The Lunar Petrographic

Educational

Thin Section Set

Charles Meyer

Astromaterials Curation
NASA Lyndon B. Johnson Space Center
Houston, Texas 77058

September 2003

Foreword

Precautions

In addition to the security precautions that must be followed, there are several precautions relating to the use of this set of thin sections. Please be careful not to scratch or break the sections. The thin sections in this set are uncovered and highly polished so that the opaque minerals may be studied by reflected light microscopy. A good-quality research microscope with dry, high-power objectives is required. Do not use oil. These samples were prepared without the use of water. Do not clean or repolish. The sections are not all of a standard thickness (i.e. 30 microns), so beware of false interference colors.

Objective Petrography

Petrography students are expected to write their own descriptions of these thin sections of lunar rock. In general, petrographic descriptions should be strictly objective, leaving all discussion of petrogenesis to the end. However, the petrographic descriptions in this booklet are based on those given in scientific literature and do not necessarily serve as good examples of strict objectivity. Such is the nature of lunar science! In preparing this student booklet, it was important to convey some of the excitement inherent in lunar sample science; thus, some discussion of sample origin has unavoidably crept in. But, remember, it is important to describe nature, before trying to explain it!

Disclaimer

Some important lunar science topics are not discussed in this booklet because they are not illustrated by the samples included in the provided sets. Moreover, many of the most important lunar rocks could not be used to make these sets of educational thin sections. However, the Apollo astronauts did collect several samples that were large enough for both scientific investigation and educational activity. From these, NASA has prepared 20 sets of thin sections (12 each) for use in petrology classes and an additional 201 encapsulated lunar disks (6 samples each) for use in secondary schools. The supplied samples necessarily differ slightly for each set; thus the general descriptions given in this booklet are only a guide to your own observations. For example, although it is not mentioned, you may find a big metal grain in your section. Furthermore, the photographs in this booklet may not be exactly like the thin section contained in your set.

A little background

The information posted at this web site (or CD) is an update of a booklet composed by Chuck Meyer in 1987 to accompany microscope thin sections made of a carefully selected subset of lunar rocks. This site is not a comprehensive, or even an introductory, treatise on lunar science. It provides only enough information to provide some context for the study of the thin sections that the NASA curator loans to upper division petrography classes. It needs to be supplemented by educational materials of the instructors's choosing. NASA has been providing these sets of petrographic thin sections to colleges and universities for over thirty years. Hopefully the students that get to study these precious samples already have vast experience using advanced microscopes to study polished thin sections of a variety of terrestrial samples. And, hopefully, they will closely follow the Precautions above.

Lunar Sample Science Today

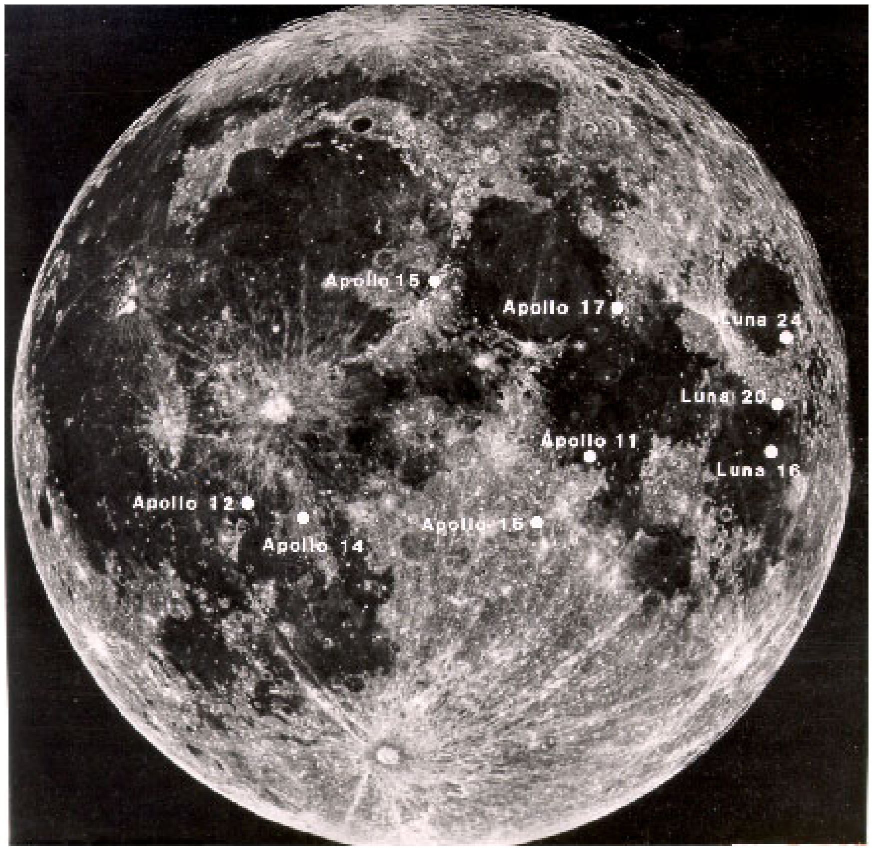

Figure 1. The Moon is divided into two basic physiographic regions: smooth maria and cratered highlands. The smooth maria fill the large circular basins and spill out onto low lying regions. They were sampled by Apollo 11, 12, 15 and 17 and Luna 16 and 24. The ejecta balnkets of the large basins were sampled by Apollo 14, 15 and 17. The heavily cratered highlands were sampled by Apollo 16 and Luna 20. Note the great distances covered by rays from fresh craters. NASA photo no. 84-31673 (Lick Observatory)

The scientific rationale for lunar exploration is to establish the Moon's composition, internal structure, and history (or evolution). Before man walked on the Moon, scientists thought that the Moon was a relatively primitive (simple) object that would record the earliest history of the Solar System. Scientists also hoped that the lunar surface would contain a record of the Sun's history and of cosmic radiation, and they wanted to know if life had ever existed beyond that on Earth.

More than 50 U.S. and U.S.S.R. spacecraft have flown near or landed on the Moon. A total of 24 U.S. astronauts have observed the Moon in close proximity (3 astronauts went twice!) and 12 U.S. astronauts have walked on the lunar surface (including one geologist!). During 80 hours of surface activities, the astronauts carefully collected 382 kg of lunar samples (table 1).

In addition to the samples gathered from the six Apollo (U.S.) sites, we also have samples collected from the three Luna (U.S.S.R.) missions. Many exotic samples in the Apollo collection come from rays that extend as much as halfway around the Moon (fig. 1). Recently, numerous meteorites found in Antarctica and the Sahara desert have been shown to have originated on the Moon (Korotev 2003).

The scientific objectives and results of each Apollo mission are summarized in table II. From these missions, we learned that the Moon is not the simple, primitive object we once thought it to be, but, rather, a satellite that has been melted and differentiated twice in its history. The first melting occurred shortly after formation and apparently resulted in a Moon-wide magma ocean that cooled to form a thick crust of

Table I. – Lunar Sample Inventory

20 petrographic thin section sets (12 each)
199 lunar educational disks (6 each)
65 permanent and 15 traveling displays (~150 grams each)
3 "touchstones"

By Mission	Weight	Number	EVA length	Distance
Apollo 11	21.5 kg	58	2.2 hr	0.5 km
Apollo 12	34.4	69	7.6	2.0
Apollo 13	aborted			
Apollo 14	42.3	227	9.2	3.4
Apollo 15	77.3	370	18.3	23.0
Apollo 16	95.7	731	20.1	20.7
Apollo 17	110.5	741	22.0	31.6
Total Apollo	382 kg	2196	89 hr	81 kg
Luna 16	0.101 kg	35 cm*		
Luna 20	0.050	27		
Luna 24	0.170	160		

Lunar Meteorites

Dhofar025	0.751 kg	ALH81005	0.031 kg
Dhofar081	0.4	Y791197	0.052
Dhofar026	0.4	Y983885	0.29
Dhofar302	0.2	Calcalong	0.019
Dhofar733	0.1	QUE94281	0.023
Dhofar489	0.035	SaU169	0.206
NWA482	1.015	Y793274	0.195
DaG400	1.425	EETA87521	0.084
DaG262	0.513	Y793169	0.006
DaG996	0.012	Asuka881757	0.442
MAC88104	0.724	NWA032	0.456
Y82192	0.712	Dhofar287	0.154
QUE93069	0.025	NWA773	0.633
YA1153		LAP02205	1.226
PCA02007	0.022		

By Type	weight	number
Soils	80 kg	167
Breccias	133	79 over 300 g each
Basalts	80	134 over 40 g each
Cores**	20	24 holes
Other	69	mostly small breccias
Meteorites	~10	29***

* The Luna samples were collected as small cores.
** Total length of Apollo cores is 15 meters (52 segments)
*** Number of lunar meteorites is increasing

Table II. – Summary of Findings from Apollo Missions

Apollo 11 Mare Tranquillitatis

Objective: sample relatively old mare surface

Results: Basalts high in Fe, Ti, approximately 3.7 BY

Conclusions: - water not important
- Maria are very old
- Maria are volcanic

Apollo 12 Oceanus Procellarum

Objective: sample relatively young mare; possible ray from Copernicus

Results: Basalts approximately 3.15 to 3.35 BY

Conclusions: - "Young" maria are very old!
- Copernicus may have formed approximately 0.9 BY ago
- Granite exists on the Moon!

Samples: 12002, 12005

Apollo 14 Fra Mauro

Objective: sample Imbrium ejecta, possibly deep material

Results: Variety of breccias, approximately 3.9 to 4.0 BY.
No deep material.

Conclusions: - Region is ejecta blanket of Imbrium basin
- Imbrium basin formed approximately 3.9 to 4.0 BY ago
- Trace-element-enriched rocks very abundant

Sample: 14305

Apollo 15 Hadley/Apennine

Objectives: sample mountainous rings of Imbrium basin, Hadley Rille and Imbrium Mare

Results: Mare basalts, approximately 3.2 BY; breccias, approximately 3.9 to 4.1 BY.

Conclusions: - Imbrium mare not produced by impact (took 600 MY to fill)
- Rille realated to collapsed lava tube
- Highlands complex in composition

Sample: 15299

Apollo 16 Descartes

Objectives: sample highland plains

Results: Impact breccias approximately 3.8 to 4.2 BY

Conclusions: - Most flat highland areas formed by pooled impact ejecta; probably related to major multi-ringed basins
- Highlands are anorthositic

Samples: 60025, 65015

Apollo 17 Taurus-Littrow

Objectives: sample massifs from older basin (Serenitatis), flat valley plains between mountains and dark mantling (young volcanics?)

Results: Variety of breccias, approximately 4.0 BY; basalts (like Apollo 11), approximately 3.7 BY; volcanic glass approximately 3.5 BY

Conclusions: - Very young volcanism not evident
- Variety of breccias may represent older events
- No anorthosites!

Samples: 70017, 78235, 74220, 72275

anorthositic material. While cooling to form a solid body, parts of the interior melted again to form lava flows on the front side. The heat for the first melting comes from the terminal accretion; the heat for the second melting comes from the radioactive decay of K, U and Th in the interior. Much of this heat is brought to the surface with the extruded magma. Carefully refined computer models are now available with which to illustrate the thermal evolution of many planetary bodies, including that of the Earth.

From our study of lunar and meteorite samples, we have learned that different planets and moons have different chemical and isotopic signatures. For example, meteorites can be distinguished from samples of the Earth and the Moon by their high Ir and Au contents. Similarly, lunar samples can be distinguished from Earth samples by identifying their low Mn/Fe and K/U ratios. Small extraterrestrial samples have high He and D (^{2}H) contents. Martian samples have high $^{15}N/^{14}N$ ratios such as were found by the Viking missions to Mars. Using such signatures, scientists have shown that several meteorites found on the ice in Antarctica are actually lunar samples (Bogard 1983). A clay layer found at the Cretaceous-Tertiary boundary has been identified as having an extraterrestrial cause. Tektites, once thought to have come from the Moon, have proven to be of terrestrial origin. Can chemical signatures like these be used to tell whether we have samples of other planets in meteorite collections?

We have discovered the bombardment history of the Moon by careful radiometric age dating of lunar samples (fig. 2). A surprising result was that most of the samples from the lunar highlands gave the same age; *i.e.*, 3900 to 4000 million years (Ryder 1990; Cohen 2001). This indicates that the Moon (and perhaps other planets as well) was subjected to an intensive period of bombardment late in its evolutionary history. The lack of intense cratering on the mare surface, which has been dated to as great an age as 3800 million years, means that this intense bombardment ended suddenly (a cataclysm). However, there appears to be no record of this cataclysmic bombardment in meteorites. Can we deduce from this the age of heavily cratered terrain either on Mars or Mercury?

A search for the oldest lunar rock is still ongoing but the identification of the most ancient sample has remained elusive (*see* Table V in the section of Plutonic Rocks). Perhaps it is the anorthosite sample 60025 included in this set. This research has continued for 30

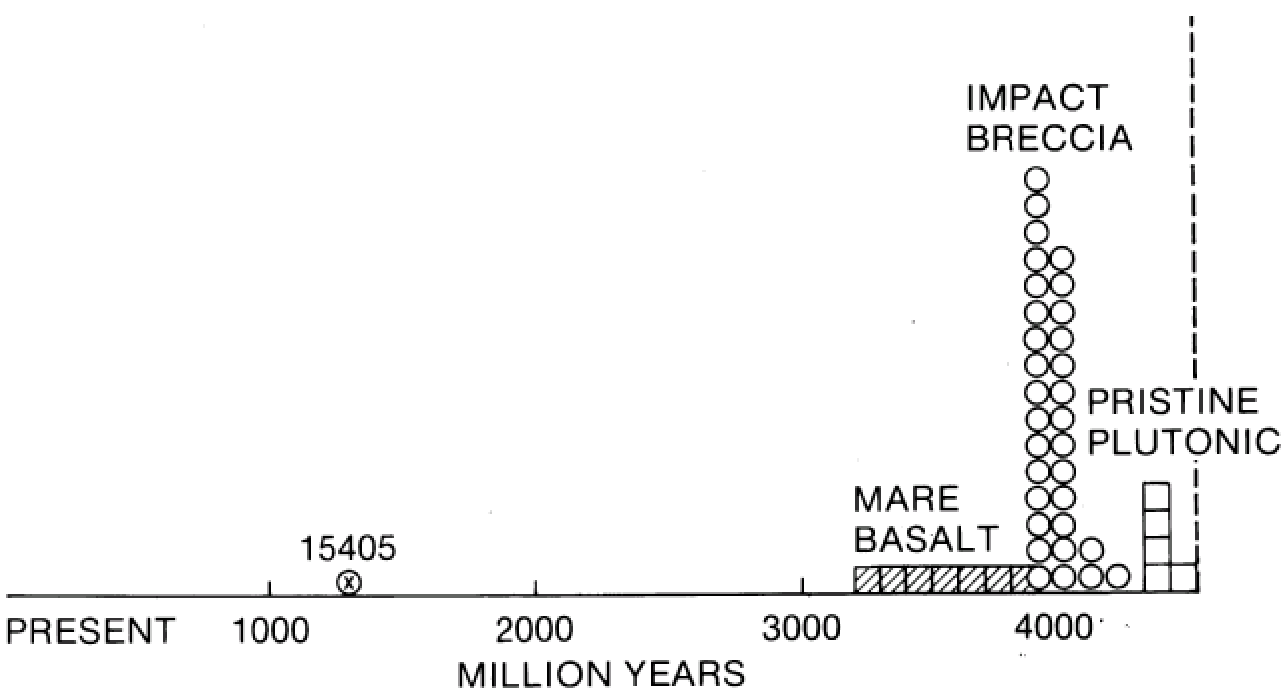

Figure 2. Cartoon. Impact breccias from the rims of large basins and the lunar highlands, all dated 3900-4000 million years. This has been termed the lunar cataclysm. Clasts of pristine lunar plutonic rocks are older. Mare basalts have ages spanning 3200-3900 million years. A few breccias are younger (e.g. sample 15405).

years after the last Apollo mission, because new instrumental techniques and revised procedures have had to be developed in order to date the oldest lunar rocks.

New laboratory techniques include Sm/Nd and Lu/Hf age dating, U/Th/Pb ion microprobe age dating, $^{39}Ar/^{40}Ar$ plateau age-dating, ferromagnetic resonance analysis (Is/FeO), and low-level neutron activation analysis for Au, Ir, and REE. These improvements have also directly benefited the study of terrestrial samples and several, well-equipped geochemical laboratories await additional extraterrestrial samples from other planetary bodies. Scientific studies of lunar samples currently in progress include; trace element partitioning between mineral phases and melt, initial isotopic ratios of lunar reservoirs as a function of time, analysis of volcanic glasses, dating of zircons and granite clasts, and modeling of Zr/Hf fractionation.

If we are clever enough to unravel the multiple processes which occur on the lunar surface, lunar samples might also reveal the history of the Sun and cosmic irradiation over hundreds of millions of years. This is because the lunar surface is directly exposed to micrometeorites, solar wind and cosmic radiation. A general conclusion which might be drawn from the study of solar-wind-implanted ions and tracks in soil grains is that the ancient Sun greatly resembled the modern Sun. The ratios of rare gases, hydrogen (H), and Fe in the Sun have remained almost constant.

Speculation and even some theory concerning the Moon's origin is discussed in Hartmann *et al.* 1986 and Canup and Righter 2000. Briefly, it is now thought that the Moon was formed from debris left over after a large impact occurred on the Earth. This theory is mainly supported by the fact that lunar samples are found to have the same trend of oxygen isotopes as terrestrial samples.

About 50 meteorite fragments are now recognized as having a lunar origin (surprisingly none before 1982). Some of these are paired with one another such that there are about 29 different lunar meteorites (listed in Table I). They represent a great addition to the Apollo and Luna collections, because they provide a more statistically representative sampling of the lunar surface (Korotev 2003). One wonders whether these would have been recognized as having a lunar origin, if we did not have the Apollo and Lunar collections with which to compare!

Remote sensing of the lunar surface has continued with Earth-based telescopes, Galileo flyby (Belton *et al.* 1992), Clementine (*see* Science 266, 1994) and Lunar Prospector (Lawrence *et al.* 1998). These missions have discovered water in the regolith at the poles, confirmed the Th-rich region around Procellarum , mapped the Fe and Ti over the whole lunar surface and provided context with which to understand the rocks.

Lunar sample science is documented most fully in the Lunar Sourcebook (Heiken *et al.* 1991) and Lunar Samples (Papike *et al.* 1998). The books by Ross Taylor (1975, 1982) and Peter Cadogen (1981) provide great summaries of what was learned during Apollo. The web sites provided by Eric Jones and Kevin Clarke are highly recommended if one wants to revisit the excitement that was Apollo. Essays on various topics by Jeff Taylor are always worth reading and might be the best way for the student to get started (*see* References and some Links).

Lunar Sample Mineralogy

Lunar sample mineralogy is relatively simple with only the following major minerals: plagioclase, pyroxene, olivine and ilmenite (Smith and Steele 1976; Papike *et al.* 1998). This simple mineralogy of lunar samples results because lunar rocks were formed in a completely dry and very reducing environment with no hydrous minerals. Grain boundaries between minerals on the Moon are remarkably distinct with no alteration products. Residual melt, in the form of glass, is present in the mesostasis of igneous rocks. Metallic iron grains are found in many rocks. Troilite is the only sulfide. Minerals, which might have been added by meteorites, have all been melted or vaporized by impact.

Table III lists most of the minerals reported in lunar samples. Very little Na is found in lunar rocks; thus, most lunar plagioclase is almost pure anorthite. Maskelynite (shocked plagioclase) is common. Some feldspars with ternary (Ca, Na, K) composition were found in rare lunar felsite clasts. Two phosphates were found; apatite and "whitlockite". Whitlockite has since been identified as merrillite.

The extensive study of lunar pyroxene has helped mineralogists understand the phase relations, polymorphism, and exsolution of this complex mineral. In fact, the augite-pigeonite solvus at one atmosphere was first worked out using pyroxenes from a lunar mare basalt! The coarse exsolution of augite and low-Ca pyroxene found in some lunar plutonic rocks are the result of prolonged annealing in the solid state. Strong ordering of Mg and Fe in the structural states of some low-Ca pyroxenes also requires prolonged subsolidus annealing at a relatively high temperature.

Pyroxenes from lunar basalts have a wide range of composition - traditionally reported on the En-Fs-Di-Hd quadrilateral (*provided herein with each thin section description*). Pyroxene nucleates easily, and the Mg/Fe ratio of the first pyroxene corresponds closely to the ratio of the liquid. Chemical zoning of the pyroxene follows the liquid composition as other phases compete for the elements. Rapidly crystallized pyroxenes reveal very complex trends that are not uniform even in the same crystal! Pyroxene compositions are useful to indicate the degree of re-equilibration in clastic breccias. Highly metamorphosed or recrystallized breccias have uniform pyroxenes, while poorly metamorphosed breccias have a wide range of pyroxene composition.

Table III. – Lunar Mineralogy

Major phases	Rough formula
Plagioclase	$Ca_2Al_2Si_2O_8$
Pyroxene	$(Ca,Mg,Fe)_2Si_2O_6$
Olivine	$(Mg,Fe)_2SiO_4$
Ilmenite	$FeTiO_3$
Minor phases	
Iron	Fe (Ni,Co)
Troilite	FeS
Silica	SiO_2
Chromite-ulvospinel	$FeCr_2O_4$-Fe_2TiO_4
Apatite	$Ca_5(PO_4)(F,Cl)$
Merrillite	$Ca_3(PO_4)_2$
Ternary feldspar	$(Ca,Na,K)AlSi_3O_8$
K-feldspar	$(K,Ba)AlSi_3O_8$
Pleonaste	$(Fe,Mg)(Al,Cr)_2O_4$
Zircon	$(Zr,Hf)SiO_4$
Baddeleyite	ZrO_2
Rutile	TiO_2
Zirkelite-zirconolite	$(Ca,Fe)(Zr,Y,Ti)_2O_7$
New minerals	
Armalcolite	$(Mg,Fe)(Ti,Zr)_2O_5$
Tranquillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$
Pyroxferroite	$CaFe_6(SiO_3)_7$
Yttrobetafite	$(Ca,Y)_2(Ti,Nb)_2O_7$

Several unique features are present in lunar rocks. Quenched, Fe-rich, and silica-rich immiscible liquids are found in the mesostasis of the mare basalts; melt inclusions are found frequently in olivine; and surface coatings of ZnS are found on volcanic glass spheres. Rocks exposed to the micrometeorite environment have a patina of glass-lined craters and glass splashes.

Three new minerals have been identified: armalcolite, tranquillityite and pyroxferroite. Armalcolite, named after Apollo astronauts Armstrong, Aldrin and Collins, has over 70 percent TiO_2. Armalcolite has a pseudobrookite structure with a $Ti^{4+} + Fe^{2+} = 2Fe^{3+}$ substitution. One variety of armalcolite has high Cr or Zr content. Tranquillityite is a minor phase found in the late residua of some mare basalts. It is hexagonal, but tranquillityite's exact crystal structure is unknown. Pyroxferroite is an Fe-rich pyroxenoid with a seven-repeat silicate chain that has crystallized metastably in the late residua of mare basalt. Yttrobetafite (a pyrochlore) was found but could not be structurally identified because of radiation damage caused by high U and Th (Meyer and Yang 1988). Such unique features and the new minerals are difficult to illustrate in these sets of thin sections.

Lunar minerals do not react appreciably with the Earth's atmosphere, although akaganeite (FeO(OH)) was found on the surface of one Apollo 16 breccia. Slow oxidation of metallic Fe grains does occur, but the classic problem of catalytic oxidation by lawrencite ($FeCl_2$) does not seem to be the problem that it is with some meteorites. The Apollo Lunar Sample Collection is preserved in dry nitrogen cabinets.

