic minerals in pristine plutonic lunar rocks (after Ryder 1982).

16 collected samples from the eastern part of Tranquility, Luna 20 from the highlands and Luna 24 from Mare Crisium (Vinogradov 1971, 1973, Barsukov 1977).

The Consortium Approach

Some lunar samples were studied in "consortium mode". The allocation committees (LSAPT, LAPST and CAPTEM) often encouraged consortium studies and the consortium reports, where they exist, are the best reference to individual sample studies. The consortium approach still remains the best way to study a sample, when it involves close cooperation of scientists with different backgrounds.

James and Blanchard (1976) state: *"Most lunar breccias are extremely complex rocks. They consist of aggregates of materials broken, melted, transported and recombined by impact processes. Each fragment has its own unique history. To understand the origin of such a rock and its constituents requires data from many disciplines and a coordinated approach to obtaining this data. Coordinated study insures that the various types of data can be correlated (a problem in such heterogeneous rocks), and that the investigators can relate their results to a general understanding of rock genesis and history. This is the rationale that underlies the "consortium" approach to studies of lunar breccias."*

Geologic History of the Moon

The best reference for the geological history of the Moon remains:
http://cps.earth.northwestern.edu/GHM/

Stöffler and Ryder (2001) reviewed the stratigraphy of lunar geologic units and summarized the age dating that has been accomplished. Nyquist et al. (2001) reviewed the ages and discussed the initial isotopic ratios. Gillis et al. (2004) provide an excellent review of recent chemical mapping of the moon.

Briefly, the grand sampling strategy for Apollo was to try to sample the interior of the moon by studying the basalt flows in the maria, and the ejecta blankets of really large basins (Imbrium, Serentitatis) at different distances. The basalt flows represent liquids derived by melting the interior of the moon; thus their composition and ages tell us about the melting and thermal history of the lunar interior. The ejecta blankets provide shocked materials of the original crust. Cratering mechanics predicts that samples from different radial distance from the basin rim will provide materials from different depths beneath the lunar surface.

Already, in 1893, Gilbert saw that distinctive textured terrain extended out from the Imbrium Basin. Just prior to Apollo, the Lunar Orbiter returned pictures of another large basin (Orientale) with distal ejecta with the same general pattern (figure 1), confirming Gilbert's interpretation for Imbrium (Head 1976a). Figure 2 illustrates this material draping over the ancient crater Fra Mauro; hence the name Fra Mauro Formation. This, then, was the target for Apollo 14 where numerous breccia sample were found. The location of Apollo 15 was intended to sample the Apennine Front near the inner rim of the Imbrium Basin, where deeper material should be found. Apollo 17 was from the edge of the Serenitatis Formation and Apollo 16 from the Central Highlands. Indeed, a number of samples of plutonic rocks were found in these locations, and they have been related to an anorthositic crust of the moon (prior to basin formation). From a study of these plutonic samples, it is now thought that the original crust of the moon may have formed by plagioclase floatation from an early magma ocean (figure 3).

Detailed study of fragments of pristine lunar samples from the non-mare regions, shows that the belong to

