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.

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	$(Ca,Y)_2(Ti,Nb)_2O_7$

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.

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).