Geological processes special or important to the formation of lunar samples include; shock rnetamorphism (French and Short 1968), cratering-mechanics (Roddy *et al.* 1976), basin formation (Howard *et al.* 1974), breccia formation, regolith gardening, and partial melting to form basalt (Basaltic Volcanism Team 1981). Knowledge about each of these subjects was greatly advanced during the lunar program (Proceedings 1970-1991). Advanced petrology students should carefully consider the evidence for a lunar magma ocean (Warren 1985).

Shock Metamorphism

Transient, high-pressure shock waves have passed through lunar samples repeatedly, altering the nature of minerals (Roddy *et al.* 1976). Mosaicism is characteristic of shock damage to silicate minerals and is evidenced by unusually strong, irregular undulatory optical extinction. Deformation bands are lamallar-shaped regions in crystals whose orientation differs from the host crystal's. The bands' orientational differences include "kink bands" and "mechanical twins". At higher shock pressures, planer elements occur in multiple sets of planer or slightly bent optical discontinuities. Minerals shocked to this degree have bulk density and refractive indices that are lower than normal. At extreme pressures, the mineral becomes optically isotropic and is known as a diaplectic glass. Diaplectic glass frequently becomes partly crystalline again. Different minerals are affected to different degrees with advancing shock pressures. Generally, plagioclase is the first lunar mineral to be affected by shock. Eventually, high shock pressure is associated with heating and the rock melts or is vaporized (fig. 3).

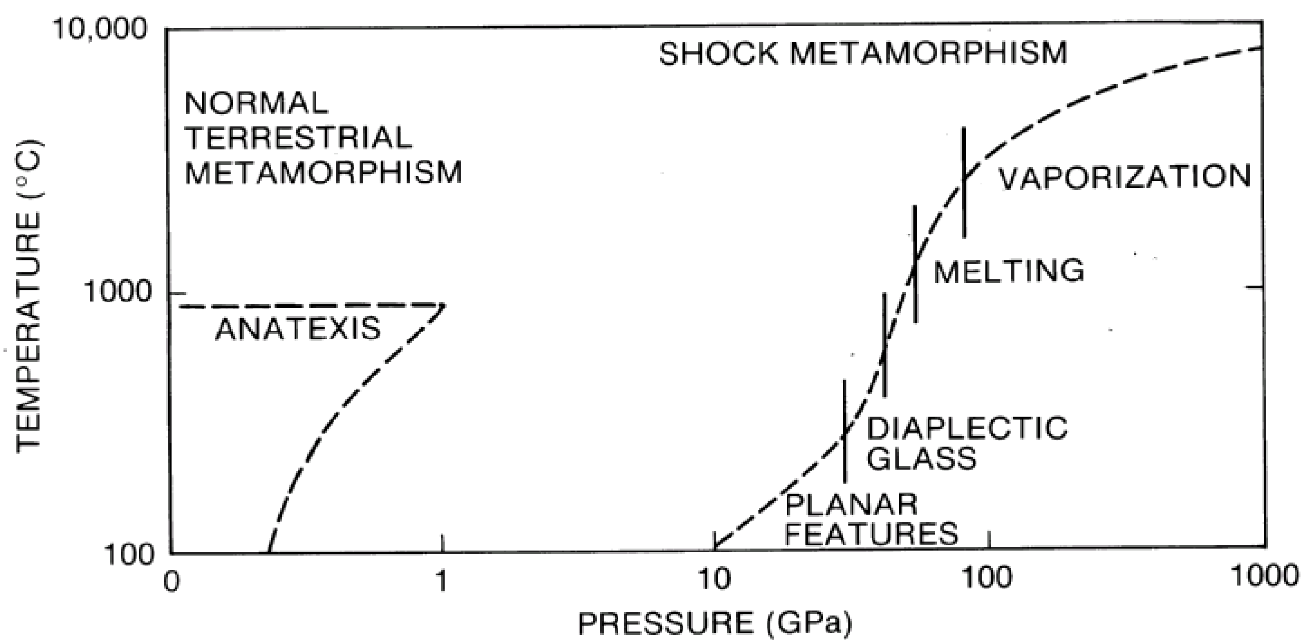

Figure 3. - Comparison of shock metamorphism with normal terrestrial metamorphism. The transient high-pressure shock wave causes heating leading to melting and vaporization of some material. At intermediate shock pressure, some minerals lose their crystallinity and form diaplectic glass while maintaining their chemical compsition. Minerals subjected to low shock pressure exhibit mosaicism and planer feature.

Sampling the Moon

First it was important to obtain both mare and highland materials. The Apollo 11, 12, 15, and 17 sites and the Luna 16 and 24 sites were all on lunar Maria. Apollo 15 and 17 were carefully placed next to the highlands. The Apollo 16 and Luna 20 sites were selected specifically to be entirely on the highlands.

Figure 4 is a profile of the Al/Si ratios across the Maria and highlands obtained by the X-ray experiments onboard the Apollo 15 and 16 command and service modules. The highland regions were very Al rich. Results from these orbiting experiments were entirely consistent with samples returned from areas under these groundtracks.

The frontside of the Moon (fig. 5) has several large basins formed by giant cratering events (Imbrium, Serenitatis, Crisium, Nectaris, etc.). The Orientale basin (fig. 6) situated on the left limb of the Moon is the best preserved of these giant impact structures. Radial deposits of ejecta can be seen extending great distances beyond the outer rim of the crater (Hevelius Formation). This observation was extended to the radial deposits of the Imbrium basin (the Fra Mauro Formation) in

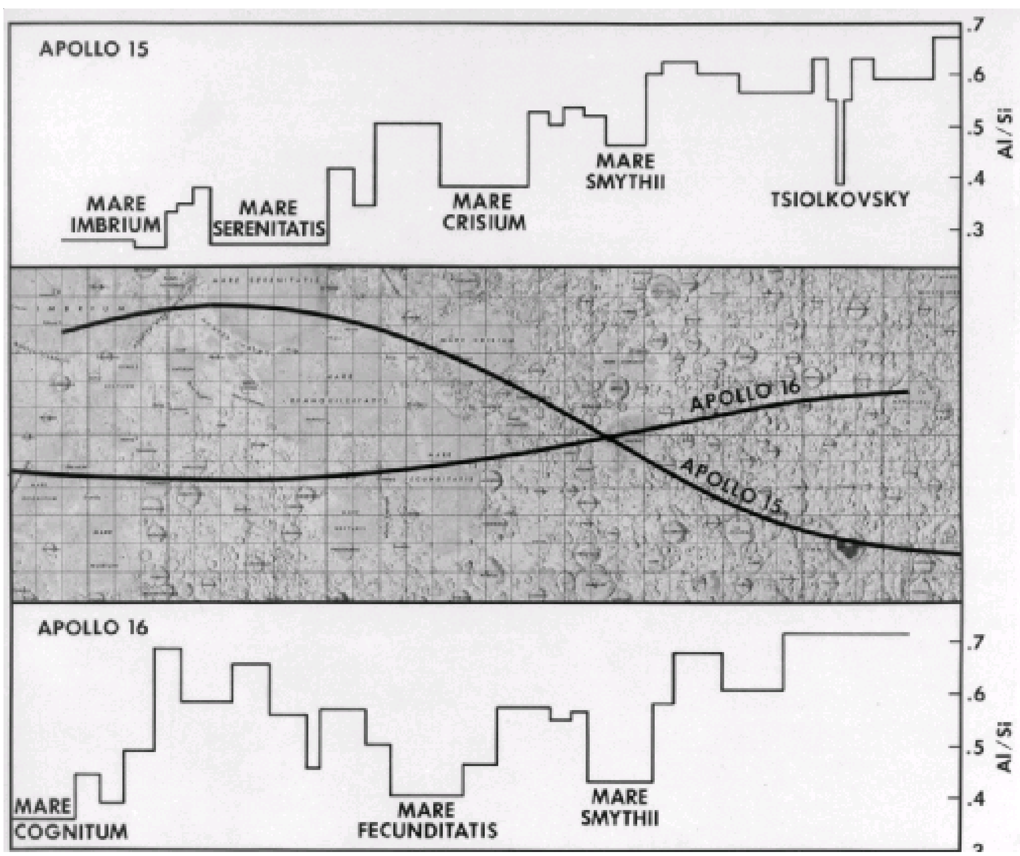

Figure 4 - Al/Si ratios of the lunar Maria and highlands as obtained by the orbiting X-ray fluorescence experiment onboard the Apollo 15 and 16 command and service modules. Solar radiation excites X-rays from light elements (Mg, Al, and Si) that were counted by the X-ray spectrometer as it orbited the Moon. Ratios were normalized to “ground truth” obtained from soil samples returned from landing sites overflown by the experiment. Only the sunlit side of the Moon could be measured, but the highlands were always high Al.

order to devise a strategy for sampling the interior of the Moon. The Apollo 14 and 15 sites were picked to give two different radial samples of Imbrium ejecta and, thus, samples from two different depths in the lunar crust. The results of this sampling strategy are confusing. All the material brought back from Apollo 14 was breccia (similar to sample 14305 included in this study set) indicating that we were successful in obtaining samples of the Fra Mauro Formation at this site. At the Apollo 15 site, rare noritic breccias (samples 15445 and 15455) were found that may have come from deep within the Imbrium target. However, the relationship of the samples collected at the Apollo 16 and 17 sites to ejecta collected from large basins is not known.

Currently, scientists are planning a mission to sample the even larger crater (SP-A) discovered on the backside of the Moon (Taylor 1998)!

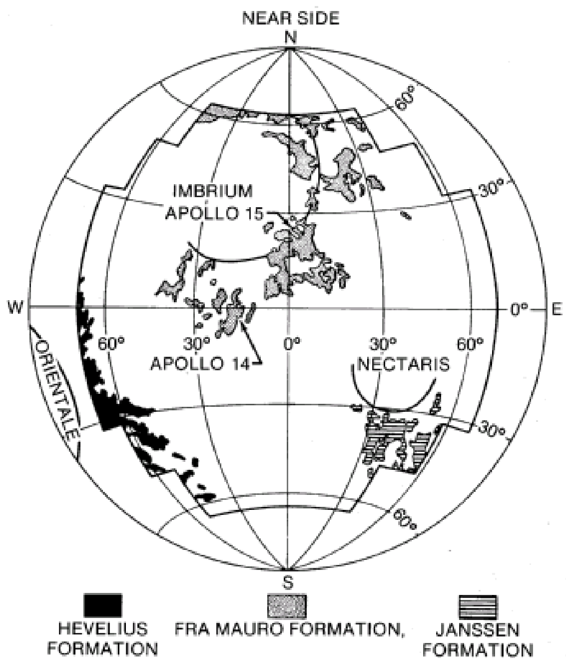

Figure 5 - Ejecta blankets of large lunar basins as mapped by Howard *et al.* 1974. The Hevelius Formation, extending out from Orientale, served as a model for photointerpretation of the older Imbrium deposits. The Fra Mauro Formation extending outward as radial deposits from Imbrium, was sampled by Apollo 14 and 15.

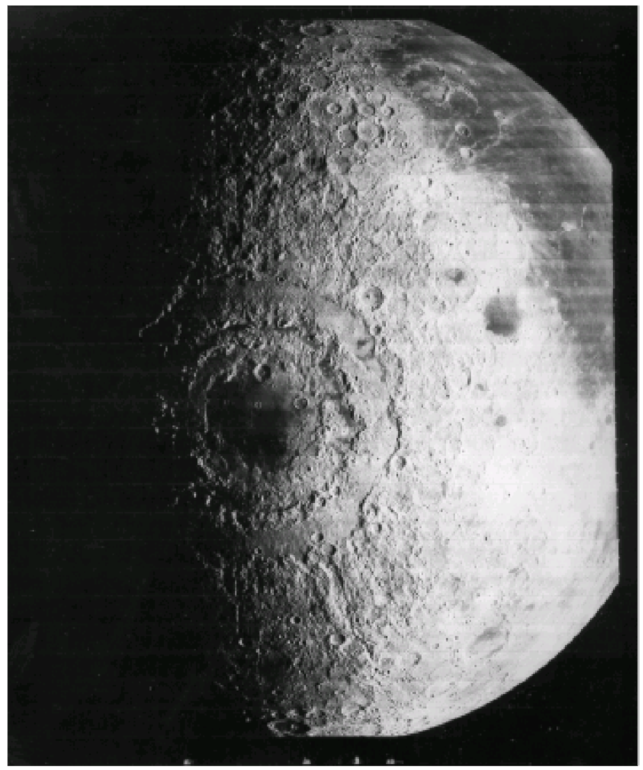

Figure 6 - The giant Orientale basin is the most recent of the large impact craters on the Moon. It is as large as Texas! This photo of the eastern limb of the Moon was taken by Lunar Orbiter. Orientale ejecta may have been spread all over the Moon, but it has not been recognized in the lunar samples that have been returned.

Apollo 17

The last mission to the Moon (Apollo 17) serves as a good starting point for a student interested in acquiring more information on the relationship of field geology and sample collection (fig. 7). Several samples in this set of petrographic thin sections are from the Apollo 17 collection. One sample is a pristine norite (78235), one sample comes from a landslide off the highlands (72275), two samples are of the dark mantle (74220 and 70181), and another sample is of the mare surface (70017). The U.S. Geological Survey study of the Taurus-Littrow Valley (Wolf *et al.* 1981) is a good model of a professional report for students interested in planetary science.

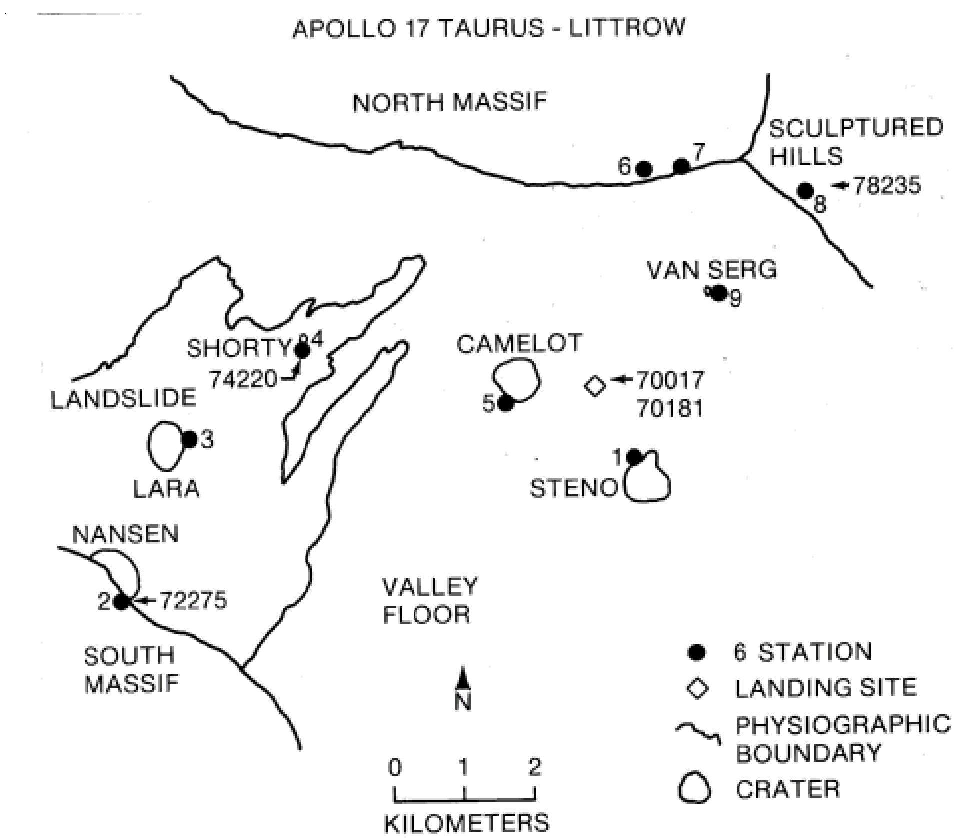

Figure 7 - Sketch map of the Apollo 17 Taurus-Littrow landing site showing locations of some of the samples used for thin sections in this study set. The valley floor was covered with mare basalts and a dark mantle. The landslide off the South Massif is a light mantle on top of the valley material. Boulders that rolled down from the North Massif were sampled at stations 6 and 7 (*see* figure 44). A geologist and his commander spent 22 hr exploring 31 km of this valley, representing one of the most outstanding human accomplishments ever. *And you are looking at the samples collected!*

Questions

Questions are more important than answers (fig. 8). Science students should learn to formulate clear questions about nature and, once formulated, ask them of several authorities. In the process, the student will probably learn that it is necessary to personally observe nature closely. The petrographic microscope is one of the most important tools available to the geologist.

Some questions related to lunar science are suggested below:

1 What evidence supports the notion that lunar anorthosites are very old?

2 Are the numerous lunar craters a result of comets or disturbed asteroids? How could you tell them apart?

3 What evidence exists for plagioclase flotation in a global magma ocean?

4 Rays are evidence that exotic materials travel great distances. Why is so little mare material present at the Apollo 16 site?

5 Did the Earth have a megolith (deep regolith) after the lunar cataclysm?

6 Why don't meteorites record the 3900- to 4000-million-year event?

7 Are catastrophic events important to a planet's thermal history?

8 How many separate chemical reservoirs have been sampled in the solar system?

9 Are any of the samples returned by the Apollo missions likely to be Orientale ejecta?

10 What is the chemical composition of the whole Moon?

11 Is the interior of the Moon still molten?

12 Is frozen water present in the permanently shadowed regions of the lunar poles?

13 What was the gas that evolved during basaltic volcanism?

14 How can magma form from a source that is already "depleted" in trace elements?

15 Does erupted volcanic liquid always assimilate crustal material during volacanism?

These questions, and others that you might formulate, have not been fully answered yet!

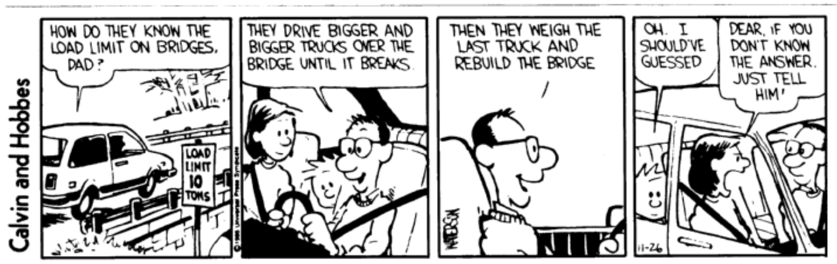

Figure 8.— Questions are more important than answers because answers are guesswork by authorities.

Mare Basalt Volcanism

The lunar Maria are dark, low lying, and relatively uncratered. At a low Sun angle, they exhibit wrinkle ridges (fig. 9) indicating that they refilled with frozen liquid. Before we went to the Moon, we thought these Maria were relatively young because they were so poorly cratered. Surprise! The extensive collection of many, very fresh, basalt samples returned from several of the mare surfaces by the Apollo 11, 12, 15, and 17 and Luna 16 and 24 missions showed that these lunar surfaces were very old and that the cratering flux was much less than expected. In the Apollo collection, 134 samples of mare basalt are greater than 40 g; the largest sample is 9.6 kg. These basaltic samples have a wide variety of textures and compositions. Mare basalts also are represented by glass beads that have formed in basaltic lava fountains on the lunar surface. Spectral studies by Earth telescope indicate that we did not sample all the lunar basalt types (Head 1976).

Chemically, mare basalts can be divided into two broad groups (fig. 10); the older high-Ti group (age 3550 to 3850 million years, TiO_2 content 9 to 13 percent) and the younger, low-Ti group (age 3150 to 3450 million years, TiO_2 content 1 to 5 percent). Samples from the Apollo 11 and 17 missions were exclusively from the high-Ti group, and samples from the Apollo 12 and 15 and Luna 16 missions were from the low-Ti group (fig. 11). The age differences and the wide variety of lunar basalt chemistries (TiO_2 content from 1 to 13 percent) means that mare basalts cannot be generated from one common source region or common parental magma through different degrees of partial melting. Chemically, isotopically and mineralogically distinct source regions within the lunar interior are required. Experimental studies show that the low-Ti basalts could have been derived from an olivine-pyroxene source rock at depths ranging from 200 km to 500 km, while the high-Ti basalts

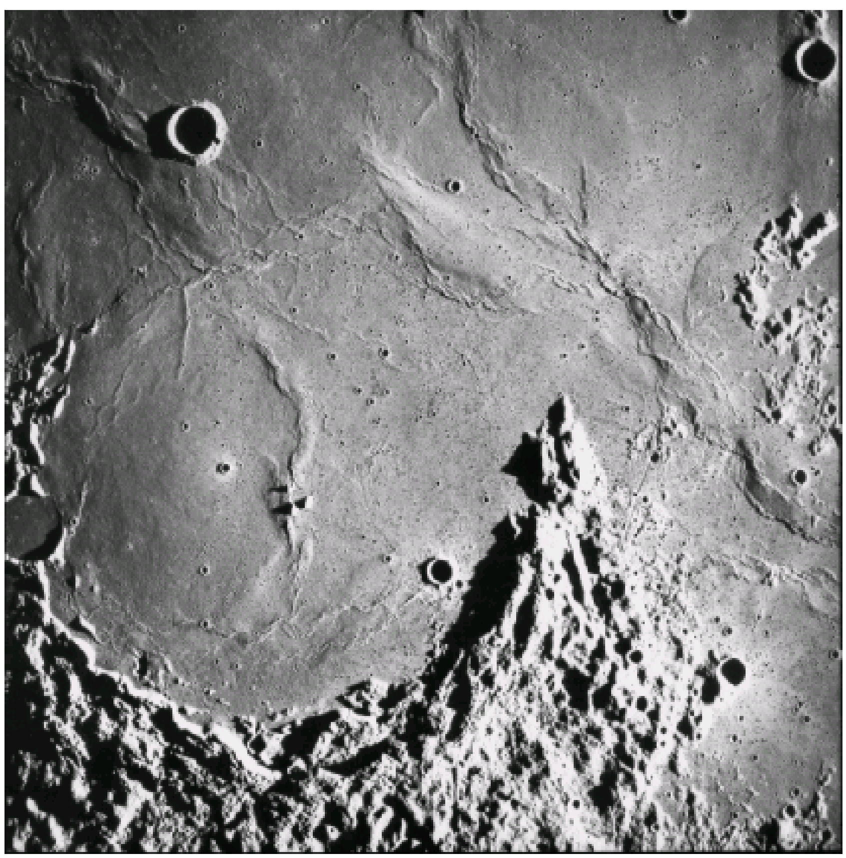

Figure 9 - Wrinkle ridges and flow fronts of mare basalts can be seen in Oceanus Procellarum (Letronne crater). This photo (no. 2994) was taken at low Sun angle by the metric camera onboard the Apollo 16 command and service module.