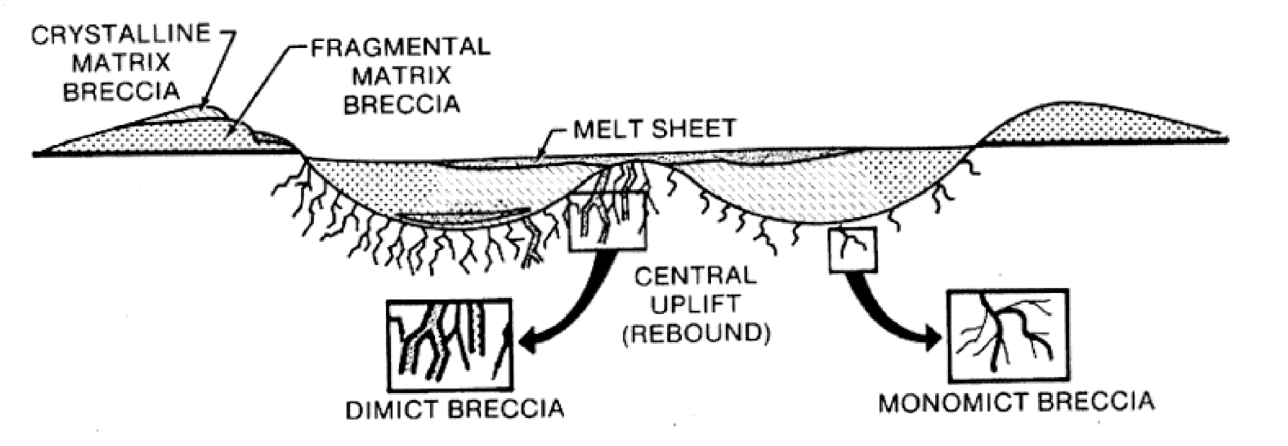

Figure 5: Geologic setting of impact breccias in a hypothetical giant lunar crater (a la Stoffler). The shock wave granulates the underlying, preexisting bedrock producing monomict breccias with glass veins. Dimict breccias form if the veins are filled with impact melt. Fragmental breccia occurs beyond the crater rim. Crystalline matrix breccia forms if the crater is large enough and the hot fallback debris

two general trends (figure 4). The ferroan anorthosites (e.g. 60025) have very calcic plagioclase and various Fe-contents for the mafic minerals. The mg-suite contains troctolite (e.g 76535), norite (78235) and trends towards Na-rich plagioclase with Fe-rich mafic minerals (see for example, clasts in 15405).

Lunar Mineralogy

The mineralogy of lunar samples is rather simple, with only a few major minerals (plagioclase, pyroxene, olivine and ilmenite). The rocks formed in a completely dry and very reducing environment, such that the iron is mostly in a plus two oxidation state with minor metallic iron. Grain boundaries between minerals are remarkably distinct, with no alteration products. Glass is present in the mesostasis. Minerals that might have been added by meteorite bombardment have generally been vaporized.

There are a few unique features in lunar rocks; plagioclase is almost pure anorthite, maskelynite is common, rare ternary feldspar (Na, K and Ca) is found. Pyroxene has a wide range of composition, somewhat characteristic of each rock type. New minerals include armalcolite, tranquillite, pyroxferroite, and yttrobetafite. Akaganeite (FeOOH) was found on one Apollo 16 breccia. ZnS coatings were found on volcanic glass beads.

The surface of lunar rock that were exposed to space have a thin brown patina of glass splashes and glass-lined micrometeorite craters (zap pits). Solar flare tracks are abundant beneath these surfaces. Depth profiles of cosmic ray induced radio-nuclides extend to depths of 10 cm.

Rock Types

The landing sites for Apollo missions were limited to mildly-cratered, flat spots, which generally turned out to be lava flows. The basalts from these lava flows were sampled in abundance. Although fresh in appearance, they measured to be quite old – 3.2 to 3.9 b.y. There are 134 samples of basalt greater than 40 grams, 42 greater than 500 grams, 24 greater than one kilogram, 11 greater than two kilograms and the largest 9.6 kilograms (15555). They have textures of a crystallized liquid – ranging from variolitic to subophitic to equilgranular. Most are fine-grained with an average about 0.5 mm, but some have phenocrysts over one cm.

Most of the lunar basalts are Fe-rich, often Ti-rich, and have abundant opaque minerals. Some are very vesicular, with interconnecting vugs and vesicles (15016). A few lunar basalts are greatly enriched in rare-earth-elements (14310, 15382, 15386). 70215 is the largest mare basalt (8100 grams) and, perhaps, one of the best studied. All true basalts were found to have low siderophile (Ni, Ir and Au) content.