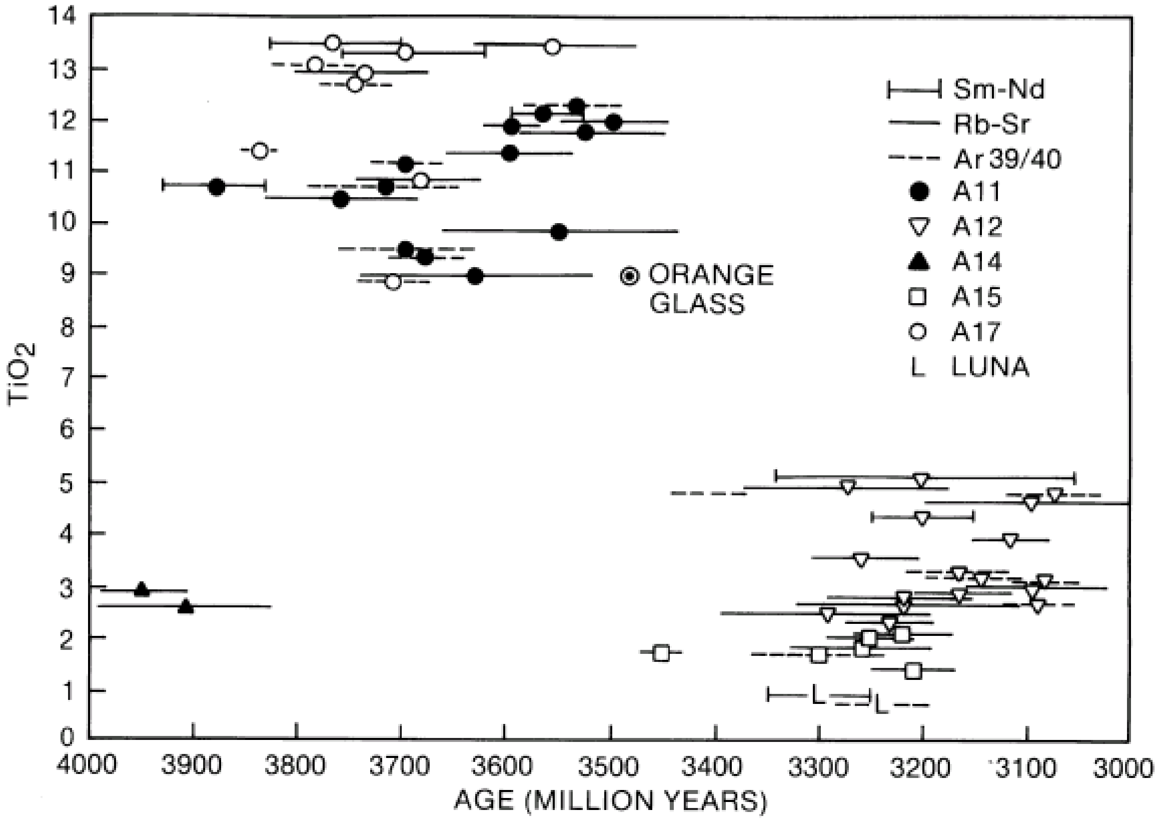

Figure 10 - The ages of the Apollo 11 and 17 high-Ti basalts are older than the Apollo 12 and 15 low-Ti basalts. The age of the orange glass sample 74220 is younger than the Apollo 17 basalts and could be the cause of the dark mantle that covers the edge of Mare Serenitatis.

could have been derived from olivine-pyroxene-ilmenite cumulates in the outer 150 km of the Moon (Papike *et al*. 1976).

Near-surface separation of early formed olivine, ilmenite, armalcolite, metallic Fe, and/or chromite from the basaltic liquid has altered the chemistry of many rocks collected from that of the primary chemistry of the liquid that was extruded from the lunar interior. The addition or subtraction of olivine is responsible for the composition range of the low-Ti basalts, and the addition or subtraction of Fe-Ti oxides has altered the chemistry of the high-Ti basalts. Near-surface fractionation was aided by low viscosity due to the low SiO_2 contents. The viscosity of mare basalt liquids (fig. 12) is much less than that of terrestrial volcanics (Weill *et al*. 1971).

A sequence of textural types within each basalt category represents different cooling histories. The textures range from vitrophyric to porphyritic to subophitic to intersertal to equigranular (see appendix I for definition of terms and/or appendix II for examples of texture). Most samples are fine-grained and have an average

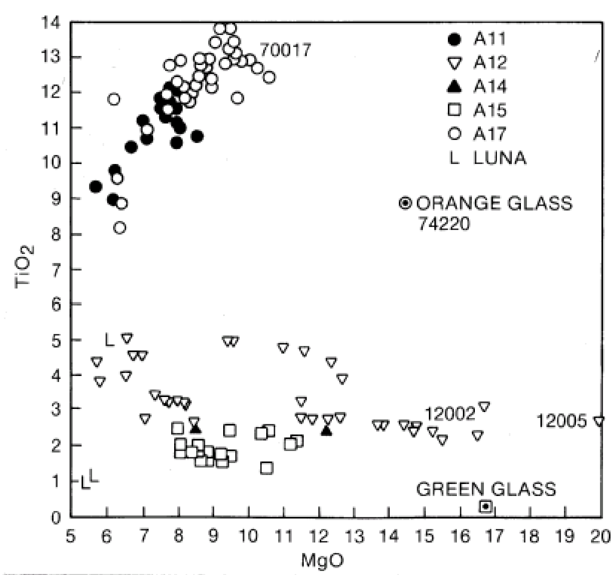

Figure 11 - The composition of the four basalt samples in this study set compared with the composition of other lunar basalts. Compositions are given in table IV and Basaltic Volcanism 1981.

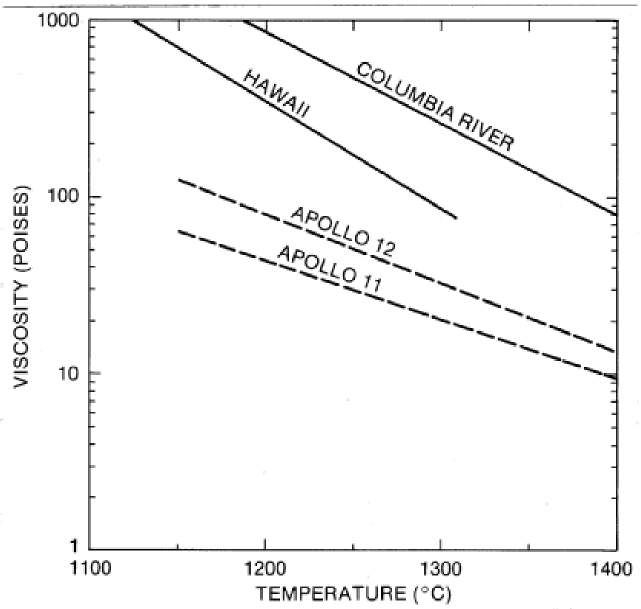

Figure 12 - Viscosity of mare basalts compared with that of terrestrial basalts. Viscosity can be calculated as a function of temperature from oxide concentrations by the methods of Weill *et al.* 1971.

grain size of 0.5 mm, but some samples have phenocrysts of olivine or pyroxene measuring over 1 cm. Some samples are vesicular with interconnecting vugs and vesicles (fig. 13).

Vitrophyric basalts have skeletal phenocrysts of olivine and/or pyroxene set in devitrified glass. Porphyritic basalts have partially resorbed phenocrysts set in a holocrystalline matrix. Subophitic basalts have tabular plagioclase intergrown with subhedral pyroxene. Intersertal and equigranular basalts have interconnecting anhedral crystals of plagioclase, olivine, pyroxene, and opaques. Lofgren *et al.* 1974 have shown that many of these textures can be reproduced experimentally. The mare basalt liquids must have crystallized rapidly if their textures can be reproduced in the laboratory!

The most important mineralogical phases in mare basalts are silicates (pyroxene, plagioclase, and olivine) and oxides (ilmenite, armalcolite, and chromite-ulvöspinel). Pyroxenes are the most abundant phase in mare basalts. Many studies of pyroxene chemical zoning were performed to try to follow the crystallization sequence

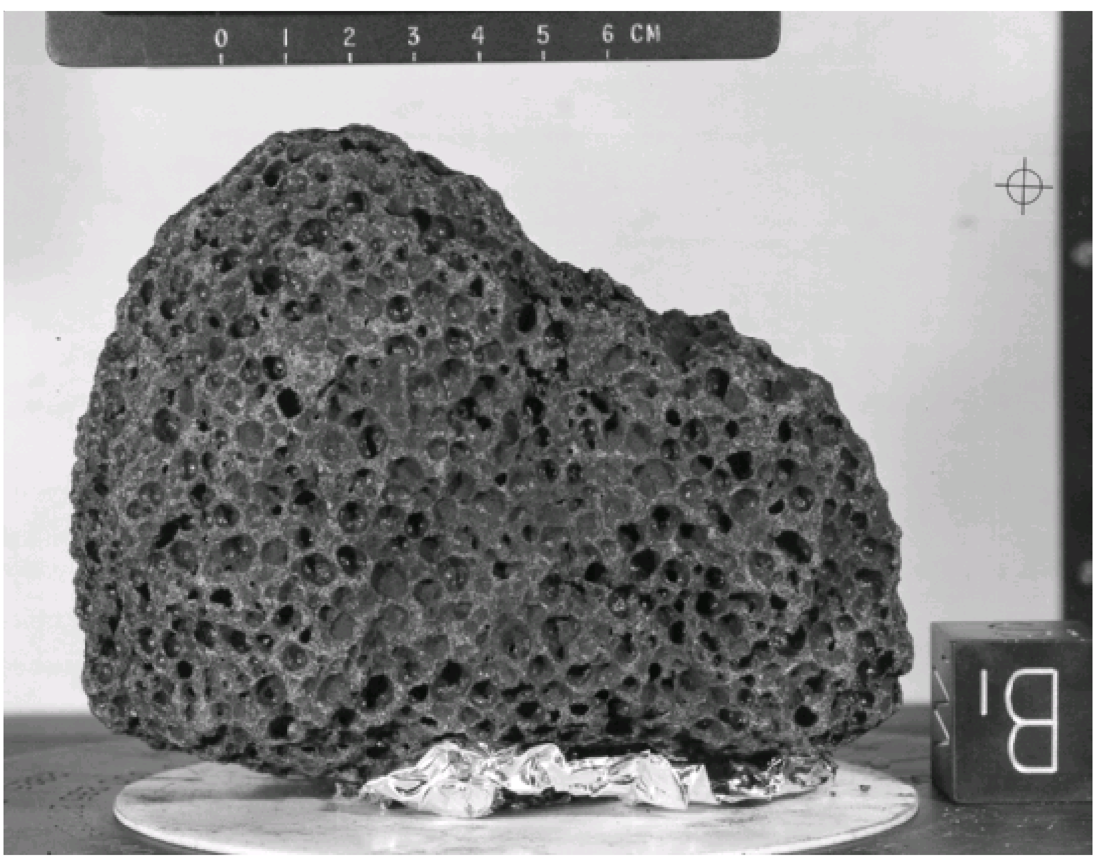

Figure 13 - Vesicular mare basalt 15016. Sample is 12 cm long. See photo of thin section in appendix 2. NASA photo no. S71-46986

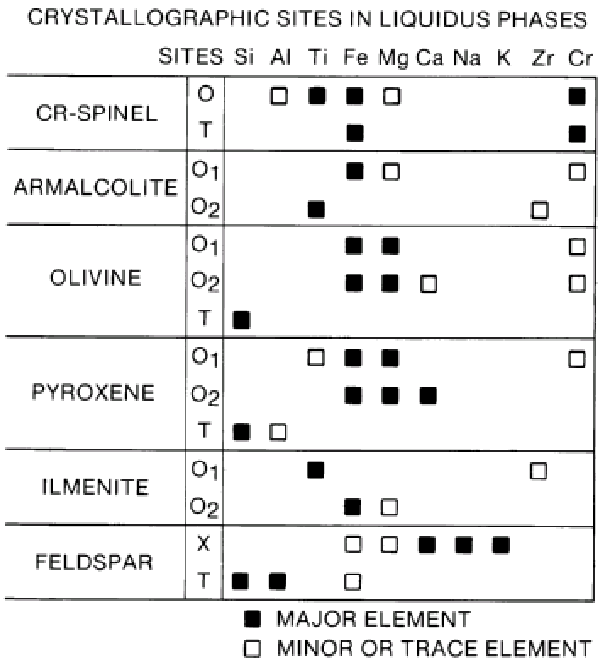

Figure 14 - Distribution of elements among 14 different crystallographic sites in 6 different liquidus phases in mare basalts.

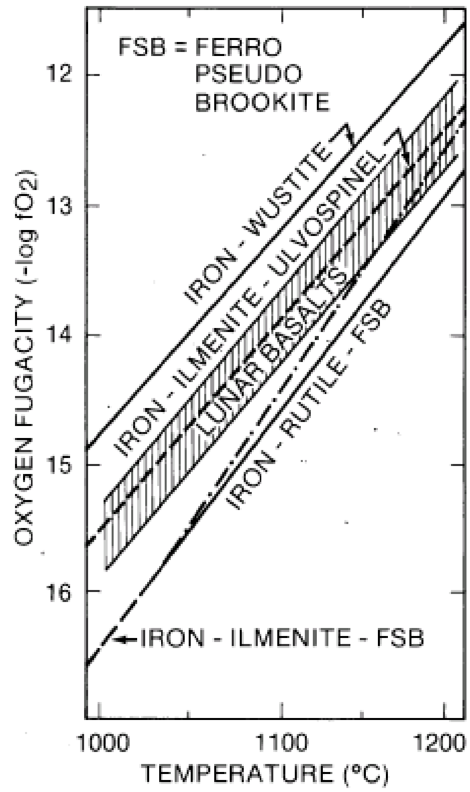

Figure 15 - Partial pressure of oxygen in equilibrium with lunar basalts (from Sato *et al.* 1973).

and, hence, the path of differentiation of the basaltic liquids. However, pyroxene phenocrysts are complexly zoned in lunar mare basalts. Sector zoning in different crystallographic directions is beautifully illustrated in some pyroxenes. Extreme Fe enrichment, (to pyroxferroite) occurs in other pyroxenes. The plagioclase in mare basalts is very calcic because lunar samples are all very low in Na. Ilmenite, armalcolite, and chromite-ulvöspinel are abundant in high-Ti basalts. In some basalts, the olivine content is as high as 40 percent; in other basalts, there is no olivine. The mesostasis between the major minerals contains interesting accessory phases including, silica, frozen immiscible silicate liquids, troilite, metallic Fe, apatite and/or whitlockite, and a new Ti, Zr-silicate, tranquillityite. The mesostasis in lunar basalts does not alter as it would on the Earth.

Many factors influenced the mare basalt crystallization sequence. Although phase diagrams and experimental studies can be used to predict the initial crystallizing phases, metastable chemical trends in minerals and delayed nucleation of some phases often occurred as crystallization of mare basalts progressed. Figure 14 (*after* Papike *et al.* 1976) summarizes how the major elements are distributed over the various crystallographic sites in the six major minerals to crystallize from mare basalts. In this diagram, T designates the tetrahedral sites, 0 designates octahedral sites, and X designates the large cation sites in feldspar. Altogether, there are 14 different crystallographic sites among the 6 major phases crystallizing from mare liquids. Thus, the chemical composition of the crystallizing liquid (as recorded by the pyroxenes) changes in a complex manner as a result of the sequence of crystallization of phases and distribution of elements among crystallographic sites. In addition, rate processes such as diffusion in the liquid and minerals and the often incomplete reaction of early formed minerals with the liquid also apparently affected the chemical path of the crystallizing liquid. Examples of different crystallization sequences are: delayed nucleation of plagioclase in some mare basalt liquids causing a significant effect on the Ca content of the liquids and the resulting pyroxenes; partial and incomplete reaction of early formed olivine and armalcolite influencing the chemical paths of other basalts yielding free silica in their mesostasis although

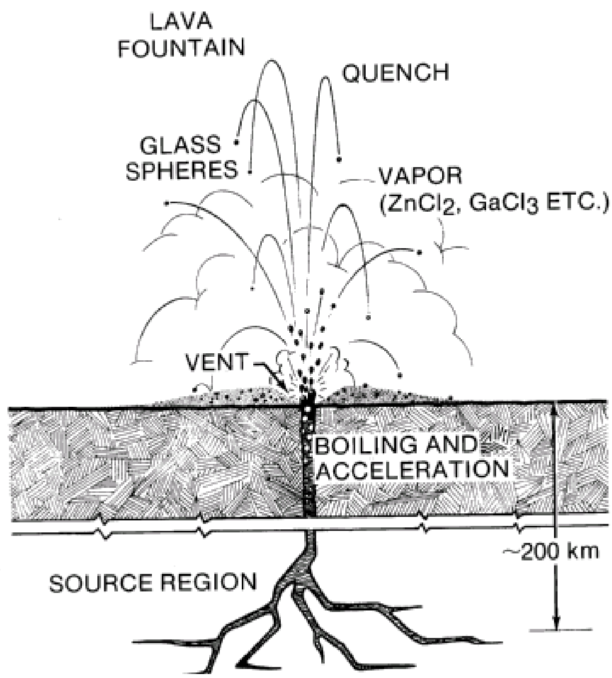

Figure 16 – Cartoon of a hypothetical lunar lava fountain producing glass spheres (Meyer *et al.* 1975). Quenched spheres become coated with volatile elements as they fall back to the surface.

they were undersaturated in SiO_2 initially; and extreme Fe enrichment of the residual liquid of low-Ti mare basalts which yielded pyroxferroite in the mesostasis. However, the high-Ti basalts did not yield pyroxferroite because the Fe was used up by the early-formed ilmenite.

Mare basalts formed and crystallized at very low partial oxygen pressures. They were in equilibrium with metallic Fe, which is found as one of their accessory minerals. Figure 15 shows the oxygen fugacity of mare basalts as a function of temperature. At 1100 deg C, the oxygen fugacity in mare basalts is about 10^{-13} compared with about 10^{-58} in terrestrial lavas. Throughout the mare basalt crystallization, water was not stable and could not have been the gas that caused vesiculation of some basalts. Under these very reduced conditions, all of the Fe in the liquid is Fe^{2+}, most of the Cr is Cr^{2+}, and some of the Ti is Ti^{3+}. These reduced valence states also affected both the chemistry and stability of the minerals that crystallized from mare basalts. For example, there is no magnetite present and the only sulfide is pure troilite. Minute metallic Fe grains often are adjacent to chromite-ulvöspinel, suggesting the redox reaction $Fe^{2+} + 2Cr^{2++} = 2Cr^{3+} + Fe$ during precipitation of chromite from the liquid.

Glass droplets of possible pyroclastic origin are present in the soil samples of the Apollo 11, 15, and 17 sites (Heiken *et al*. 1974; Delano and Livi 1981). These are the extreme case of vesiculation (fig. 13) where the small triangles between vesicles contract by surface tension into spheres. There is no aerodynamic drag in the vacuum, so the molten droplets fall to the surface as frozen glass spheres (fig. 16). These are coated by condensed volatiles from the gas that brought them to the surface, but this gas phase is as yet unidentified (Meyer *et al.* 1975). Several interesting dark deposits are seen in orbital photos on the lunar surface that may represent concentrations of volcanic glasses.

Table IV. – Composition of Mare Basalts

	12002	12005	70017	74220
SiO_2	43.56	41.56	38.54	38.57
TiO_2	2.6	2.72	12.99	8.81
Al_2O_3	7.87	5.3	8.65	6.32
Cr_2O_3	0.96	0.75	0.5	0.75
FeO	21.66	22.27	18.25	22.04
MnO	0.28	0.3	0.25	0.3
MgO	14.88	10.07	9.98	14.44
CaO	8.26	6.31	10.28	7.68
K_2O	0.05	0.04	0.05	0.09
Na_2O	0.23	0.16	0.39	0.36
P_2O_5	0.11	0.04	0.05	
S	0.06	0.04	0.16	
Total	100.43	99.46	100.59	99.06
Mineral mode				
Olivine	18	30	1	2
Plagioclase	18	11	26	
Pyroxene	50	56	50	
Opaques	8	2	22	2
Mesostasis	5	trace	trace	
Silica	trace	0	1	
Glass	1	0	trace	96

note: additional compositions in table VI

Three mare basalt samples and one volcanic glass sample are included in this set of petrographic thin sections. The two Apollo 12 samples are low-Ti basalts. Although sample 12002 may represent a primitive liquid, sample 12005 is thought to be a near-surface olivine cumulate. The Apollo 17 sample 70017 is a vesicular, high-Ti mare basalt that is also thought to have been a primitive liquid. The Apollo 17 orange soil sample 74220 is the only colorful (non-gray) material that the astronauts saw on the lunar surface. This unique sample has been the object of much attention by scientific investigators. The orange glass must represent a primitive liquid derived deep in the lunar interior by endogenous partial melting (with little if any assimilation of crustal material during eruption!). Other examples of lunar basalt are found in the breccia and soil sections. Chemical compositions of the samples included in this set are given in tables IV and VI so that you may calculate the norm and compare with the mode.

Brief Description of 12002

Rock 12002 is a medium-grained, porphyritic basalt containing phenocrysts, of colorless olivine and red-brown clinopyroxene in a variolitic matrix of intergrown plagioclase and clinopyroxene (fig. 17). In the matrix, the intergrown plagioclase and pyroxene form bundles radiating from a common nucleus. Rock 12002 is a low-Ti basalt from the Apollo 12 site that has been studied by Grove *et al.* 1973. Modal and chemical analyses of this sample are presented in table IV.

Olivine - Colorless, anhedral phenocrysts of olivine Fo_{76-61} have abundant devitrified melt inclusions (fig. 19). Some sections contain large olivines with relict skeletal form surrounding crystallized groundmass.

Figure 17 – Texture of mare basalt 12002. Rounded and speckled phenocrysts of olivine and large elongate phenocryst of clinopyroxene. Groundmass contains intergrown plagioclase, pyroxene and ilmenite.

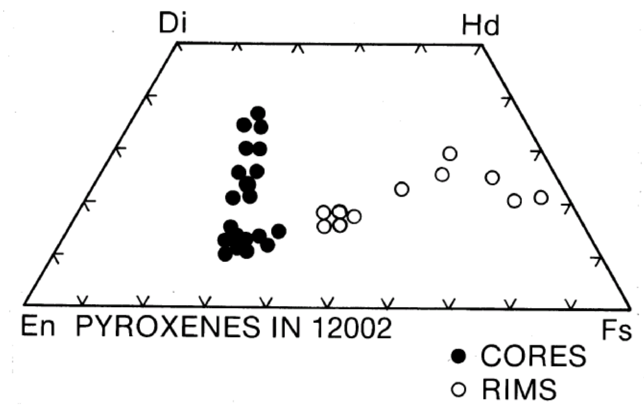

Figure 18 - Compositions of pyroxenes in 12002 as represented on En-Fs-Di-Hd quadrilateral. The Mg-rich cores zone to become Fe-rich rims. Chemical zoning is also different in different crystallographic orientations.

Pyroxene - Large clinopyroxene phenocrysts grew as laths containing hollow sectors which are now filled with groundmass minerals. The red-brown pyroxenes become intensely colored toward their rims, and they have complex chemical zoning growing from pigeonite cores to subcalcic-augite in one sector while growing to ferropigeonite in the other sector (fig. 18). Subcalcic, augite rims and groundmass pyroxene are very Fe rich and are intergrown with plagioclase and ilrnenite.

Plagioclase - Anorthite plagioclase An_{95-89} is intergrown with clinopyroxene in variolitic fashion. Some lath-shaped plagioclase crystals are hollow with intrafasciculate texture (fig. 20).

Opaques - Laths of light-gray ilmenite are found in the groundmass and within the Fe-rich rims of the pyroxene. Blocky glomeraphyric clusters of dark, gray chromite are common. Brown ulvöspinel overgrowths or reaction rims occur on many chromites (fig. 21). However, euhedral chromite inclusions within olivine phenocrysts lack the ulvöspinel rims. Blebs of native Fe are often associated with chromite-ulvöspinel grains. Blebs of immiscible troilite and metallic Fe are found in the matrix.

Figure 19 – Large melt inclusion trapped in olivine in 12002. The melt inclusion has crystallized to ilmenite and an intergrowth of plagioclase and pyroxene. Melt inclusions form in olivine because olivine grows as skeletal crystals that surround some of the melt during the crystallization.

Figure 20 - Intrafasciculate texture of plagioclase laths in 12002. Bundles of hollow plagioclase crystals are intergrown with pyroxene, ilmenite, and mesostasis.