The majority of rocks on the lunar surface are breccias. Most lunar breccias are the lithified aggregates of clastic debris and melt generated by meteorite bombardment in the ancient lunar highlands (3.9 b.y. ago). There are 59 lunar breccias larger than 500 grams, 39 greater than one kilogram and 19 greater than two

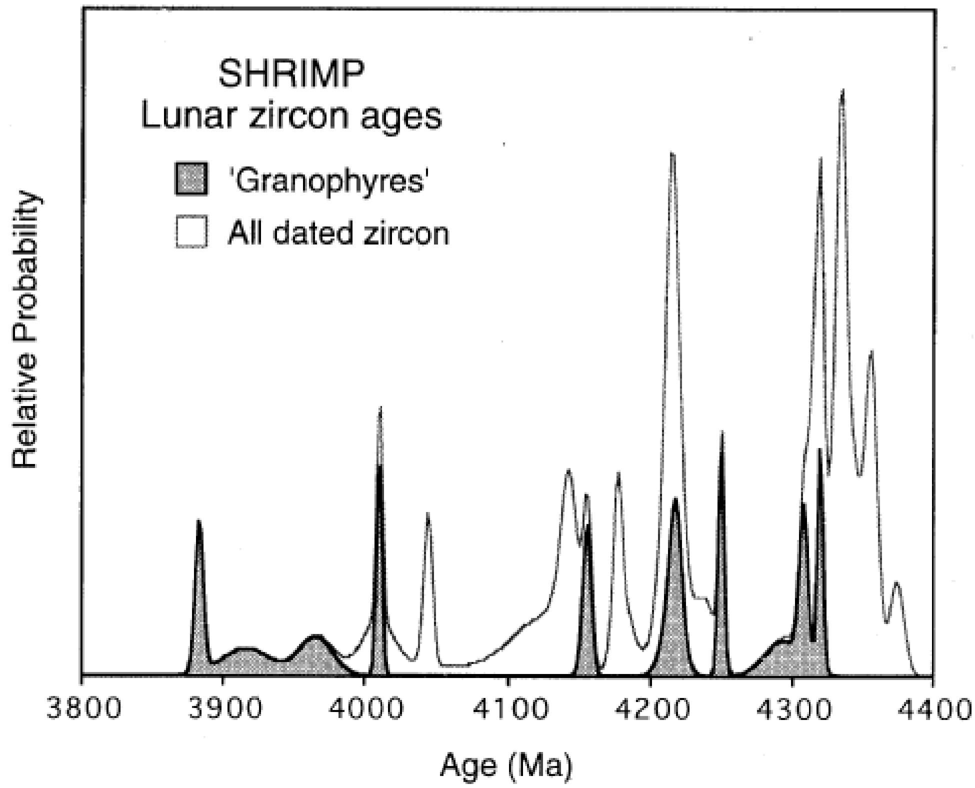

Figure 6: Summary of all lunar zircon ages determined by the SHRIMP I ion microprobe method (Meyer et al. 1996). This relative probalility curve was generated by summing the gausian curves representing each age determination and its analytical uncertainty. Zircons from K-rich lunar rocks are highlighted. The oldest zircon age measured was 4375 +/- 5 m.y. Refractory zircons and some lunar samples have survived the cataclysmic basin-forming events at 3.9-4.0 b.y.

kilograms. Many of the breccia samples are ejecta from the giant basin-forming events. Others are interpreted as melt sheets from the fallback of hot ejecta into the large lunar basins (figure 5). Some have a fragmental matrix made up individual mineral fragments, while others have a crystalline matrix from slow cooling of initially molten matrix. A few lunar breccias are soil breccias containing glass beads and a component of solar wind. Most breccia samples are polymict, containing a wide variety of clasts, which are themselves breccias of an earlier generation. Key to the understanding of soils and breccias are measurement of otherwise trace element gold and iridium (which indicate the amount of admixed meteoritic material). Breccia clasts with low levels of gold or iridium are termed "pristine", meaning they haven't been contaminated by meteoritic materials and must be remnant pieces of the original lunar crust. Using trace siderophile and volatile element signatures, some scientists have even assigned breccias to specific lunar craters! (see Moon as a Target below)

An early discovery of lunar samples was that the lunar highlands must contain an abundance of plagioclase-rich material – termed ANT (for anorthositic, noritic and troctolitic). Scientist have found two major trends in these anothositic materials – some have a high Fe/Mg ratio and are termed ferroan anorthosites (15415, 60025), and the others are generally termed mg-gabbro norites, trending to alkali norites. These materials are generally quite old, and probably represent the original crust of the moon, presumably formed after differentiation of an original, global magma ocean. One sample of dunite was returned (74215). Late-stage differentiation of the magma ocean presumably led to the rocks such as the quartz-mozodiorite in 15405, the sodic-ferrogabbro in 14306 and the "granite" in 14303, 72275 etc. However, zircons from these rocks indicate continuous magma activity from 4.4 to 3.9 b.y. (figure 6).