Mesostasis - Interstitial areas contain brown glass and trace silica. Spongy pyroxferroite is found in some sections (fig. 22).

Petrogenesis - Chrornite inclusions in olivine and pyroxene phenocrysts indicate that chromite was an early phase. The texture and skeletal nature of minerals in this rock indicate that it was cooled rapidly and might represent a primitive lunar liquid. This composition has been experimentally studied (Grove *et al.* 1973) to discern the depth of origin at 300 km with a source of olivine plus clinopyroxene.

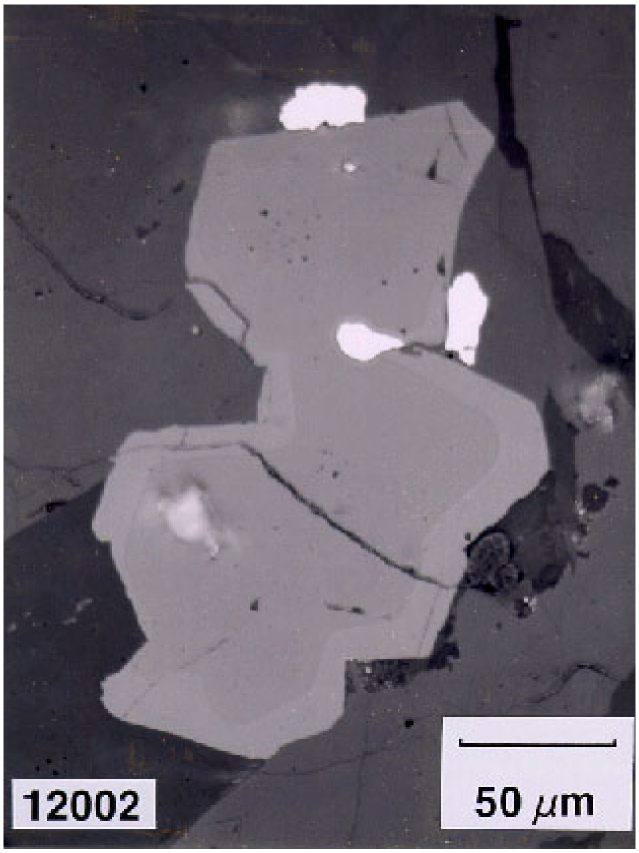

Figure 21 - Glomerophyric chromite grains are overgrown with ulvöspinel rims in 12002. They are associated with troilite and metallic Fe grains. Chromite inclusions in olivine are not overgrown. This is a reflected light photo.

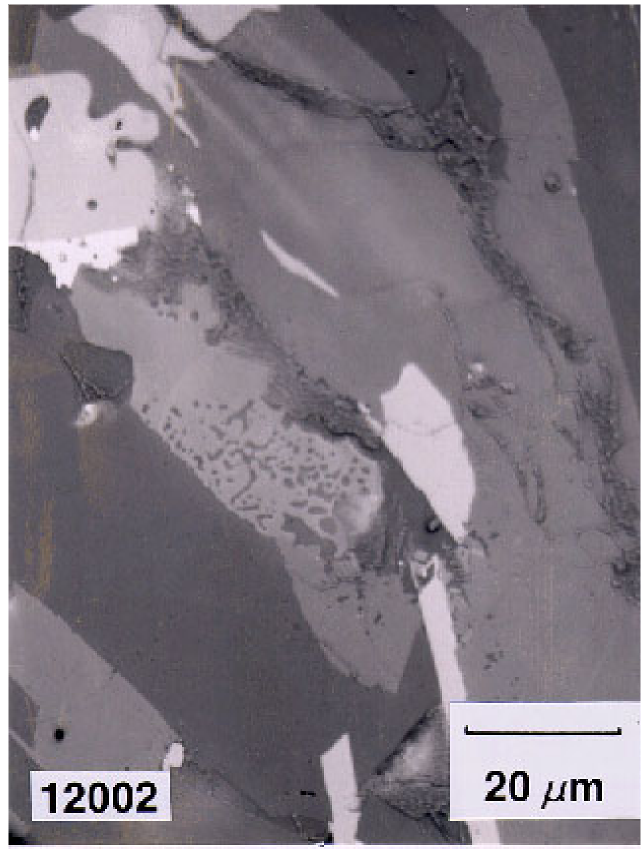

Figure 22 - Spongy pyroxferroite is found adjacent to brown glass in mesostasis of 12002. This is a reflected light photo.

Description of 12005

Rock 12005 is a medium-grained, olivine basalt possessing exceptionally high Mg content. Large pyroxene oikocrysts enclose an early crystallizing assemblage of rounded and embayed olivine (fig. 23). Patches of glomerophyric olivine are present in some areas. This Apollo 12 rock has been studied (Dungan and Brown 1977); its composition is given in table IV.

Olivine - In this rock, a duality of olivine textures may be noted. Large olivine grains (up to 5 mm) are rounded and embayed and contain relict inclusions; they also have relict skeletal shapes. Smaller, euhedral olivines are poikilitically enclosed within plagioclase or pyroxene oikocrysts. The larger olivines are more magnesian than are the euhedral grains in the plagioclase.

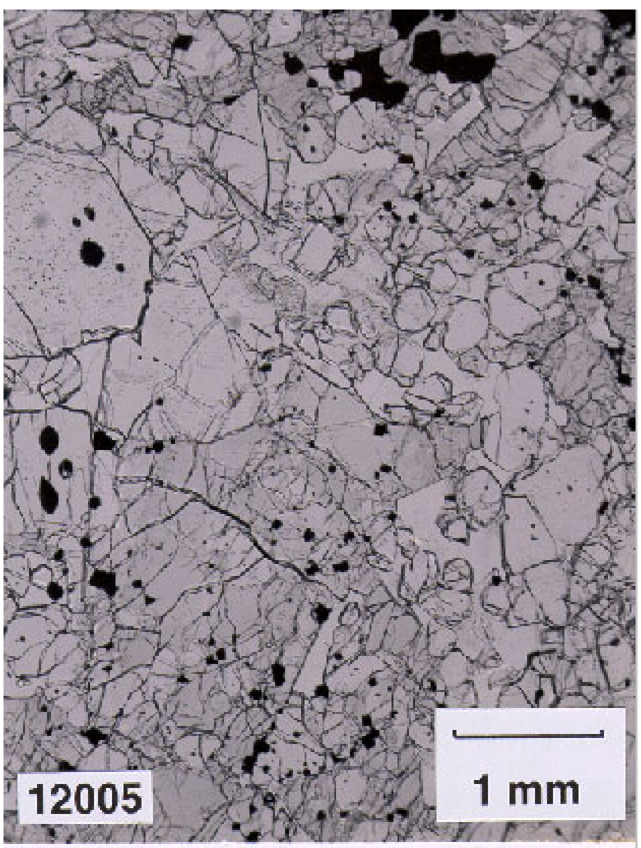

Figure 23 - Texture of mare basalt 12005. Speckled olivine phenocrysts containing inclusions of chromite and melt are surrounded by pyroxene. Large oikocrysts of plagioclase enclose equant olivine crystals.

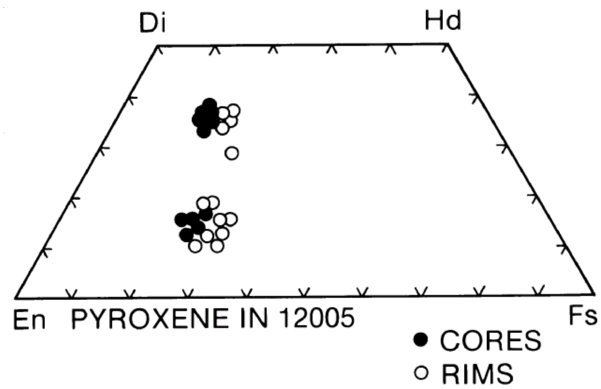

Figure 24 - Pyroxene quadrilateral for 12005. Note apparent separation of high-Ca and low-Ca pyroxene. The lack of Fe enrichment in pyroxenes indicates that this sample cooled slowly.

Pyroxene - The majority of large pyroxene grains in sample 12005 are composed of augite cores rimmed with low-Ca pyroxene. However, several of the largest include augite plus low-Ca pyroxene grains intergrowths in their cores. Additionally, some partially resorbed olivine grains are partly mantled by low-Ca pyroxene. The relatively complete separation of augite and low-Ca pyroxene on the pyroxene quadrilateral (fig. 24) was not observed in other lunar basalts.

Plagioclase - Large oikocrysts of plagioclase enclose equant olivine grains. Plagioclase grains are intergrown with pyroxene oikocrysts at their margins. Plagioclase is unzoned An_{93-86} except where it is alkali-rich at the very edge adjacent to rare segregations of K-feldspar and phosphate.

Opaques - Euhedral chromite-ulvöspinel grains and associated metallic Fe occur as inclusions in the olivine. Individual chromites are not zoned to ulvospinel but range in composition throughout the relative crystallization sequence. Intergranular ilmenites poikilitically enclose olivine and pyroxene. Subsolidus exsolution in ilmenite and ulvöspinel are widespread in sample 12005 (fig. 25).

Mesostasis - In this basalt, the less than 0.5 percent mesostasis is often located in embayments within

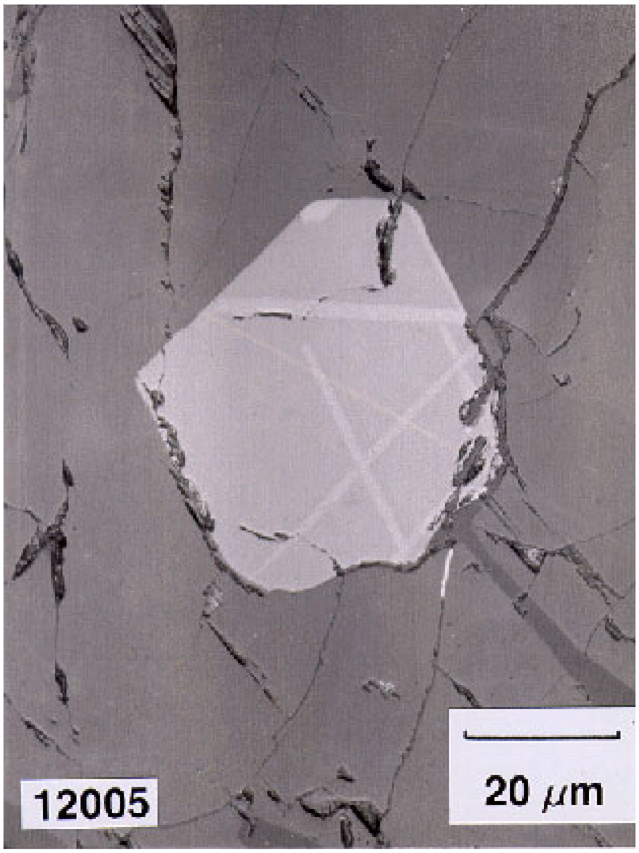

Figure 25 - Euhedral ulvöspinel with an exsolution of ilmenite in 12005. This is a reflected light photo.

poikilitic ilmenite. Were it occurs, mesostasis includes minute troilite, K-feldspar, bytownite, and whitlockite.

Petrogenesis - This rock probably represents a slowly cooled, olivine cumulate from a lake of basaltic lava on the lunar surface! The wide separation of pyroxene composition indicates an approach to an equilibrium solvus.

Description of 70017

Lunar sample 70017 is a vesicular, medium-grained, high-Ti basalt from Apollo 17. Large, equant, subhedral pyroxene, phenocrysts enclose embayed olivine, ilmenite, and armalcolite (fig. 26). Large anhedral crystals of poikilitic plagioclase (up to 5 mm in some sections) enclose euhedral crystals of olivine, clinopyroxene, and ilmenite. The interstices include abundant silica, trace brown glass, and minor troilite-iron grains. This sample has been studied by Longhi *et al,* 1974. The sample's composition is given in table IV.

Olivine - Olivine Fo_{69-66} is included in the cores of the clinopyroxene phenocrysts as small, irregular grains and is present as euhedral crystals Fo_{61}, poikilitically enclosed by plagioclase.

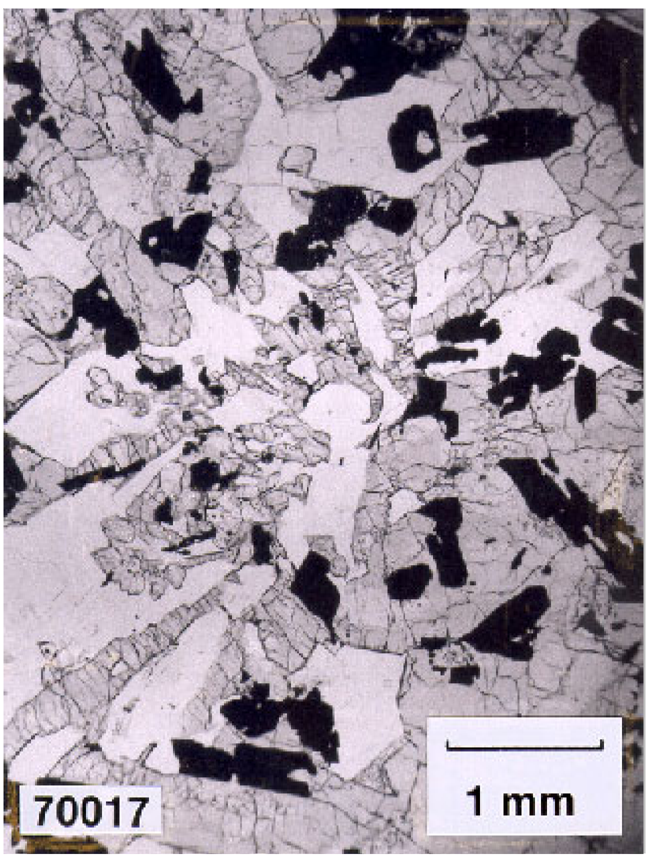

Figure 26 - Texture of mare basalt 70017. Large, subhedral pyroxene phenocrysts enclose embayed olivine, ilmenite, and armalcolite crystals. Note the abundance of opaques in this high-Ti basalt.

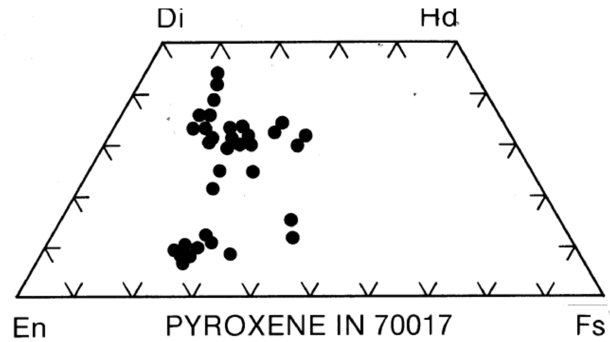

Figure 27 - Composition of pyroxenes in 70017. Pigeonite cores are surrounded by subcalcic-augite rims.

Pyroxene - Pink, Ti-rich augite cores of large pyroxenes are surrounded by low-Ti augite and pigeonite. Large pigeonite crystals are surrounded by low-Ti augite rims. In this basalt, there was little Fe enrichment during crystallization (fig. 27).

Plagioclase - Large plagioclase grains An_{88-69} do not penetrate the cores of clinopyroxene. Plagioclase poikilitically encloses olivine and pigeonite (fig. 28).

Opaques - Both ilmenite and armalcolite are present in this rock but it is hard to tell them apart. Ilmenite is generally anhedral (embayed), although it was originally lath-like. Exsolution lamellae of Cr-spinel and rutile are included in ilmenite (fig. 29). Minor armalcolite has slightly darker reflectivity and has characteristic "barrel-shaped" boundaries in the elongate direction but euhedral shape in cross section (fig. 30). It occurs in glomerophyric clusters of small crystals enclosed in clinopyroxene.

Mesostasis - A very complex mesostasis of glass, silica, troilite-iron, and trace tranquillityite occurs in this rock. Look for the distinctive cracked appearance of silica in reflective light (fig. 31). Rb-rich glasses are associated with ilmenites such that "ilmenite" separates provide the highest Rb "phase" for Rb-Sr isochrons of high-Ti lunar basalts!

Petrogenesis - Early formed, armalcolite reacted with the liquid and ilmenite eventually became the stable

Figure 28 - Partially-polarized-light photo of polysynthetic twinning in plagioclase poikilitically enclosing equant olivine crystals in 70017.

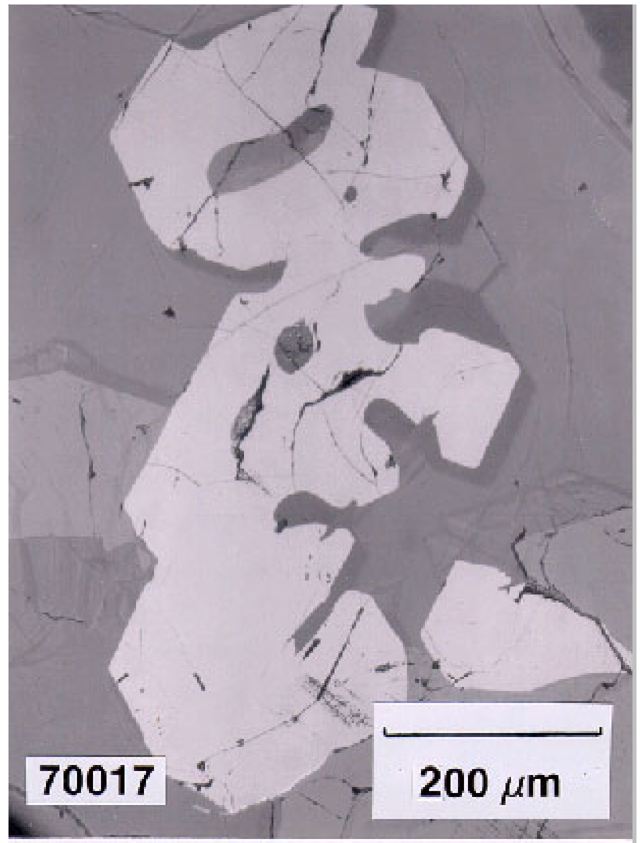

Figure 29 - Embayed, euhedral ilmenite in 70017. This is a reflected light photo.

Fe-Ti-oxide. This quickly cooled basaltic liquid has been considered a primitive lunar basalt. High-pressure melting experiments by Longhi *et al.* 1974 show that this liquid can be generated by partial melting of an olivine-clinopyroxene-ilmenite source at depths of 100 to 150 km in the Moon. Sample 70017 is about 3700 million years old. The old ages of Ti-rich basalts indicate that these liquids were generated shortly after the giant impacts that produced the basins.

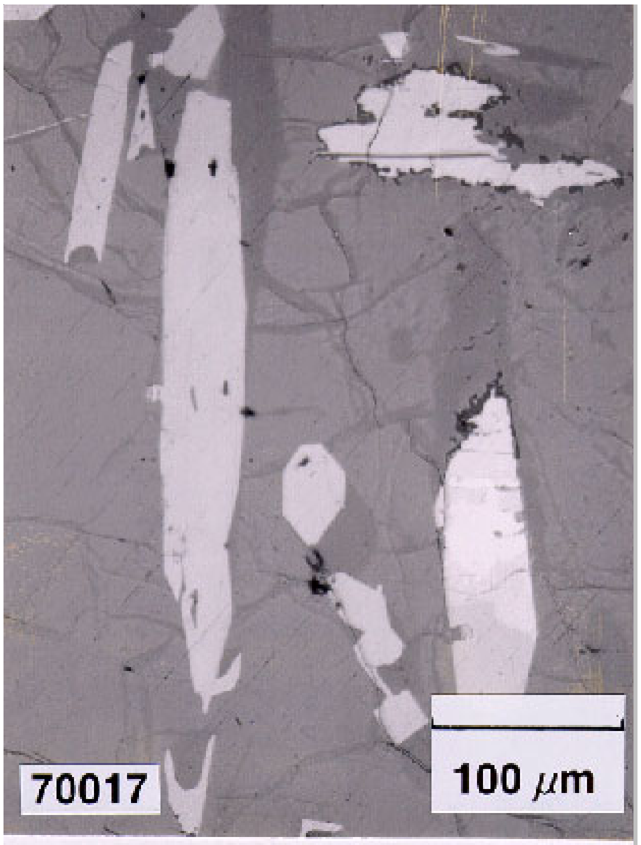

Figure 30 - Barrel-shaped armalcolite in 70017. The armalcolite is very hard to distinguish from ilmenite except by its habit. It is hexagonal in cross section but tapered in the elongate direction. This is another reflected light photo.

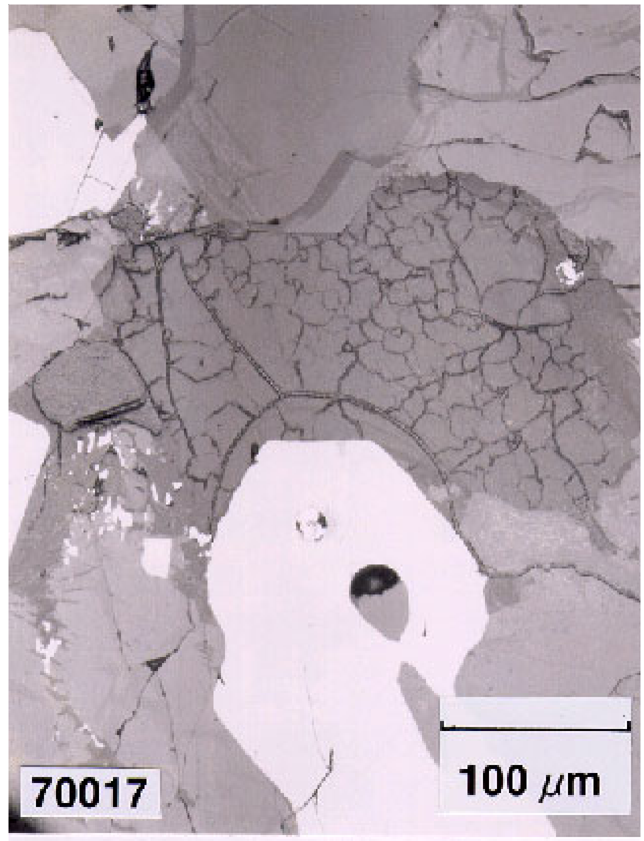

Figure 31 - Reflected light photo of cracked silica in 70017.

Description of 74220

Lunar sample 74220 was collected from an orange soil near a small crater at the Apollo 17 site. It is thought to be a sample of the "dark mantle" that covers a wide area around the Apollo 17 site. The sample is composed primarily of sma11 orange glass spheres, fragments of spheres, and black devitrified spheres (fig. 32). The sample also contains a small amount of admixed fragmental debris of mare basalts. This sample has been studied by Heiken *et al.* 1974 and Meyer *et al.* 1975. The glass composition is given in table IV and figure 11. This glass is 3480 million years old (fig. 10).

Glass - The uniformly colored, homogeneous orange glass particles have spheroidal and oblate spheroidal shapes. Many of them are broken and/or devitrified. A small number of composite - glass particles have been reported. No vesicles or schlieren are present in the glass. Glass spheres range in size from a few microns to as large as 100 microns and commonly have a uniform size of about 40 to 60 microns. The grain size distribution of this soil is compared with other lunar soils in figure 54.

Olivine - Olivine needles originate at common nucleation centers on walls of the glass spheres. Barred olivine chondrules are also present (fig. 33). Occasional large subhedral olivine phenocrysts are found in a few spheres.