Glass

Glass is an important component in lunar samples, and has been studied extensively by many investigators. Glass occurs as mesostasis in basalts, as melt inclusions

Figure 7: Meter-size craters in the lunar regolith are capable of producing soil brecias like 15299. Fresh craters 10 m and larger are required to dig up hand specimens from the bedrock. NASA # AS12-47-6939.

in minerals, as beads from volcanic eruptions, as agglutinates formed by meteorite bombardment of gas-rich soil and as splash on rock surfaces. Agglutinates are an odd characteristic of lunar soils and a measure of its maturity. They are fragment-laden-vesicular glass that is formed by meteorite bombardment and melting of solar-wind-enriched lunar soil. During agglutinate formation, solar-wind implanted hydrogen reacts with silicate glass, forming minute iron grains with strong magnetic properties (Housley et al. 1975). In addition, about 20 groups of clear glass beads prove to be of volcanic origin (Delano 1986). Two deposits of this material (orange glass in 74220 and green glass in 15425) have been studied extensively. Glass is also found in abundance splashed on the surface of rocks that were returned and even as glass objects (64455). Some of this glass may be from South Ray Crater. Some investigators have measured the compositions of thousands of glass fragments in the soil in the hope of discerning 'rock types'. Ropy glass fragments, found in the soil at Apollo 12, were related to the crater Copernicus (Meyer et al. 1973).

The Regolith

As the moon is an airless planet, meteorites hit the surface at full force, creating craters large and small, fragmenting the lunar surface and forming what is known as the lunar regolith (figure 7). The bulk of the regolith is a fine gray soil with a density of about 1.5 g/cm^3, but the regolith also includes breccia and rock fragments from the local bedrock. About half the weight of a lunar soil is less than 60 to 80 microns in size. Calcalong Creek is a meteorite from the moon that nicely illustrates what the lunar regolith looks like (figure 8). Samples 15295-15299 are closely comparable.

Regolith samples included many soil samples, several drive tubes and three deep drill cores. It should be noted that the Russians automatically returned three short cores form three additional places on the moon.