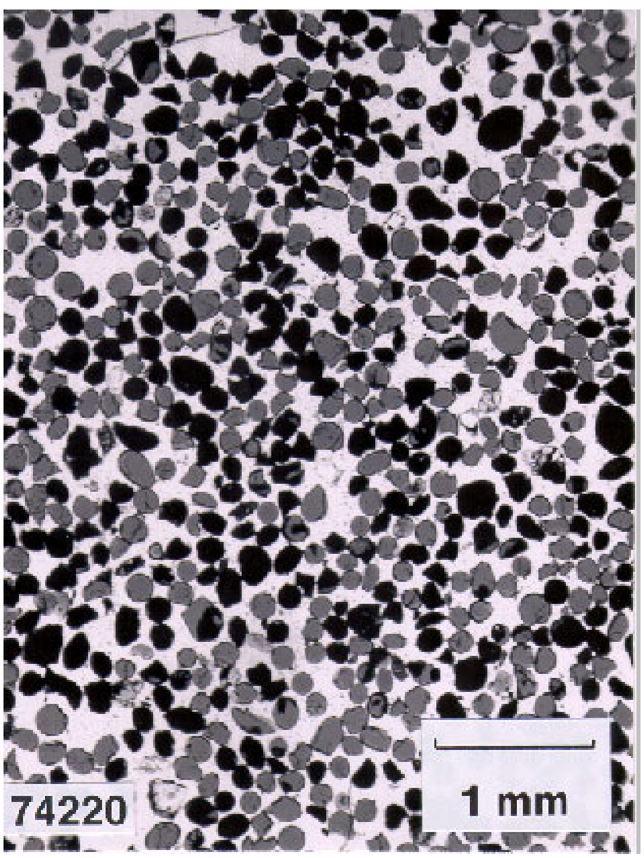

Figure 32 - Thin section photo of orange soil 74220. Spheroids of glass and devitrified glass (opaque) make up most of the sample. Sizes range from 40 to 80 microns.

Figure 33 - Barred olivine chondrule from 74220. Olivine is coated with minute crystallites of opaque ilmenite.

Opaques - Dendritic crystallites of ilmenite often form as parallel intergrowths with olivine or as minute submicroscopic crystallites coating olivine needles causing the devitrifidd glass to appear opaque (fig. 33).

Petrogenesis - It has been variously proposed that this glass could have originated by (1) endogenous lunar volcanism with associated lava fountaining, (2) an exogenic meteorite impact with associated vapor condensation to form the spheres, or (3) a meteorite impact into a liquid lava lake. Most lunar scientists now accept the lava fountain hypothesis, because trace element data do not support a meteorite origin. Composite glass particles formed by collisions in flight while the glass was still liquid (fig. 16). Volatile coatings (primarily ZnS) were found on the outer surfaces of the spheres by Meyer *et al.* 1975. Of course, no "Pele's hair" is found on the Moon, because there was no atmospheric drag on the liquid glass droplets.

Plutonic Rocks

The photograph of the back side of the Moon (fig. 34) illustrates how thoroughly the lunar highlands have been cratered. From this, it is easy to see why it has proven difficult to obtain many unaltered samples of the early lunar crust. It is safe to say that all samples from the lunar highlands must have undergone several cratering events.

The main criteria for identification of lunar plutonic rocks has been for homogeneous mineral chemistry combined with very low Ir and Au concentrations. For this, electron microprobe and instrumental neutron activation analyses have proven to be the most useful analytical tools of the lunar program. Coarse grain size and/or distinctive polygonal texture also are used (*see* last figure in appendix 2). Other criteria were given by Warren and Wasson 1977 and Warner and Bickel 1978.

Most plutonic rock fragments were found at the Apollo 16 and Luna 20 sites on the lunar highlands or at the Apollo 15 and 17 sites adjacent to the highlands. Table V is a list of the some of the "pristine" fragments of the original lunar crust. Plutonic samples mainly are mainly found enclosed as clasts in breccia samples from these sites, and most of them have crushed and/or annealed textures. Thin sections of anorthosite 60025 and norite 78235, included in this study set, illustrate the rather severe effects of shock, granulation and annealing that have modified these rock and made it difficult at best to date and or model their origin.

The lunar highlands contain an abundance of anorthositic material without a significant complementary, mafic component. Although many large anorthosite samples were returned, only one large dunite (72415) and one

Figure 34 - Back side and west limb of the Moon as photographed by the Apollo 16 metric camera (no. 3021) as the crew headed home. Note that heavily cratered highlands cover most of back side.

large troctolite sample (76535) were found. This observation has led to the interpretation that the Moon originally had an anorthositic crust. This crust must be relatively thick, otherwise the large basin's would have yielded numerous mafic fragments along with the abundant anorthositic material.

Lunar anorthosites have relatively high Fe/Mg ratios and are termed ferroan anorthosites. Two additional suites of plutonic rock, Mg-norite and Mg-gabbronorite, have been identified (James and Flohr 1983), but they have a different trend of Fe/Mg ratios in the mafic minerals with increasing Na in the plagioclase (fig. 35). Apparently, the Mg-norites and Mg-gabbronorites did not form during the initial differentiation which produced lunar anorthosite. Instead, they probably crystallized from mafic parent magmas that were generated after the primordial anorthositic lunar crust was formed. It is thought that the norites formed in layered intrusions that formed from basaltic magma generated by partial melting of subcrustal rocks.

Table V. – Pristine Plutonic Fragments of the Original Lunar Crust

Sample	Rock Type	Weight, grams	Age / Technique million years		Special Features
72415	Dunite	55	4450 ± 100	Rb/Sr	symplectite
76535	Troctolite	155	4260 ± 60	Sm/Nd	old Rb/Sr age
78235	Norite	400	4340 ± 40	Sm/Nd, Rb/Sr	
77215	Norite	846	4370 ± 70	Sm/Nd, Rb/Sr	
73255,27	Norite	clast	4230 ± 50	Sm/Nd	
72275	Norite	10	4080 ± 50	Rb/Sr	
76255	Norite	300			
15455	Norite	200	4480 ± 120	Rb/Sr	
72435	mafic clast				cordierite
15405,57	quartz monzodiorite (e)		4294 ± 26	U/Pb	zircon
15455	mafic clast				cordierite
15445,17	Norite clast (b)		4460 ± 70	Sm/Nd	
15445,247	Norite clast (b)		4280 ± 30	Sm/Nd	
15455,228	Anorthositic norite (b)		4530 ± 290	Sm/Nd	
67435	Troctolite	2			Mg spinel
15405,57	Monzodiorite	3	4320 ± 20	U/Pb	zircon
14321,1027	Granite (e)	clast	3965 +20/-30	Rb/Sr, U/Pb	pyrochlore
14303,209	Granite (e)	clast	4308 ± 3	U/Pb	zircon
14306,60	Ferrogabbro (e)	clast	4200 ± 30	U/Pb	zircon
15362	Anorthosite	4			
15415	Anorthosite	269			"Genesis rock"
60025	Anorthosite	1836 (d)	4440 ± 20	Sm/Nd, U/Pb	
67016,328	Ferroan noritic anorthosite (f)		4562 ± 68	Sm/Nd	
67075	Anorthosite	219			
67667	Lherzolite		4180 ± 70	Sm/Nd	
78155	Granulite	401	4200	U/Pb	
62236	Ferroan anorthosite (a)		4294 ± 58	Sm/Nd	
67215	Ferroan noritic anorthosite (c)		4400 ± 110	Sm/Nd	
Y86032GC	Ferroan anorthosite		4490 ± 90	Sm/Nd	meteorite clast

references: (a) Borg *et al.* 1999, (b) Shih *et al.* 1993, (c) Norman *et al.* 2003, (d) Carlson and Lugmair 1988, (e) Meyer *et al*. 1996, (f) Alibert *et al*. 1994

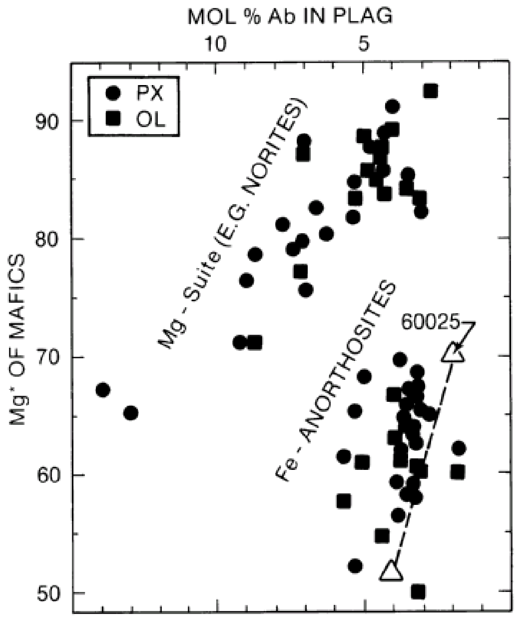

Figure 35 - Chemical composition of co-existing plagioclase and mafic minerals in pristine plutonic lunar rocks. The Mg-norites and Fe-anorthosites have different trends and are presumed to be from unrelated series of rocks. Note that the mafics in 60025 vary widely (from Ryder 1982).

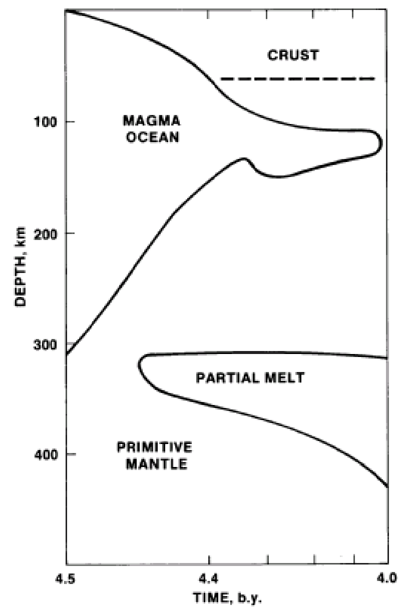

Figure 37 - Simplified thermal model of the Moon illustrating the depth of the magma ocean as a function of time (after Solomon and Longhi 1977). Radioactive decay of U extends the life of the magma ocean and initiates partial melting of the primitive interior.

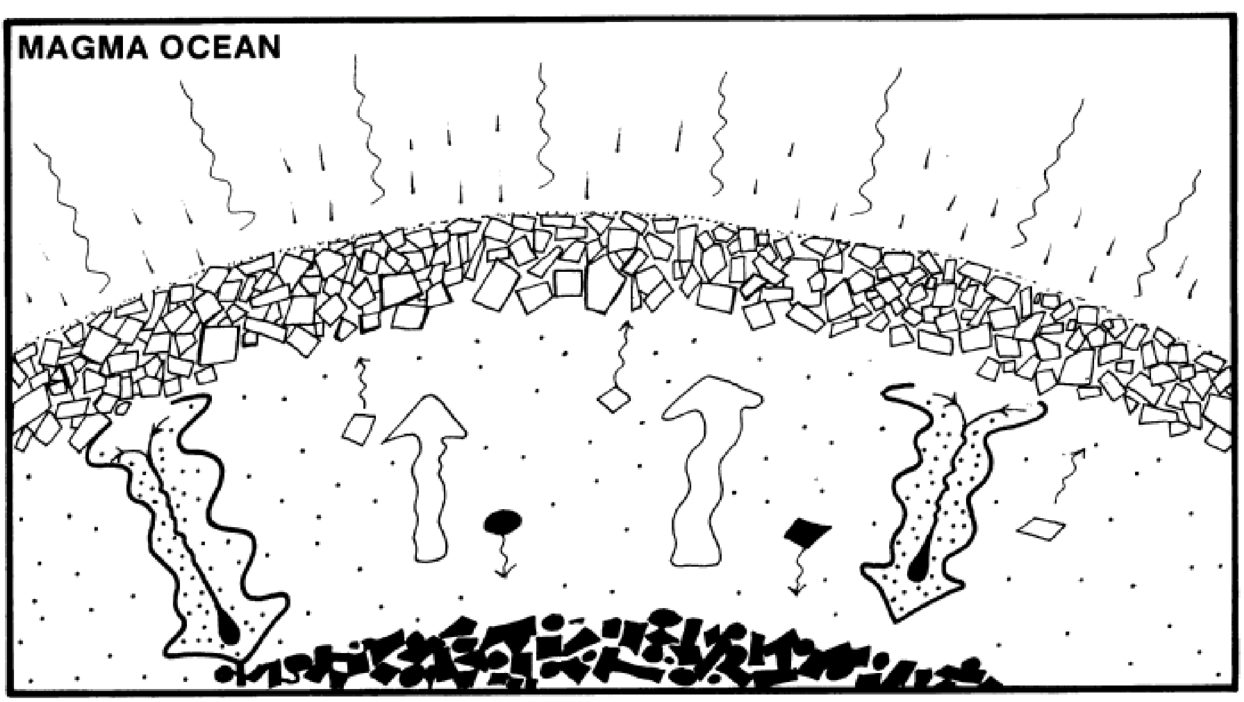

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Figure 36 - Cartoon of lunar magma ocean (after Walker 1983). In this model, mafic minerals sink as "density masses" and plagioclase crystals float or are formed at the surface. This model has been used to explain the apparently thick feldspar-rich original crust of the Moon. Convection is required to remove heat rapidly so that there is a rigid crust by the time of the basin-forming events.

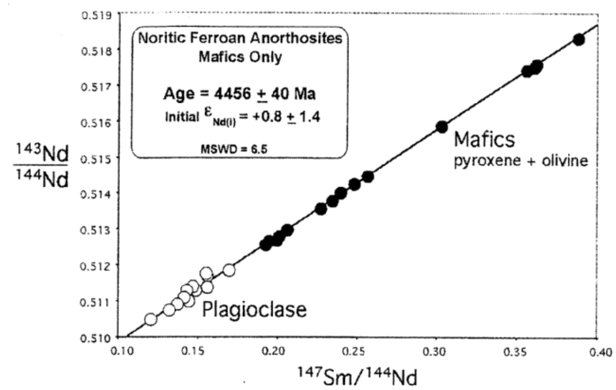

Figure 38 - Model age for formation of lunar crust based on mafic minerals from ferroan anorthosites (Norman *et al.* 2003, MAPS **38**, 659).

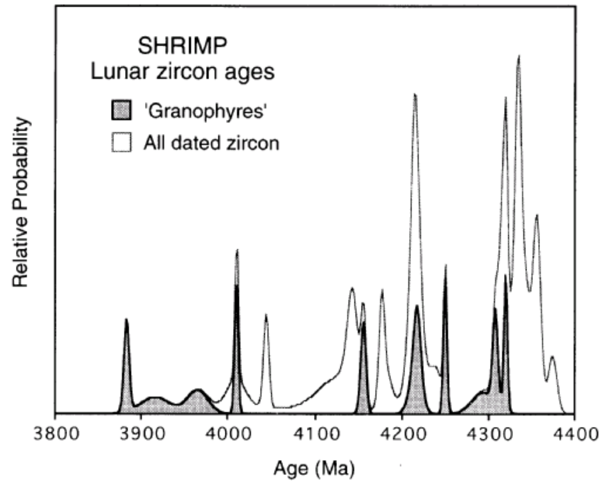

Figure 39 - Summary of ages of lunar zircons (from Meyer *et al*. 1996, MAPS **31**, 383). Some zircons are from "granophyre" but others are from norite and other plutonic rocks.

The global distribution and high chemical purity of lunar anorthosite has led to the model of a global lunar magma ocean hundreds of kilometers thick (Warren 1985). It is apparent that Ca-rich plagioclase (anorthite with a density of 2.7 g/cm^3) floats in anhydrous magma of bulk lunar composition (Walker and Hays 1977). Figure 36 illustrates the flotation of plagioclase and sinking of mafic minerals in a lunar magma ocean. The initial heat source for this magma ocean was the rapid terminal accretion of the outer part of the Moon. Figure 37 illustrates one of the early thermal models for the solidification of such a magma ocean, but perhaps you can see what is obviously wrong with such a model! There are many alternatives to this simplified model (*see* Proceedings of the Lunar and Planetary Science Conferences).

Tremendous effort has been invested to radiometrically date fragments of lunar plutonic rocks and determine their initial isotopic composition (see summary Table V). Some samples, like troctolite 76535, have yielded "discordant" ages by different techniques! Much work remains to be done in the isotopic study of old lunar rocks, and we have learned that it needs to be led by careful petrography. Figure 38 is an "isochron" of mafic fractions of various anorthosites and perhaps represents the best way to obtain the age of the original anorthositic crust of the moon. Figure 39 is a summary of the ages obtained U/Pb ion microprobe dating of lunar zircons. New techniques need to be developed and applied.

Description of 60025

Lunar sample 60025 is a cataclastic anorthosite from Apollo 16. In detail, this sample is found to be a densely lithified mixture of pieces of plagioclase-rich rock from a related sequence of lunar anorthosites (Ryder 1982). It is 98 percent plagioclase and only about 2 percent pyroxene (fig. 40). Small "clumps" of mafic minerals are in the hand specimen, but these are not represented in the thin sections. The composition of this rock is given in table VI. The age of this rock is 4440 million years.

Olivine - Trace olivine Fo_{65-67} is found with low- Ca pyroxene in "mafic clumps."

Pyroxene - Small subhedral grains of augite and orthopyroxene are found in the fine-grained matrix. Some pigeonite grains are exsolved. The pyroxenes exhibit a wide miscibility gap on the pyroxene quadrilateral (fig. 41) indicative of equilibration at relatively low temperature. There is a rather wide range of pyroxene composition En_{50-75}.

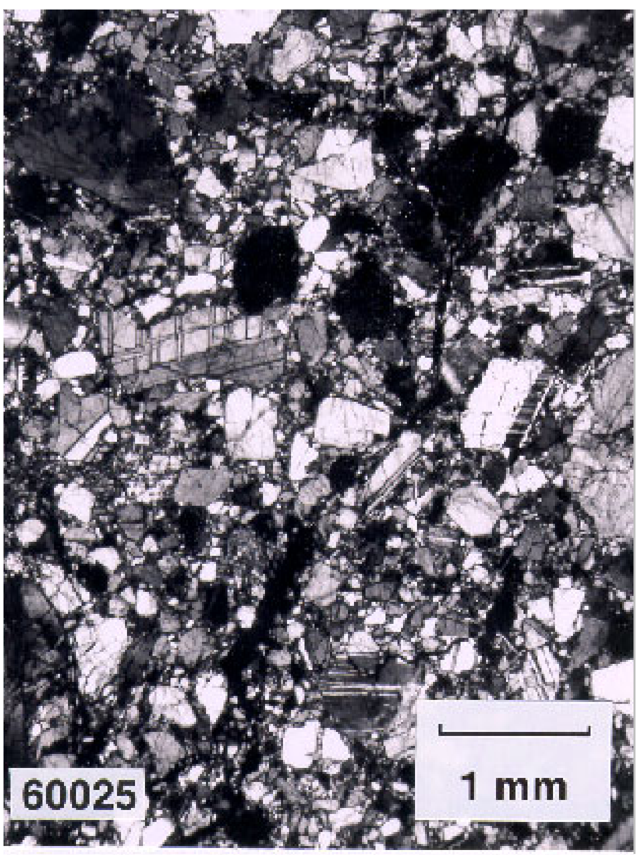

Figure 40 - Cross-polarized-light photo of cataclastic anorthosite 60025. Note the "kink banding" of the polysynthetic twinning in the shocked plagioclase.

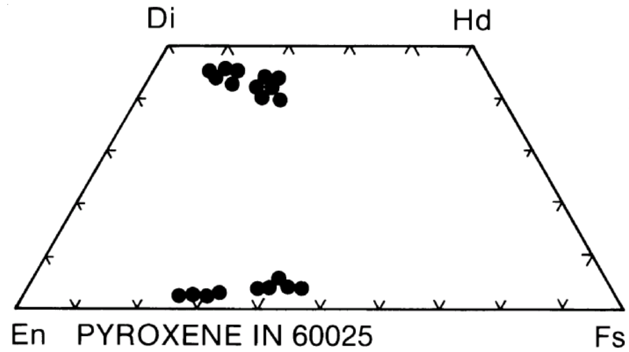

Figure 41 - Composition of pyroxene in cataclastic anorthosite 60025. This is a rather wide range for pyroxene in a plutonic rock and indicates that sample 60025 has formed from a series of related anorthosites.

Plagioclase - Large plagioclase crystals have been fractured and crushed. Some of the crystals show polysynthetic twinning. Twin lamellae are often bent or offset by fractures and/or strain induced by shock. The plagioclase in this rock is An_{95-97}.

Opaques - Minute crystals of ilmenite, metallic Fe, and troilite have been found as inclusions within plagioclase. Chromite has been reported in the "mafic clumps."

Petrogenesis - The monomineralic nature of this rock requires a cumulate origin. Actually, the range in pyroxene composition requires that it be a mechanical mixture of a series of related anorthosites (Ryder 1982). The relatively Fe-rich nature of trace mafic minerals is typical of lunar anorthosites and has led to the term ferroan anorthosite.

TABLE VI.— COMPOSITION OF PLUTONIC ROCKS, SOILS, AND BRECCIAS

	Plutonic Rocks		Soils		Breccias		
	60025	78235	68501	70181	14305	15299	72275
SiO_2	43.9	49.8	45.2	40.9	49.2	46.4	48.3
TiO_2	.02	.19	.58	8.1	1.7	1.5	1.0
Al_2O_3	35.2	17.1	26.6	12.3	16.0	16.3	16.3
FeO	.67	7.5	5.5	16.4	9.5	12.0	11.0
MnO	.03	.12	.07	.24	.18	.15	.17
MgO	.27	15.0	6.3	9.8	12.0	11.1	10.3
CaO	18.9	9.9	15.3	11.0	7.4	11.8	11.0
Na_2O	.49	.35	.47	.35	.85	.49	.44
K_2O	.03	.06	.11	.08	1.2	.20	.25
Cr_2O_3	.04	.35		.44	.17	.34	.35
Total	99.55	100.37	100.13	99.61	99.1	100.28	100.01

note: Composition of Mare Basalts are given in table IV and figure 11.

Description of 78235

Lunar sample 78235 is a heavily shocked norite from the lunar highlands. This sample is a coarse-grained (5 mm) plutonic rock composed of about 50 percent plagioclase and 50 percent orthopyroxene with numerous veinlets of brown glass. Despite a high degree of shock, the mineral boundaries of the original cumulate have been well preserved (fig. 42). Lunar sample 78235 has been studied by Steele 1975, Sclar and Bauer 1975, McCallum and Mathez 1975, and Dymek *et al.* 1975. The composition is given in table VI.

Pyroxene - Orthopyroxene is light brown and shows undulatory extinction and mosaicism. It is highly cracked, because of the expansion of the adjacent plagioclase. There is no pyroxene exsolution. Rare grains of clinopyroxene occur as inclusions in the plagioclase and in the mesostasis. Pyroxene compositions are given in figure 43.

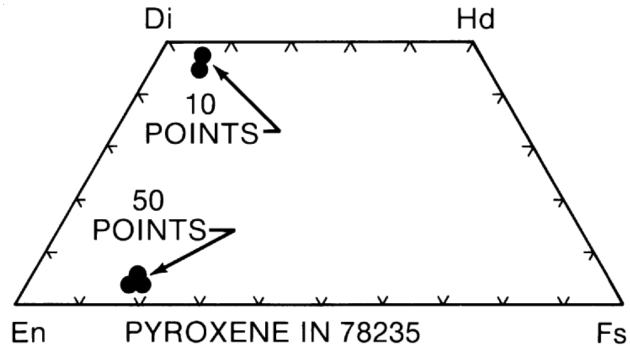

Figure 43 - Composition of pyroxenes in 78235. The orthopyroxene host contains exsolved augite indicating slow cooling in a plutonic environment.