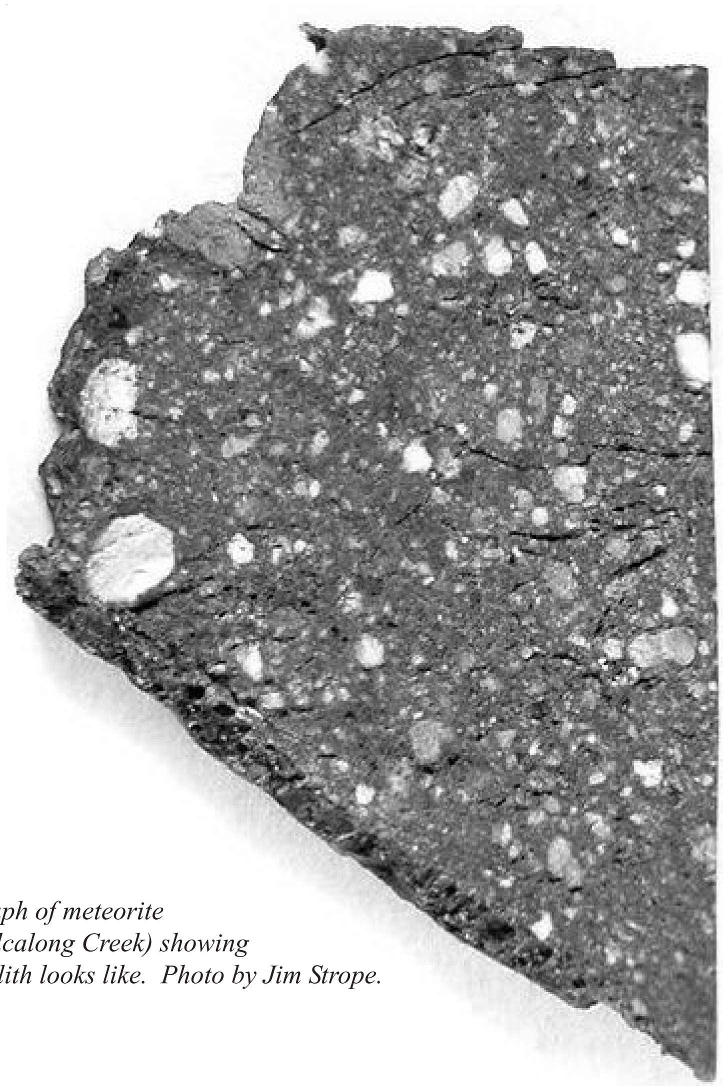

Figure 8: Photograph of meteorite from the moon (Calcalong Creek) showing what the lunar regolith looks like. Photo by Jim Strope.

Section on these samples will be added to this Compendium in the future. Meteorites from the moon will be treated separately.

The Moon as a Beam Stop

The Moon is an airless body that acts as a "beam stop" for high energy cosmic rays and solar flares which penetrate the surface materials causing nuclear reactions (Lal 1972). Cosmic rays and solar flares are primarily (>90%) high energy protons (Reedy 1987). The high-energy (~1 GeV) galactic-cosmic-ray particles produce a cascade of secondary particles, especially neutrons, that penetrate meters into rocks and soils. The relatively low-energy (~10 to 100 MeV) particles emitted from the sun (solar cosmic rays) are rapidly stopped in rock within a few cm. A few percent of cosmic rays are heavy ions (e.g. Fe) that cause radiation damage in minerals along their final track.

The neutron flux resulting from this comic ray interaction with the lunar surface produces measurable variation in the isotopic composition of elements that have large cross sections for neutrons (Gd, Mn etc.). Some isotopes are themselves radioactive and decay with time (e.g. ^{14}C, ^{26}Al, etc.) Lunar samples whose orientation was known from lunar photographs and matched with photographs in the laboratory have been carefully sawn to provide samples at different depths for these isotopic studies. These studies have, in turn, provided data for the models of the cosmic ray energy and flux over time.

Perhaps the most useful information obtained from a study of the cosmic ray produced nuclides is the measure they give of the length of exposure time at or near the lunar surface. When several samples from the rim of a young crater give similar exposure ages, we think we have learned the age of the crater! Reviews by Arvidson (1975), Eugster (2003) and others, summarize these studies.