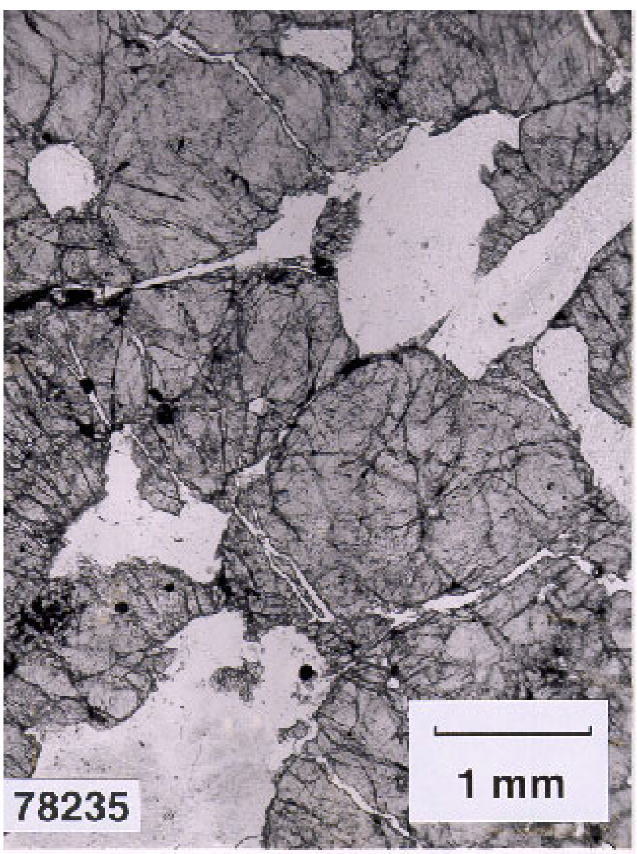

Figure 42 - Photo of shocked norite 78235 showing large cracked pyroxenes and maskelynite. The expansion of the diaplectic plagioclase has caused the cracks in the pyroxene.

Plagioclase - Most of the plagioclase has been shocked to isotropic maskelynite. It is chemically homogeneous at An_{95}. Some plagioclase has partially recrystallized.

Mesostasis - Interstitial areas between the pyroxene and plagioclase crystals have the triangular shape characteristic of cumulate rocks. Accessory minerals in the mesostasis include silica, troilite, Fe-metal, Nb-rutile, chromite, whitlockite, and baddeleyite.

Glass - Numerous glass veins penetrate this rock. It has been highly shocked.

Petrogenesis - Lunar sample 78235 is a pristine norite of cumulate origin. The original crystallization age of this norite was about 4300 million years. Several other lunar rocks originated at this time (Table V). Sample 78235 has been highly shocked, but has retained its original mineralogy and texture. It was chipped off of a small, glass-covered boulder on the surface of the regolith at the Apollo 17 site. The boulder could have been locally derived or it could have been thrown there from a great distance away.

Lunar Breccia

Figure 44 - The large boulder at station 6, Apollo 17, has rolled down from the North Massif. Samples of this boulder are all breccias with a poikiloblastic texture typical of a melt sheet. NASA photo AS-17-164-5954. *(note the astronaut pushing his rover back uphill)*

Lunar breccias are the lithified aggregates of clastic debris and melt generated by meteorite bombardment of the lunar surface. Most of the breccias returned by the Apollo missions were formed in the ancient lunar highlands about 3900 to 4000 million years ago. A few breccias (sample 15405) are younger and were formed from the lunar regolith (fig. 2). In the Apollo collection, 59 breccia samples weigh over 500 g each, and there are many more samples with smaller sizes. These breccias have a wide variety of matrix-textures - from fragmental to vitric to crystalline. A wide range of crater sizes are found on the Moon, and it is easy to see why a wide range of breccia types is also present. Lunar breccias can originate from either large or small craters and/or from different radial distances from large craters.

This thin section set includes five different lunar breccias from the lunar highlands. Sample 60025 is a cataclastic anorthosite that has already been discussed as a plutonic rock. Sample 14305 is a crystalline matrix, fragmental breccia typical of the Fra Mauro Formation, which is ejecta from the Imbrium basin. An example of a breccia from a large crater is the poikilitic rock 65015, which is thought to have originated as part of a melt sheet in a large lunar crater. Poikilitic texture similar to that of sample 65015 was also typical of the large boulders at the Apollo 17 site (fig. 44). Sample 72275 is a friable fragmental breccia from the edge of the Serenitatis basin. Sample 15299 is a vitric matrix breccia that is probably from a small crater in the local lunar regolith at the Apollo 15 site. This breccia type is termed regolith breccia because it closely resembles consolidated lunar soil.

A committee report (Stöffler *et al.* 1980) classifies breccias as either monomict, polymict or dimict. The monomict breccias are cataclastic rocks formed by in-situ brecciation of a single lithology (monolithologic). Polymict (or polylithologic) breccias consist, of two main textural components which are termed matrix and clasts. Such breccias result from the mixing of different lithologies formed under different conditions at different selenological locations. Polymict breccias may have either a clastic matrix, a 'melt' matrix which is crystallized or glassy, or a metamorphic matrix. The clastic matrix consists of individual mineral grains, mineral clasts, and in some cases, of additional glassy particles. Breccia clasts, in tern, form the host for other rock clasts. The grain size of all clasts is more or less seriate. We define the matrix arbitrarily as the grain size fraction that is smaller than 20-25 microns. The 'melt' matrix is characterized by a variety of textures ranging from holocrystalline (crystalline matrix) to glassy (glassy matrix). Some crystalline and semicrystalline textures appear to result from devitrification of glass. The metamorphic matrix is represented by a recrystallization texture which is granoblastic to poikiloblastic.

In general, the breccia clasts are mineral fragments and fragments of rocks with igneous, metamorphic, and breccia texture, and glassy or partially recrystallized melt bodies or fragments thereof. Many of the clasts are themselves breccias, giving the rock a "breccia-in-breccia" texture. Dimict or dilithologic breccias are characterized by an unusual structural feature in which a crystalline matrix is combined with a monomict cataclastic breccia texture in an intrusive or vein-like relationship.

The geologic setting of breccias generated in large basin-forming impacts is illustrated in figure 45. Cratering mechanics is such that ejecta blankets have a reverse stratigraphy compared to that of the target where material that was from the bottom of the crater is deposited on top of the ejecta blanket (fig. 46). Material from the bottom of the crater also is deposited close to the crater rim, and material from the surface of the target is deposited further out *(in Texas, we call this the "laid back"' model).* Fragmental breccias are found in the ejecta blankets beyond the rims of impact craters. They can have fragmental, glassy, or crystalline matrices depending on the distance from the crater and/or the size of the crater. If the crater is large enough, melt sheets of partially digested clastic debris can form from fallback within the walls of large craters. Monomict or dimict breccias form in the bedrock or central uplift. The heat generated by frictional forces in the granular target material is carried

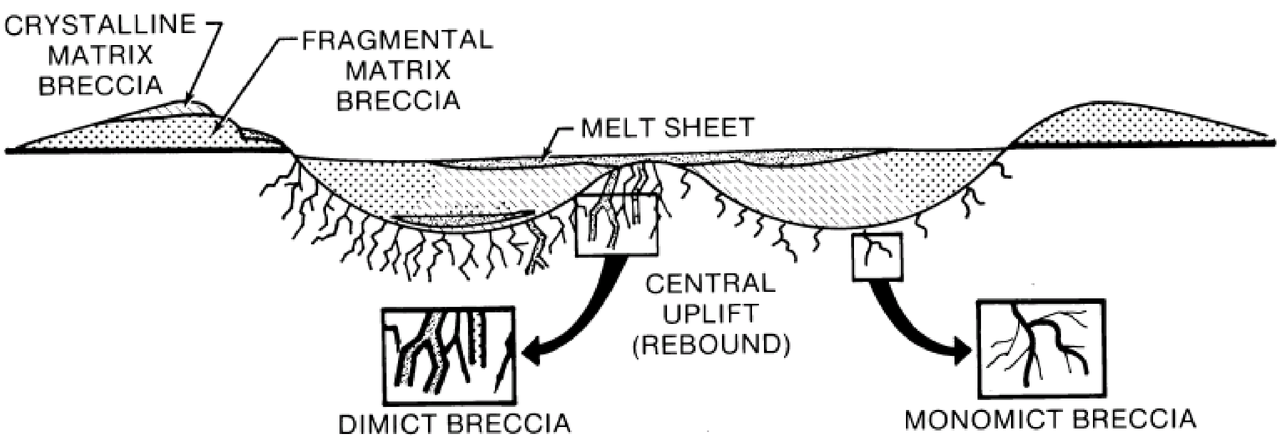

Figure 45 - Geological setting of impact breccias in a giant impact crater. The shock wave granulates the underlying bedrock producing monomict breccias. In some craters, there is a central peak formed by rebound of the substrate. Dimict breccias form when veins of shocked rock are filled with impact melt. Fragmental ejecta is ballistically thrown great distances from the crater and is a polymict mixture of rock fragments from the crater cavity. A mixture of hot and cold fragmental debris falls back into the crater forming crystalline matrix breccias and melt sheets.

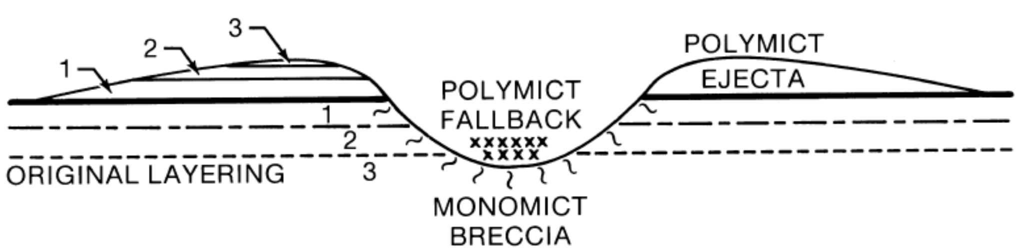

Figure 46 - The material that is thrown out of the crater is deposited in a reverse stratigraphy on the rim of the crater. This is called the overturned-flap concept. Material from the bottom of the crater is deposited on top of the ejecta blanket and close in to the rim.

to the depositional site where, consolidation occurs. Finally, lithification of the breccias is caused by sintering of the mixture of hot and cold fragmental material in the ejecta blanket or melt street.

Most lunar breccias are of a polymict nature. Mixing of rock types can occur in a single impact or can be the result of many impacts. Figure 47 is a photograph of the sawn surface of lunar breccia 14306 illustrating clasts of various rock types including mare basalts, norites, anorthosites, and microbreccias. All are included in a fine-grained matrix of lithic and mineral fragments. The compositions of lunar breccias are also consistent with mixtures of known lunar rock types (Schonfeld and Meyer 1972). All lunar breccias have relatively high Al_2O_3 content due to the abundance of plagioclase in the lunar highlands. It is not necessary to invoke a high percentage of exotic rock to explain the chemical composition of any lunar breccia. Compared with pristine lunar rock, all lunar breccias contain relatively high Ir and Au contents. It is thought that these trace elements come from meteoritic material that has bombarded the Moon. Distinctive chemical signatures of the added meteoritic component have even been used to identify the lunar basin of origin (Hertogen *et al.* 1977). Apparently, the vaporized meteorite becomes entrained and thoroughly mixed with the target material during a single impact. Calculations show that about 1 to 2 weight percent of meteorite material has been admixed, into lunar breccias. Melted iron particles from meteorites can be found in the matrix of lunar breccias. Other meteorite minerals are completely obliterated.

Figure 47 - Sawn surface of fragmental lunar breccia 14306 illustrating the polymict nature of lunar brcccias. This is a sample of the Fra Mauro Formation and is typical of ejecta from large basins. NASA photo no. 72-22103

Description of 14305

Sample 14305 is a clast-rich polymict breccia with a fine-grained recrystallized matrix (fig. 48). It is similar to most of the rocks brought back from the Apollo 14 site and is thought to be a piece of the Fra Mauro Formation. The Apollo 14 breccias are about 3820 million years old and this is interpreted as the age of the Imbrium event. Simonds *et al.* 1977 summarize the breccia samples from Apollo 14. See also figure 47 which illustrates the clastic nature of Apollo 14 breccia.

Matrix - The microcrystalline matrix is best seen in reflected light using a high, power objective (fig. 49). It has a very fine-grained subophitic texture with euhedral plagioclase and ilmenite with patches of low-Ca pyroxene.

Glass - Glass is not present now in clasts nor in the matrix. It has all been recrystallized.

Clasts - Most of the clasts in this rock are microbreccias. However, Shervais *et al.* 1983 report a wide range of igneous clast types including mare basalt, granite, gabbronorite, alkali anorthosite, and troctolite.

Petrogenesis - Several impact events are required to produce the breccia-in-breccia texture of this rock. The final thermal event produced a melted matrix but was not hot enough to digest the various lithic clasts. Sufficient heat for complete recrystallization of the melted matrix was required, however. Despite various models for the formation of the Fra Mauro Formation, scientists still don't fully understand the clast distribution or recrystallization of the matrix of these breccias!

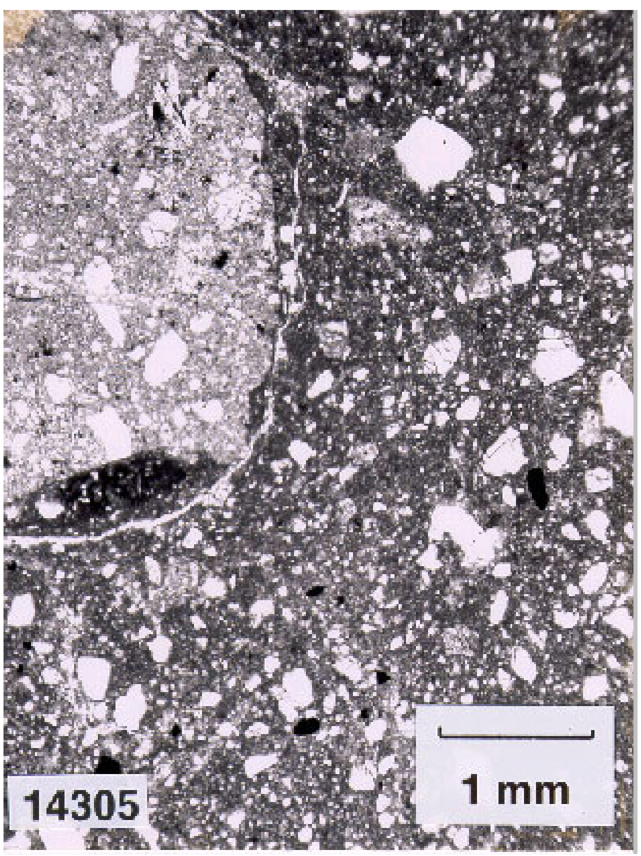

Figure 48 - Photomicrograph of thin section of polymict breccia 14305 illustrating the breccia-in-breccia texture typical of the samples of the Fra Mauro Formation.

Figure 49 - The crystalline matrix of 14305 is an intergrowth of plagioclase and orthopyroxene. This is a reflected light photo.

Description of 65015

Sample 65015 is an impact-melt breccia that was collected from the lunar highlands during the Apollo 16 mission. It is a very dense and coherent sample with distinctive poikilitic texture (fig. 50). It is clast-rich and holocrystalline and has been studied in detail by Albee *et al.* 1973. The age of the sample is about 3930 million years.

Matrix - Pigeonite oikocrysts are peppered with abundant equant chadacrysts of plagioclase and rare embayed chadacrysts of olivine and augite. Areas between oikocrysts contain irregular vug's, plagioclase laths, K-feldspar, phosphate, and troilite.

Clasts - Large plagioclase grains (1 mm) are included as the most abundant clasts. Various lithic clasts including polygonal anorthosite, gabbroic anorthosite, and intersertal basalts are present in some thin sections.

Glass -None.

Opaques - Ilmenite occurs predominantly as irregular poikilitic grains including plagioclase laths (fig. 51). It contains exsolution lamellae of rutile and Cr-rich spinel. Globules of metallic iron are present in some sections

Petrogenesis - The clast assemblage indicates that the protolith for this sample was a polymict mixture of highland rock types. The recrystallized matrix indicates that this sample is from a melt sheet of fallback breccia inside a relatively large lunar crater. It is thought that a mixture of both hot and cold fragmental material falls

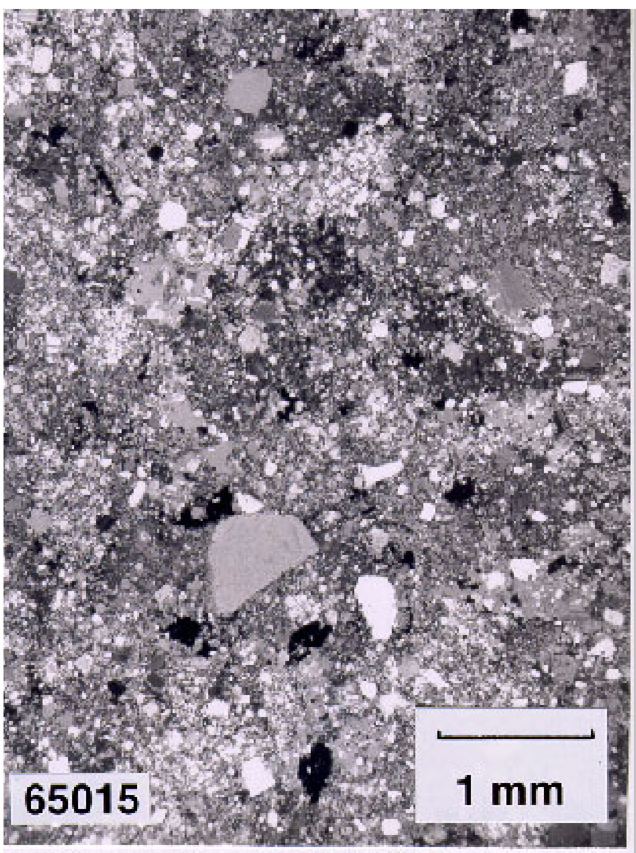

Figure 50 - Partially polarized, transmitted-light photo of the poikiloblastic texture of the matrix of 65015. Small chadacrysts of plagioclase are poikilitically enclosed in large orthopyroxene oikocrysts which fit together like pieces of a jigsaw puzzle.

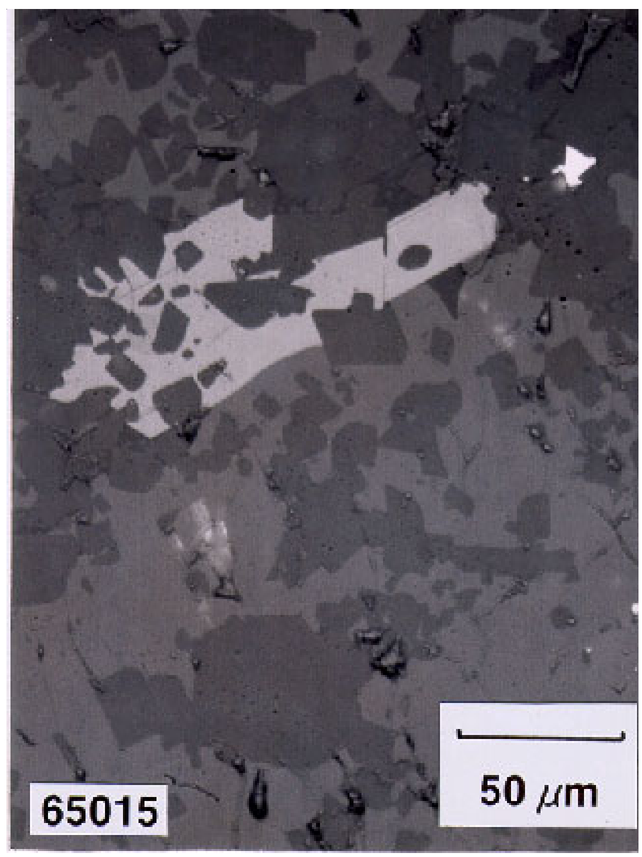

Figure 51 - Reflected light photo of poikilitic ilmenite and orthopyroxene in 65015.

back into the crater, forming a lava lake that initially cools rapidly while the cold fragments are partially dissolved by the superheated hot melt. This initial quench prevents separation of phases such as metal iron or gas (voids). In this model, the quenched lava lake equilibrates slowly, forming the unusual poikilitic texture of the matrix. Rocks with this texture are found in the melt sheets in the centers of large terrestrial craters. The large boulders sampled at the Apollo 17 site also had this texture.

Description of 72275

Lunar sample 72275 is a friable feldspathic breccia with an aphanitic matrix that was chipped from a boulder within a landslide from the South Massif at the Apollo 17 site. This sample has a wide variety of clast types derived from the lunar highlands (Stoeser *et al.* 1974). It doesn't contain any of the high-Ti mare material found at the Apollo 17 site.

Matrix - Portions of the light friable matrix of sample 72275 are very porous (5 to 30 percent). The major mineral in the matrix is feldspar. This sample has a breccia-in-breccia texture where clasts of darker microbreccia are included in the light feldspathic matrix (fig. 52). The darker areas have a higher percentage of fine matrix to clasts.

Glass - This sample is glass poor. Much that appears to be glass is really maskelynite (shocked plagioclase) or void. Void spaces are filled with epoxy and can be best detected by checking in reflected light.

Opaques - Many small grains of disseminated metallic Fe and troilite are in portions of this sample. In some thin sections, the Fe in the silicate minerals is in the process of being reduced to metal (fig. 53). The cause for this reduction is unknown. Very little ilmenite is present.

Lithic clasts - Look for subophitic basaltic clasts with felty white plagioclase laths and yellow pyroxenes that are included in some thin sections of this breccia. These are termed pigeonite basalts. There are some clasts of

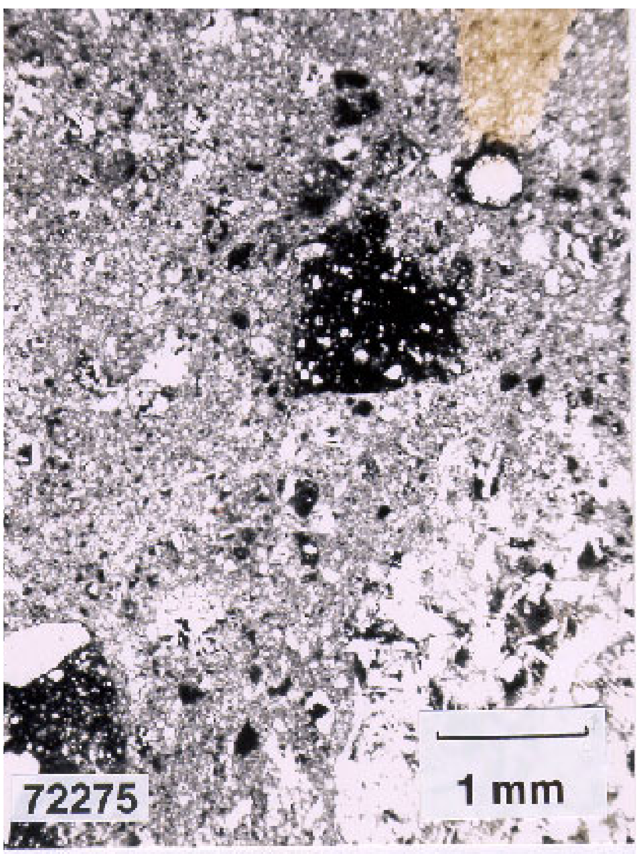

Figure 52 - Breccia-in-breccia texture of fragmental breccia 72275. This sample is feldspar rich. Note the clast of pigeonite basalt in this section.