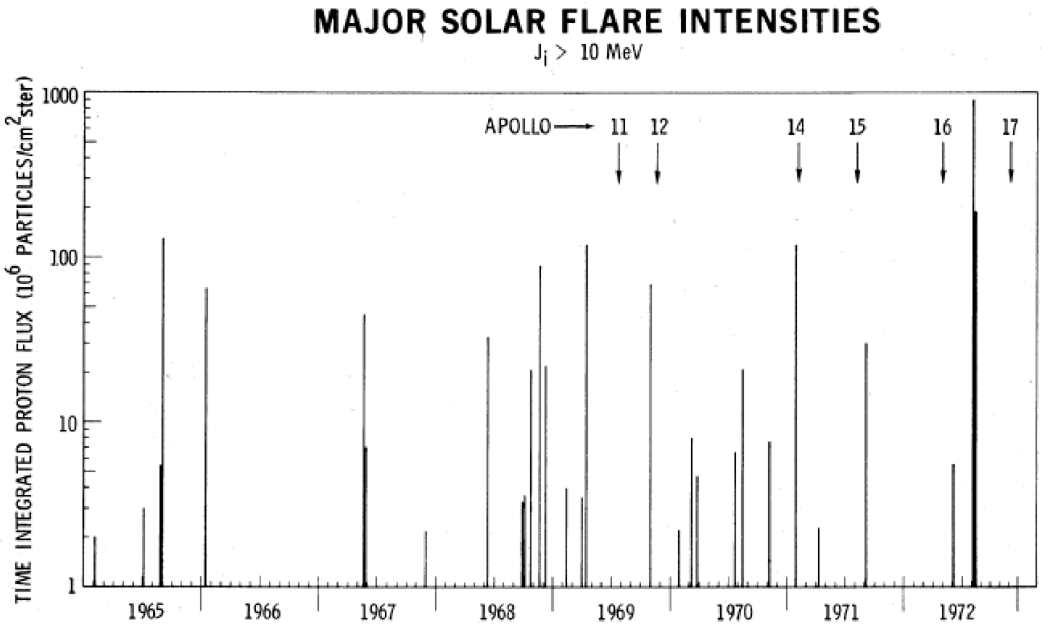

Figure 9: Major solar flare intensities and Apollo missions from (from Rancitelle et al. 1974).

In August 1972, between Apollo 16 and Apollo 17, a very intense solar flare induced high radioactivity in the surfaces of lunar sample (Keith et al. 1974a; Rancitelli et al. 1974a). Figure 9 shows the solar flare activity that occurred during the time frame of the Apollo missions.

Thus, it has proven important for these studies, to have knowledge of the lunar orientation of samples (Sutton 1981; Wolfe et al. 1981), and for exact depths of subsamples taken from within the rocks to obtain the depth profile of the radiation effects (61016, etc).

The Moon as a Target

Lunar basalts and samples least affected by meteorite bombardment are found to have very low contents of siderophile elements (generally Ni, Ir, Au, Re, Os) indicating that these elements were initially generally lacking (< 0.1 ppb). Lunar rocks with low siderophile element contents have come to be called pristine (Warren and Wasson 1977). However, lunar soils, breccias and impact melt rocks are found to have relatively high (~10 ppb), and specific contents of these elements, which are generally considered to have been added by the meteorite impacts (figure 10). Indeed, it was found that breccias and impact melts for each of the large basins had characteristic ratios of these meteoritic siderophiles (Morgan et al. 1974, 1977).

The Lunar Cataclysm

Many of the impact melt rocks returned from the highlands of the Moon dated at about 3.9 b.y. This led to the hypothesis that there was a period of late bombardment of the Moon by large objects that were stored somewhere in the Solar System for 500 m.y., before colliding with the Moon (and the Earth) in a short period of time around 3.9 b.y. ago (Tera et al. 1974a; Ryder 1990). Most of the collection of rocks from the Apollo missions come from the areas around the big basins Imbrium, Serenitatis and Nectaris, but samples from the Luna missions around Crisium, and among the meteorite collections, also seem to have an abundance of ages grouped tightly around 3.9 b.y. (Cohen 2001). This event may have also have influenced the Earth, because few terrestrial materials (if any) are older that 3.9 b.y.

Nevertheless, several zircons and some few rock clasts have been dated to be older than this terminal cataclysm (e.g. Meyer et al. 1996; Norman et al. 2003).

Lunar Nomenclature

Admittedly confusing; such as it is. However, see Stöffler et al. (1980) and Le Bas (2001). In this