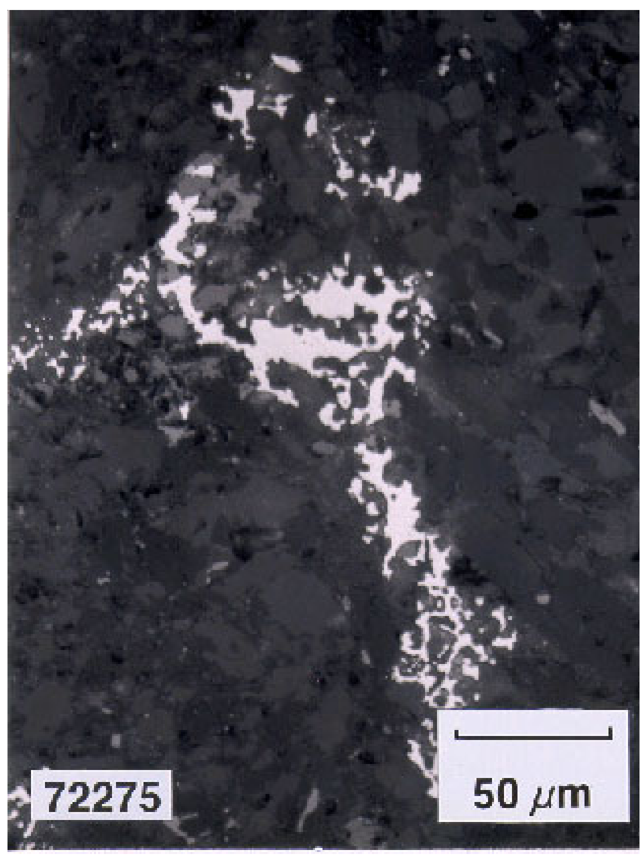

Figure 53 - Spongy mass of troilite and Fe are abundant in the matrix of 72275.

annealed plutonic rocks. These include plagioclase-rich granulitic breccias and cataclasites. These clasts have polygonal interlocking plagioclase and olivine with grain size about 100 microns and 120 deg interfacial angles. Small felsite clasts with intergrown K-feldspar and silica are also in some thin sections of this breccia. There are no clasts of mare basalt.

Petrogenesis - This is a polyrnict breccia derived from a variety of highly reworked highland rocks. The clast distribution in sample 72275 is different from the poikilitic breccias found on the North Massif. The presence of clasts with fine subophitic basalt texture indicates that at least part of sample 72275 was derived from near the lunar surface. The relationship of Apollo 17 breccias to their source of origin in the ejecta from the large lunar basins was discussed by Spudis and Ryder 1981. Can both types of breccia be Serenitatis ejecta?

Lunar Regolith

Figure 54 – Footprint in lunar soil. Few rocks are sitting out on top of mature regolith. NASA photo AS11-40-5877.

The lunar surface is covered by a layer of unconsolidated debris called the lunar regolith (fig. 53). The thickness of the regolith varies from about 5 m on mare surfaces to about 10 m on highland surfaces. 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 (reviews by Heiken *et al.* 1974 and Papike *et al.* 1982). About half the weight of a lunar soil is less than 60 to 80 microns in size. The grain size distribution is given in figure 55.

Since the Moon lacks any sort of an atmosphere, the upper few millimeters of the regolith is exposed to the bombardment of micrometeorites and to solar wind irradiation. The extensive bombardment by micrometeorites, which continues today, breaks up soil particles and melts portions of the soil. The melt, mixed with lithic fragments, forms irregular clusters called agglutinates (fig. 56). At the same time, the solar wind implants large quantities of H and He and trace amounts of other elements. Continued reworking by micrometeorites of the hydrogen-enriched soil particles causes melting, and the reaction of H with FeO forms H_20 vapor and submicroscopic metallic Fe grains in the resulting agglutinate glass. This process continues until the surface layer is buried by fresh ejecta or is broken up by a large crater. Trenches and core tubes into the regolith reveal that it is stratified with many buried soil horizons. The maturity of a regolith sample is the integrated exposure that it had to the micrometeorite and solar wind environment. Maturity is variously measured by the agglutinate content, grain size distribution, and/or the amount of implanted solar wind rare gases. However, the easiest way to measure maturity has proven to be by magnetic determination of the amount of submicroscopic iron (Morris 1978).

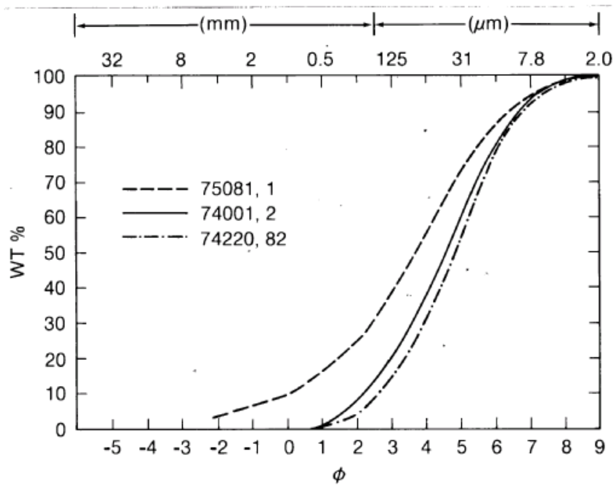

Figure 55 - Grain size distribution of mature lunar soil (75081) and orange soil (74220). About 10 percent of a lunar soil is greater than 1 mm, 50 percent is greater than 100 microns, and 90 percent is greater than 10 microns (from Heiken *et al.* 1974).

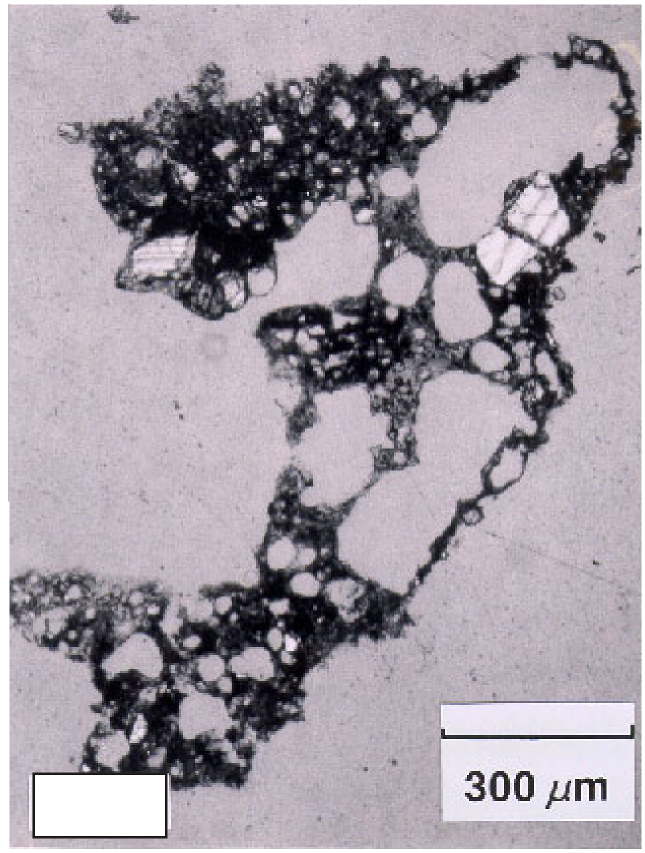

Figure 56 - Thin section photo of a lunar agglutinate. Vesicular glass welds soil particles together. Minute Fe particles are present in the glass.

The rays of Moon craters are evidence that small particles can travel great distances on the Moon. Glass and lithic fragments in the lunar soil are of great interest, because they provide clues of the nature rocks derived from well beyond the sampling site. For this reason, lunar scientists have shown great interest in the coarse-fine fraction of the lunar soil. Coarse-fines are the sand size particles in the lunar regolith. This thin section set includes 1-2 mm and 2-4 mm coarse-fines from both a highland and a mare site. The coarse-fines include glasses, locally derived and exotic lithic fragments, microbreccias, and agglutinate particles.

The astronauts found few rock samples to pick up on mature regolith surfaces. The rocks had all been comminuted to fine soil, by the micrometeorite bombardment over the past billion years. Sampling strategy dictated that rocks be returned from the rims of fresh craters that had punched through the regolith (fig. 57). However, small meter-size craters into the lunar regolith cause breccias to form from the regolith itself. Many of the hand samples returned from the Apollo 11 and 15 sites were regolith breccias. Lunar breccia 15299 (included in this set) is thought to be a regolith breccia, because it has the magnetic properties of a submature lunar soil.

Finally, the lunar regolith also can include a percentage of pyroclastic material. Although no recognizable volcanic glass was found at the Apollo 16 site, a great deal of volcanic glass was found at the Apollo 15 and 17 sites (Delano and Livi 1981). Be sure to look for evidence of green glass in sample 15299 and of orange glass in the Apollo 17 soil samples. Volcanic glass has also been reported in the Apollo 11 soil breccias. How do you distinguish volcanic glass from glass made by meteorite bombardment?

Figure 57 - Meter-size craters in the lunar regolith are capable of producing soil breccias like 15299. Many were lined with glass in the bottom. Fresh craters 10 m and larger are required to dig up hand specimens from the bedrock. NASA photo no. AS12-47-6939

Description of 68501

Lunar sample 68501 is a mature highland soil from the Apollo 16 site. We have sieved some of the larger fragments (termed coarse fines) from this soil to illustrate some of the rock types from the heavily cratered highlands. They include feldspathic crystalline rocks of anorthositic or noritic composition, but many of the particles are microbreccias (fig. 58). Some fragments have been derived from melts produced by craters in the highlands.

Many types of glass and devitrified glass are present including agglutinates of soil particles. The vesicular glass in agglutinates was produced by micrometeorite bombardment of the soil. The gas that made the vesicles was water vapor derived by H reduction of FeO. Look for trains of minute Fe particles in the glass.

It is not easy to identify fragments in the highlands that are exotic to a site because the bedrock is very complex. However, it is apparent that the highlands are very rich in feldspar and that there are few opaques or fragments of mare basalts.

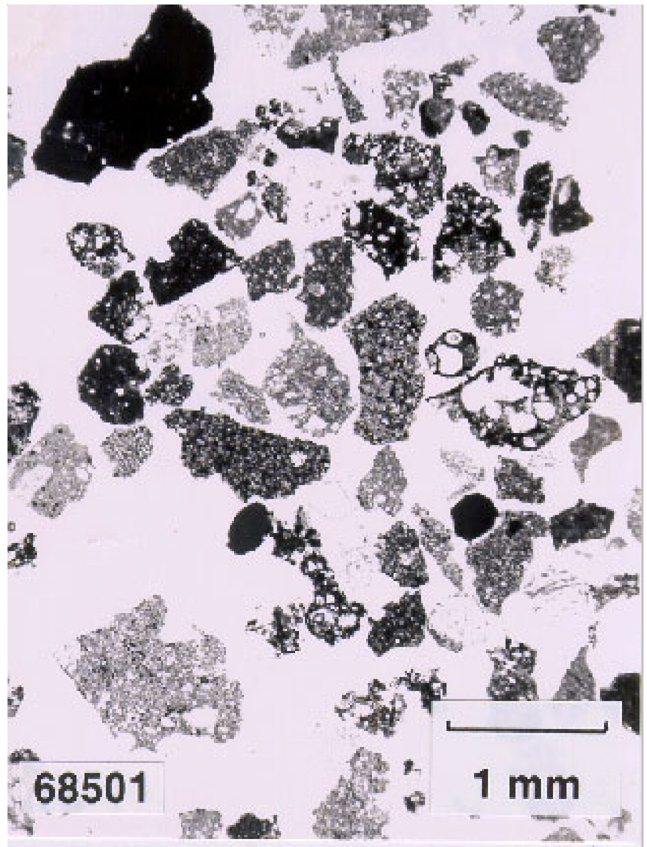

Figure 58 - Coarse-fine particles from mature highland soil 68501 including microbreccias and agglutinates.

Description of 75081

These are fragments of "coarse-fines" from a mature mare soil collected by the Apollo 17 astronauts. Most fragments are of high-Ti mare basalts that are local to the site (fig. 59). In this size range, many are only single minerals from mare basalts. There are a wide range of basalt textures. Vesicular glassy agglutinates are abundant in this soil (fig. 56). These contain trains of very fine metallic Fe grains that cause the ferromagnetic resonance signal used to determine the regolith maturity index. Larger Fe bleb may be from meteoritic debris.

Note the abundance of orange glass and devitrified glass similar to that of sample 74220. Can you find any exotic particles from the nearby lunar highlands in your thin section?

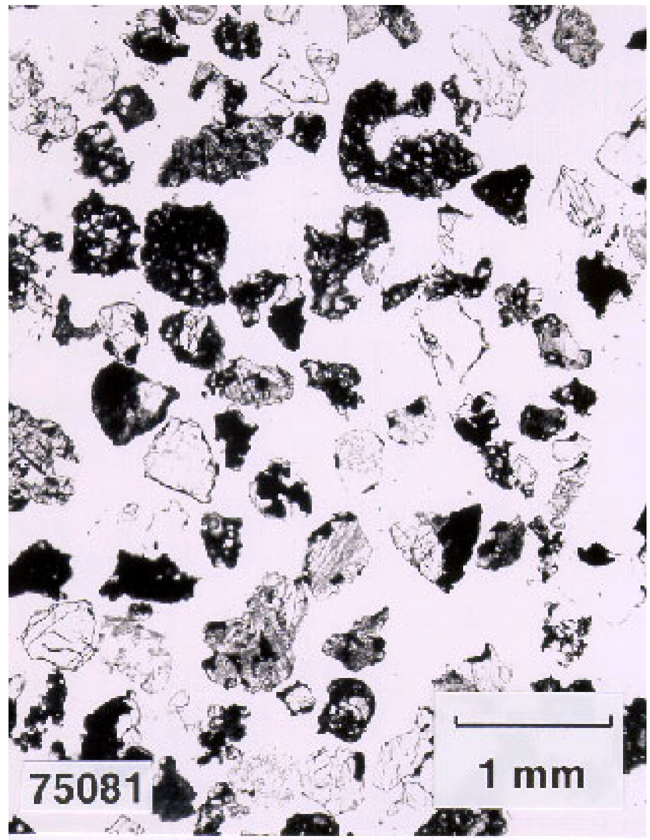

Figure 59 - Coarse-fine particles from mature mare soil 75081 illustrating fragments of mare basalt, orange glass, and rare feldspathic breccias from the nearby highlands.

Description of 15299

Lunar sample 15299 is a regolith breccia consisting of a wide variety of glass, mineral, and lithic fragments in a brown glass matrix (fig. 60). It was found part way up the slope of the Apennine front at the Apollo 15 site but it contains considerable mare material. Regolith breccias at the Apollo 15 site have been carefully studied by Simon *et al.* 1986.

Matrix - The brown glass matrix is about 30 percent by volume; porosity is about 5 percent. This is best determined with the help of reflected light. Some thin sections show vague evidence of foliation and microfractures are aligned. The bulk sample was friable.

Glass - Many glass spheres, fragments of spheres, and devitrified spheres are in the matrix of sample 15299 (fig. 61). Green glass spheres are colorless in thin section. Rare agglutinates are partly digested by the matrix. Note the tiny metallic Fe grains throughout.

Mineral Clasts - The grain size distribution is seriate. About half the clasts are individual grains of plagioclase, pyroxene, or olivine. Many have undulatory extinction typical of shock. There is a high percentage of opaque mineral fragments.

Lithic Clasts - About 10 percent of the clasts are mare basalt fragments and another 10 percent are plagioclase-rich highland fragments. Many microbreccias as clasts are within sample 15299.

Petrogenesis - Lunar sample 15299 has a composition similar to the local soil where it was found and is typical of the regolith breccias found at the Apollo 15 site. The presence of glass spheres and relict agglutinates is good petrographic evidence that the precursor to this sample was a soil. This breccia has a relatively high maturity based on the ferromagnetic resonance maturity index Is/FeO indicating that it has been formed from a submature lunar soil. The Is/FeO signal comes from

Figure 60 - Brown-glass-matrix breccia 15299 illustrating white clasts of feldspathic material from the highlands. NASA photo no. 74-32566

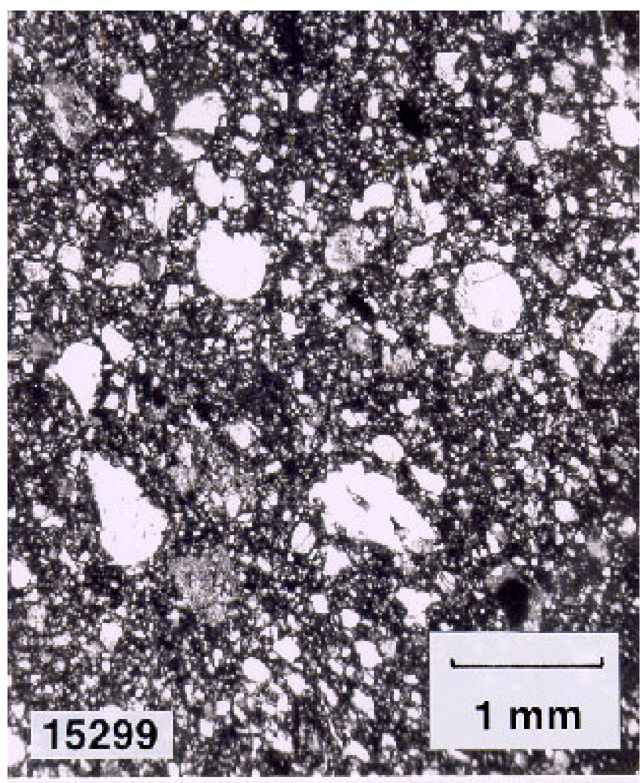

Figure 61 - Matrix of 15299 showing glass spheres which indicate this breccia was made from the local Apollo 15 soil.

the numerous tiny Fe grains that can be seen in reflected light. However, the presence of only a small percentage of recognizable agglutinates is puzzling. Perhaps these were incorporated into the brown glass matrix when the breccia was lithified.

Regolith breccias represent the opportunity to study ancient samples of the lunar regolith. We do not have a good way to date regolith breccias, but the inclusion of green glass spheres and fragments of mare basalts typical of the Apollo 15 site in this breccia proves that it is younger than 3200 million years. It could be as young as the small craters at this site.

Definitions of Lunar Terms

Agglutinates - Agglutinates consist of comminuted rock, mineral, and glass fragments bonded together with glass. The glass is black in bulk but pale to dark brown in thin section, and is characteristically heterogeneous with dark-brown flow banding or "schlieren." The glass contains many vesicles ranging in size from less than 1micron to 1cm and many minute, submicroscopic metallic Fe grains. The morphologies of agglutinates are delicate and complex. They are a common particle type in mature lunar soils.

Breccia - Clastic rock composed of angular clasts cemented together in a finer grained matrix.

Cataclysm - Describing the numerous large cratering events that occurred 3900 to 4000 million years ago.

Cataclastic - A metamorphic texture produced by mechanical crushing, characterized by granular, fragmentary, or strained crystals.

Chadacrysts - Crystals enclosed by an oikocryst in a rock with poikilitic texture. Chadacrysts are generally equant in size and smaller than the oikocryst. This term is not to be used for simple inclusions of scarce minute accessory phases.

Coarse-fines - The larger particles in the lunar soil. Generally 1 to 2 or 2 to 4 mm.

Diaplectic – Glass made from mineral by shock. Not melted.

Exotic - Foreign. Used for fragments of rock or glass that are not local to the collection site. Presumably they travelled from distant sites on the Moon to the collection site as by rays.

Felsite - Exotic lunar granite! Generally, a micrographic intergrowth of silica and K-feldspar. Some fragments contain pyroxene and zircon!

Fra Mauro Formation - Radial deposits of Imbrium ejecta.

Gardening - The reworking of the lunar regolith by small craters.

Glomerophyric - Monomineralic clusters within matrix.

Granulitic - A metamorphic texture in which minerals have triple point junctions so as to minimize surface energy of grain boundaries.

Highlands - The light-colored, heavily cratered, nonmare regions of the Moon.

lntrafasciculate - Hollow, columnar plagioclase filled with pyroxene; like a bundle of straws.

lntersertal - A goundmass texture in a porphyritic rock in which unoriented feldspar laths enclose glassy or partly crystalline material other than pyroxene.

KREEP - Potassium (K), rare earth elements (REE), and phosphorus (P). A trace-element-rich lunar rock type found in the highlands.

Mare - Latin for sea. Dark, flat regions generally in large circular basins.

Maskelynite - Plagioclase that has been transformed by shock in the solid state to a glass. Diaplectic plagioclase glass.

Matrix - Fine-grain portion of rock. Usually defined to be material finer than 20 microns in seriate texture. (Thin sections are 30 microns thick; therefore, matrix is difficult to study in transmitted light.)

Maturity - The maturity of a lunar soil refers to the degree of reworking by micrometeorites, as evidenced by grain size, proportions of agglutinates, proportions of grains with high solar flare track densities, solar wind gas content, or minute metallic Fe content as determined by Is/FeO ferromagnetic resonance measurement (Morris 1978).

Mesostasis - The last liquid to crystallize in an igneous rock. It is located in the interstices between the major minerals. In lunar samples, it is often too viscous to crystallize and remains as glass.

Microcrater - Crater produced by impact of interplanetary particle with mass less than 10^{-3} g; sometimes referred to as a "zap pit."

Monomict - A fragmented mixture of material from a single source without an admixture of unrelated or foreign material as in polymict.

Oikocryst - The large crystal that encloses the chadacrysts in a poikilitic texture rock.

Ophitic - Basaltic texture characterized by laths of plagioclase partially enclosed by anhedral grains of pyroxene. Believed to represent contemporaneous crystallization of the two minerals, rather than sequential, as in poikilitic texture.

Patina - The thin outer skin on the surface of a lunar rock caused by solar wind and rnicrometeorite erosion. Microscopically, it is composed of "zap pits" and many splashes of minute glass fragments.

Poikilitic - Relatively large crystals of one mineral enclosing numerous smaller crystals of one or more other minerals which are randomly oriented and generally, but not necessarily, uniformly distributed. The host crystal is called an oikocryst, and the included crystals are called chadacrysts.

Polymict - A mechanical mixture of genetically unrelated fragments of material.

Primitive - Unfractionated. For igneous rocks, it refers to the initial material in a sequence of fractionation.

Pristine - Rocks with primary lunar compositions produced by lunar endogenous igneous processes; melt rocks and crystalline matrix breccias are excluded. A synonym for pristine would be "unmelted, monomict". Low Ir and Au contents are required because these elements indicate meteorite contamination.

REE - Rare earth elements.

Radiated - Describing texture in which numerous elongate crystals diverge from a common nucleus.

Regolith - Layer of fragmental debris produced by impact processes on the surface of an airless planetary body. Collection of ejecta from large and small craters, primary and secondary, close by and far away. The lunar regolith has a density of about 1.5 g/cm^3.

Schlieren - Flow banding in glass.

Seriate - A rock texture in which there is a continuous range in grain size from the smallest (submicroscopic) to the largest.

Soil – The fine-grained outermost layer of the lunar regolith which was exposed to solar wind and micrometeorite bombardment. (Organic matter is not applicable to the lunar case.)

Subophitic - Common texture of basaltic rock wherein feldspar-crystals are about the same size as pyroxene and only partly enclosed by them (see ophitic).

Symplectite - An intimate intergrowth of two minerals in which one mineral has a vermicular (wormlike) habit.

Trace Elements – Generally below 0.1 weight percent. The REE are most useful. Ir and Au also are frequently termed trace elements.

Troctolite - Coarse-grain plutonic rock containing olivine and plagioclase with little or no pyroxene.

Variolitic - Radiate aggregates of elongate crystals.

Vitrophyric - Megascopically glassy. Can be recrystallized microscopically.

Zap pit - Microcrater caused by micrometeorite. Range in size from millimeters to micrometers. Commonly lined with glass and surrounded by spall zone.

Note: for a glossary of terms commonly used in planetary science see:

http://www.psrd.hawaii.edu/PSRDglossary.html

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Appendix I

Determinative Tables

(a) Transmitted Light

Mineral	Color	Relief	Birefringence	Other
Plagioclase	colorless	low	1st order gray	polysynthetic twinning
Olivine	colorless	high	2nd order yellow	melt inclusions
Clinopyroxene	tan to red-brown	high	1st order red to 2nd order blue	optically zoned, commonly fractured
Orthopyroxene	colorless	high	1st order yellow	parallel cracks, difficult to distinguish from olivine
Pyroxferroite	yellow	high	1st order yellow	rare, spongy texture, found adjacent to glass or silica in mesostasis
Silica	colorless	very low	gray	cracked
Glass	variable	- - -	isotropic	many colors including colorless
Pleonaste	red	very high	isotropic	zoned, high reflectivity
Zircon	colorless	very high	gray	unzoned, high reflectivity
Phosphate	colorless	low	gray	needles and spongy masses in mesostasis

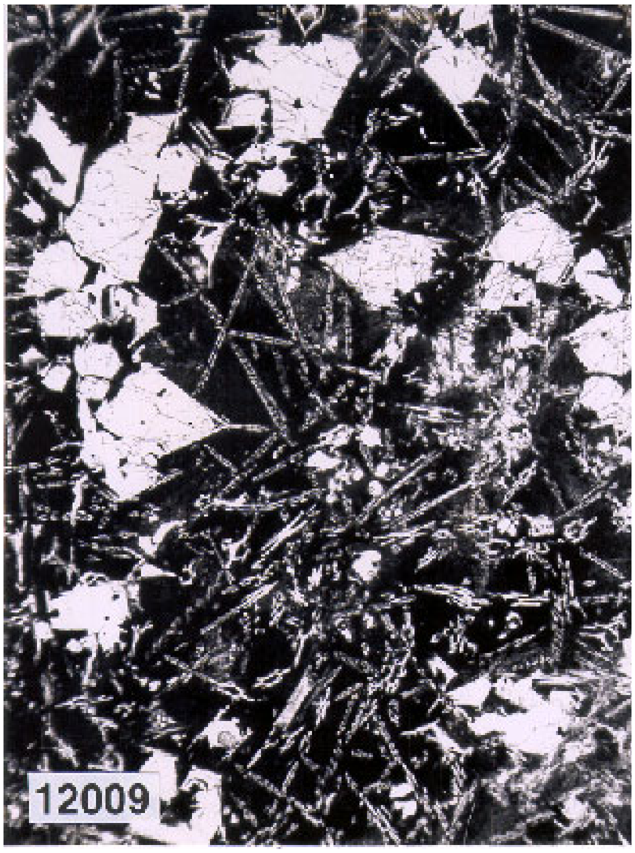
(b) Reflected light

Mineral	Color	Reflectivity	Anisotropy	Other
Ilmenite	gray	high	strong	most abundant opaque in lunar samples, thin laths are slightly transparent, red-brown
Chromite	brownish-gray	high	isotropic	hexagonal outlines, often overgrown by ulvöspinel
Ulvöspinel	brown	high	isotropic	hexagonal outlines, frequently exsolved
Rutile	light gray	high	little	exsolution lamellae in ilmenite
Armalcolite	gray	high	moderate	hexagonal barrel-shaped habit
Tranquillityite	gray	high	isotropic	tiny laths in glassy mesostasis, slightly transparent red
Fe-Ni metal	bright white	very high	isotropic	frequent blebs in troilite
Troilite	yellow	very high	strong	soft, scratches

Appendix II

Brief Atlas of Lunar Rock Textures

Textures of selected igneous lunar rocks are shown. All are to the same scale (4 mm by 5.5 mm). All are plane polarized light except samples 68415, 76535, and 15415, which photographed best in partially polarized light. Most are mare basalts except samples 14310, 68415, 15415 and 76535, which are feldspathic basalt, feldspathic melt rock, anorthosite, and troctolite, in that order.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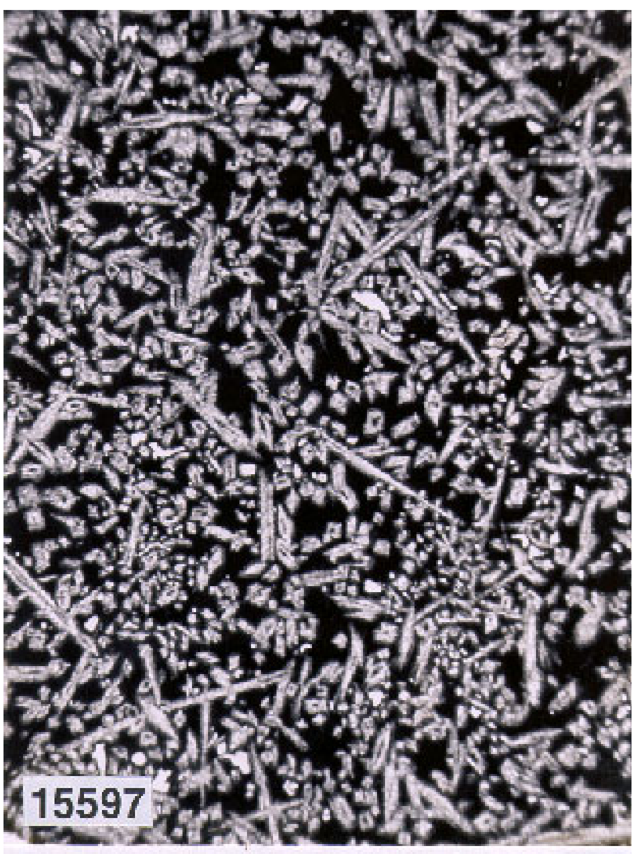
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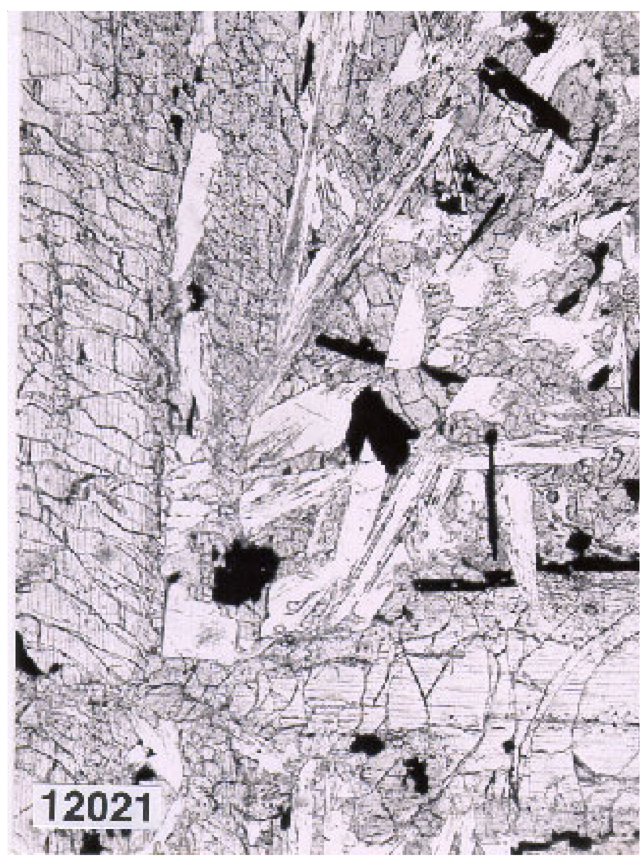
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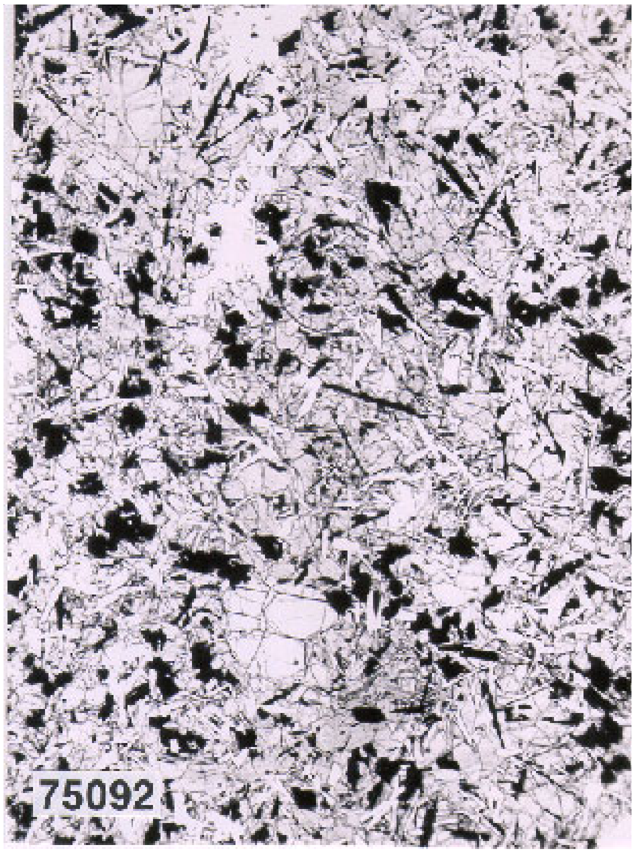
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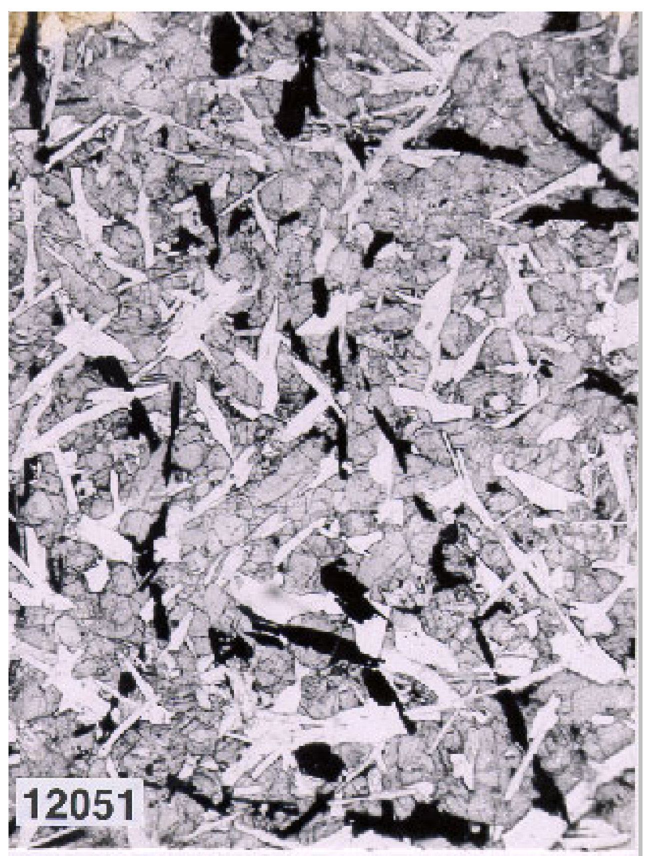
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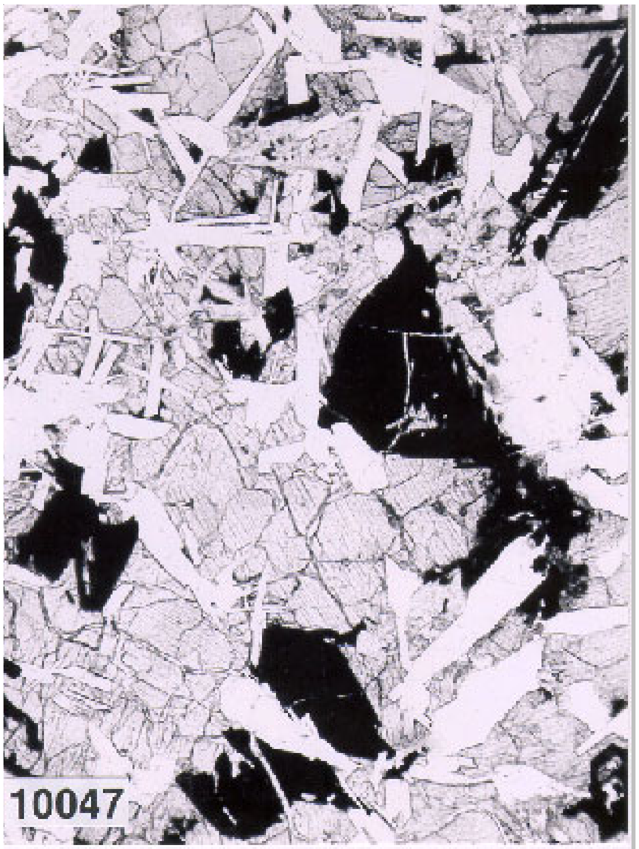
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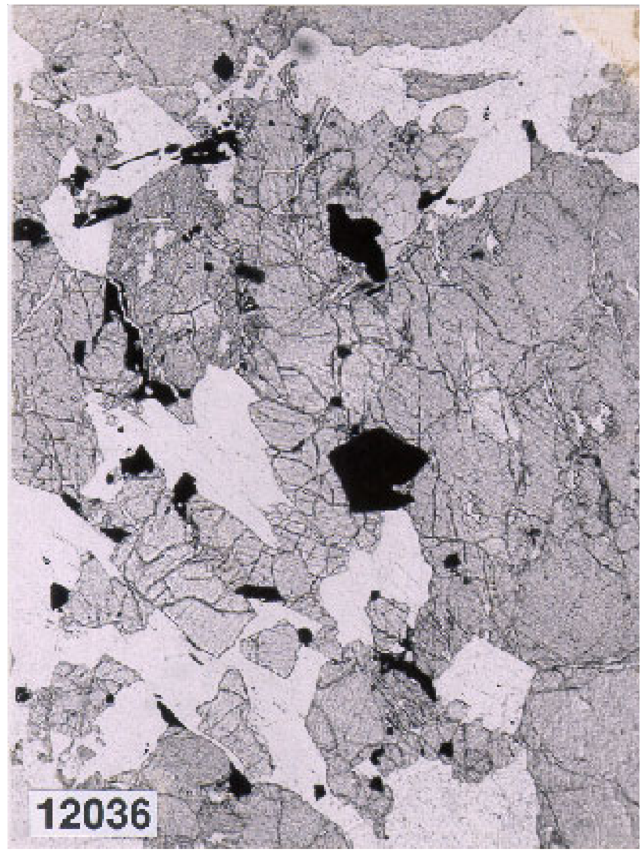
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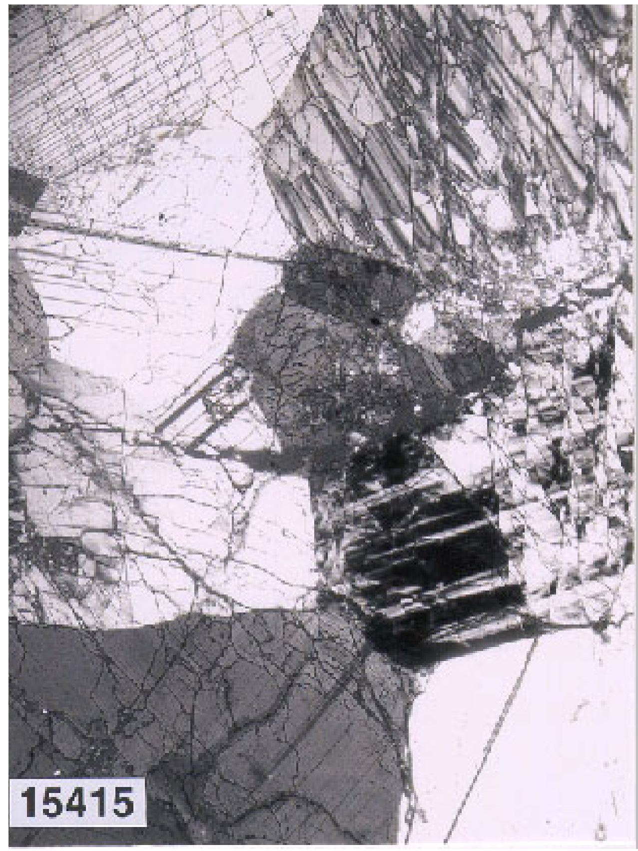
68415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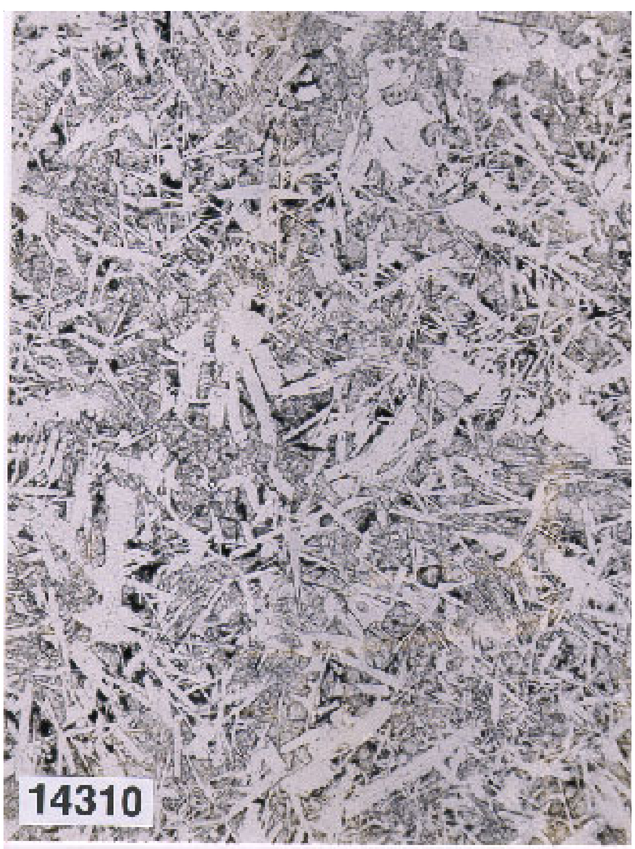
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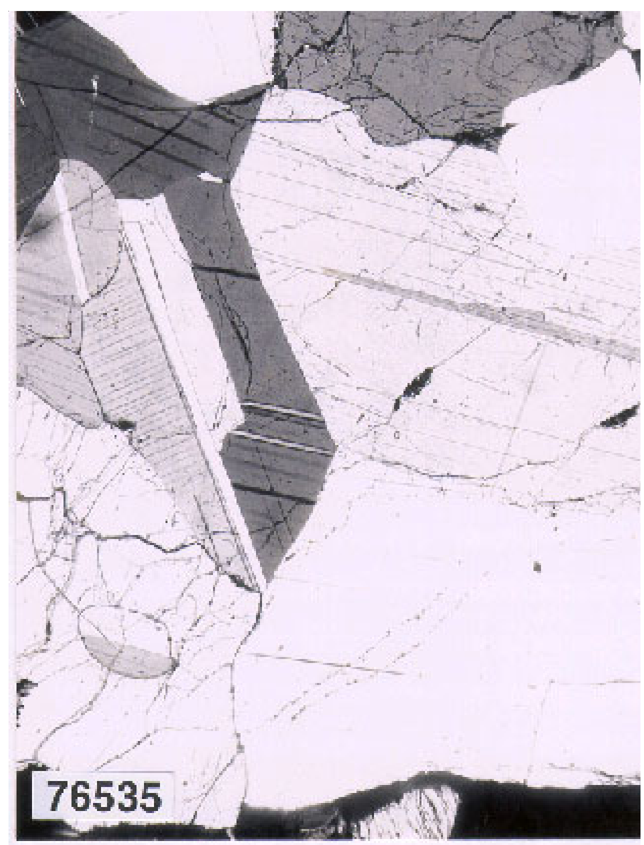
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Appendix III

Top Ten Discoveries of Apollo Missions

The Moon is not a primordial object; it is an evolved terrestrial planet with internal zoning similar to that of the Earth.

Before Apollo, the state of the Moon was a subject of almost unlimited speculation. We now know that the Moon is made of a rocky material that has been variously melted, erupted through volcanoes, and crushed by meteorite impacts. The Moon posses a thick crust (60 km), a fairly uniform lithosphere (60-1000 km), and a partly liquid asthenosphere (1000-1740 km); a small iron core at the bottom of the asthenosphere is possible but unconfirmed. Some rocks give hints for ancient magnetic fields although no planetary field exists today.

The Moon is ancient and still preserves an early history (the first billion years) that must be common to all terrestrial planets.

The extensive record of meteorite craters on the Moon, when calibrated using absolute ages of rock samples, provides a key for unraveling time scales for the geologic evolution of Mercury, Venus, and Mars based on their individual crater records. Photogeologic interpretation of other planets is based largely on lessons learned from the Moon. Before Apollo, however, the origin of lunar craters was not fully understood and the origin of similar craters on Earth was highly debated.

The youngest Moon rocks are virtually as old as the oldest Earth rocks. The earliest processes and events that probably affected both planetary bodies can now only be found on the Moon.

Moon rock ages range from about 3.2 billion years in the maria (dark, low basins) to nearly 4.6 billion years in the terrae (light, rugged highlands). Active geologic forces, including plate tectonics and erosion, continuously repave the oldest surfaces on Earth whereas old surfaces persist with little disturbance on the Moon.

The Moon and Earth are genetically related and formed from different proportions of a common reservoir of materials.

The distinctively similar oxygen isotopic compositions of Moon rocks and Earth rocks clearly show common ancestry. Relative to Earth, however, the Moon was highly depleted in iron and in volatile elements that are needed to form atmospheric gases and water.

The Moon is lifeless; it contains no living organisms, fossils, or native organic compounds.

Extensive testing revealed no evidence for life, past or present, among the lunar samples. Even non-biologic organic compounds are amazingly absent; trace amounts of carbon can be attributed to contamination by meteorites.

All Moon rocks originated through high-temperature processes with little or no involvement with water. They are roughly divisible into three types: basalts, anorthosites, and breccias.

Basalts are dark lava rocks that fill mare basins; they generally resemble, but are much older than, lavas that comprise the oceanic crust of Earth. Anorthosites are light rocks that form the ancient highlands; they generally resemble, but are much older than, the most ancient rocks on Earth. Breccias are composite rocks formed from all other rock types through crushing, mixing, and sintering during meteorite impacts. The Moon has no sandstones, shales, or limestones such as testify to the importance of water-borne processes on Earth.

Early in its history, the Moon was melted to great depths to form a "magma ocean". The lunar highlands contain the remnants of early, low density rocks that floated to the surface of the magma ocean.

The lunar highlands were formed about 4.4-4.6 billion years ago by floatation of an early, feldspar-rich crust on a magma ocean that covered the Moon to a depth of many tens of kilometers or more. Innumerable meteorite impacts through geologic time reduced much of the ancient crust to arcuate mountain ranges between basins.

The lunar magma ocean was followed by a series of huge asteroid impacts that created basins which were later filled by lava flows.

The large, dark basins such as Mare Imbrium are gigantic impact craters, formed early in lunar history, that were later filled by lava flows about 3.2-3.9 billion years ago. Lunar volcanism occurred mostly as lava floods that spread horizontally; volcanic fire fountains produced deposits of orange and emerald-green glass beads.

The Moon is slightly asymmetrical in bulk form, possibly as a consequence of its evolution under Earth's gravitational influence. Its crust is thicker on the far side, while most volcanic basins – and unusual mass concentrations – occur on the near side.

Mass is not distributed uniformly inside the Moon. Large mass concentrations ("Mascons") lie beneath the surface of many large lunar basins and probably represent thick accumulations of dense lava. Relative to its geometric center, the Moon's center of mass is displaced toward the Earth by several kilometers.

The surface of the Moon is covered by a rubble pile of rock fragments and dust, called the lunar regolith, that contains a unique radiation history of the sun which is of importance to understanding climate changes on Earth.

The regolith was produced by innumerable meteorite impacts through geologic time. Surface rocks and mineral grains are distinctively enriched in chemical elements and isotopes impacted by solar radiation. As such, the Moon has recorded four billion years of the Sun's history to a degree of completeness that we are unlikely to find elsewhere.