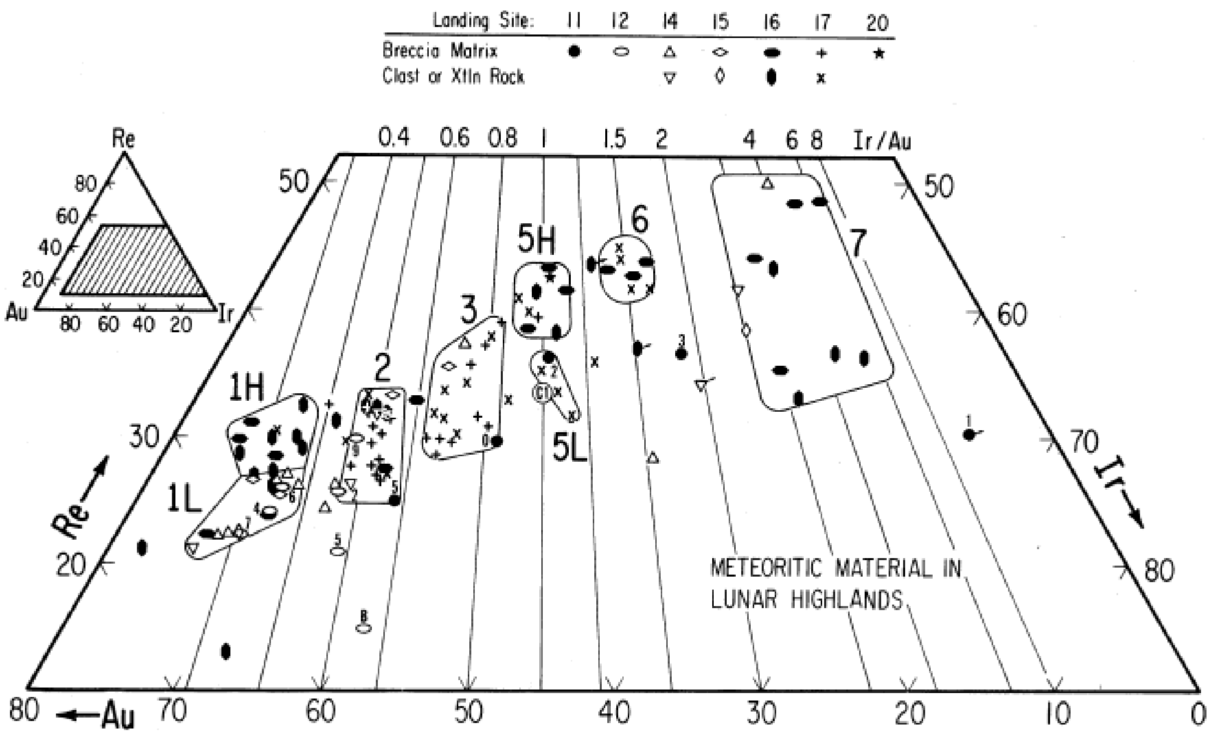

Figure 10: Truncated, ternary, chemical diagram for trace meteoritic siderophiles Ir, Re and Au content of feldspathic highland rocks (from Janssens et al. 1978). It is thought that these groupings represent the chemical composition of individual basin-producing impactors.

Compendium, rocks are simply referred to as they have been in the literature, until such time that some brave sole renames each of these rocks, and/or a consensus is reached on how to name them. Impact processes have greatly influenced lunar rocks samples such that terms like breccia, impact melt rock, agglutinate, regolith, etc. are important.

Lunar Controversies

On first reading of the vast literature one might get the impression that everything has already been done – sometimes multiple times. But nothing could be further from the truth. Many rocks remain poorly described. Analyses were generally performed on sample too small (often only 10 mg) to be representative of the whole. Ages were not concordant. Magnetic data could not be reproduced from lab to lab. Etc.

Some controversies that are still being argued include:

1) Were rocks the result of the Lunar Magma Ocean or due to Serial Magmatism?
2) Do the high Th breccias from Apollo 17 come from Serenitatus or Imbrium? – see figure 11.
3) Do lunar magmas arrive at the lunar surface without crustal assimilation?

What did we learn?

Important findings from the Lunar Sample Program are listed at:
http://www-curator.jsc.nasa.gov/lunar/lunar10.htm

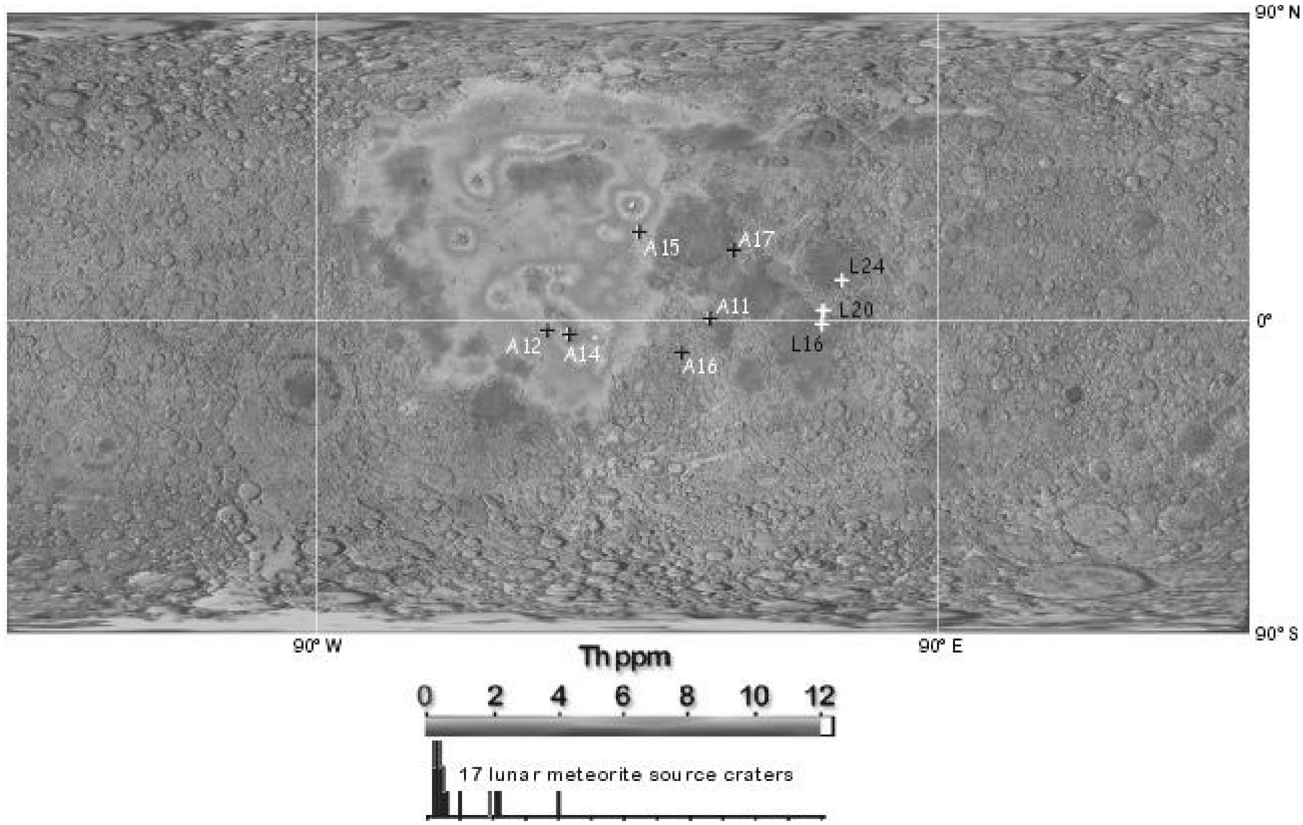

Figure 11: Th map of the Moon obtained by Lunar Prospector showing high Th in region of Imbrium basin (but not Serenitatis). Note that the low Th in most lunar meteorites indicates that they came from the regions not sampled by the Apollo missions.

In addition, we think that we have learned that:

1) Ir was a great indicator for meteoritic bombardment, leading to its use on Earth (i.e. discovery that K/T boundary was due to a giant meteorite impact).
2) There may be general chemical similarity of the Earth's mantle and the moon (Ringwood, Wänke, Clayton).
3) That meteorites may have added a late component to the Earth's mantle - after core formation (Morgan, Brandon).
4) Basaltic volcanism is common on all the terrestrial planets (BVSP 1981).
5) There are a large number of craters on the Earth.
6) Tektites do not come from the moon, but from terrestrial craters.
7) That some meteorites come from the Moon and also Mars!

If you can articulate a lunar controversy or think of other lessons learned about the Earth, by the study of the lunar samples, please forward them the charles.meyer-1@nasa.gov. Be assured that Lunar Science is just starting, and that we don't know as much as we think. After all, the Moon is the size of a planet, and we have only partially investigated a portion of it.

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
T.S.Eliot
