

RESOURCES FOR A LUNAR BASE: ROCKS, MINERALS, AND SOIL OF THE MOON

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The rocks and minerals of the Moon will be included among the raw materials used to construct a lunar base. The lunar regolith, the fragmental material present on the surface of the Moon, is composed mostly of disaggregated rocks and minerals, but also includes glassy fragments fused together by meteorite impacts. The finer fraction of the regolith (i.e., <1 cm) is informally referred to as soil. The soil is probably the most important portion of the regolith for use at a lunar base. For example, soil can be used as insulation against cosmic rays, for lunar ceramics and abodes, or for growing plants. The soil contains abundant solar-wind-implanted elements as well as various minerals, particularly oxide phases, that are of potential economic importance. For example, these components of the soil are sources of oxygen and hydrogen for rocket fuel, helium for nuclear energy, and metals such as Fe, Al, Si, and Ti.

INTRODUCTION

Based upon the nine lunar sample return missions (six from Apollo, three from Luna), we have over 380 kg (almost 840 lb) of returned lunar samples and an excellent knowledge of the nature of the rocks and regolith over a limited portion of the Moon's frontside. These are the raw materials that a lunar base can utilize. They may also be the source of certain products with which to help justify such an ambitious endeavor, e.g., ^3He , hydrogen, oxygen, Fe metal.

There have been many excellent reviews of the mineralogy and petrology of the returned lunar samples, among which the books by Ross Taylor (1975, 1982) are paramount. In addition, there are several fine review articles from which I have drawn liberally (e.g., Smith, 1974; Frondel, 1975; Papike et al., 1976, 1982; Smith and Steele, 1976; Papike and Bence, 1979; Wilhelms, 1984). I shall not attempt to repeat what has been so well written previously. Instead, I will present a brief synopsis of the basic petrology and mineralogy of the lunar samples, with particular attention to those aspects that may be of significance for lunar exploitation.

With respect to the possible future use of lunar materials, the recent publication by the Lunar and Planetary Institute (Houston), *Lunar Bases and Space Activities of the 21st Century* (1985), is essential. In addition, a book entitled *Lunar Sourcebook* (1991), coordinated through the Lunar and Planetary Institute and published by Cambridge University Press, summarizes our current knowledge of the Moon, which will be important for future lunar base endeavors.

In addition to the nature of lunar components, a listing of catalogs and documents on lunar samples, organized by mission, has been compiled and is presented in this paper. With certain studies designed to utilize lunar materials, it may be necessary to actually experiment with lunar samples. A brief outline is given that should be followed in order to apply for lunar samples for engineering or industrial investigations.

CONDITIONS OF ROCK AND MINERAL FORMATION

The Earth and its moon differ significantly in the environments at their surfaces and also in the formation conditions of their rocks, minerals, and soils. Because of its smaller mass and, hence, escape velocity, the Moon cannot maintain a significant atmosphere ($<10^{-7}$ torr) with the result that it has no "insulating blanket" that would (1) aid the retention of solar energy and (2) shield it from cosmic rays, solar wind, and meteoritic and cometary infall. Consequently, the surface of the Moon undergoes tremendous changes in temperature ($+135^\circ\text{C}$ to -130°C), and meteorites (from kilometers to submicron sizes) have bombarded the surface continually for aeons at fantastic speeds (e.g., 40,000-250,000 km/hr). These meteorite impacts result in the only effective process of weathering and erosion on the Moon. Also, because of the complete lack of any water, chemical weathering, so dominant on Earth, is nonexistent on the lunar surface. Therefore, the meteorite components, principally the minerals, are discernable and add a significant chemical signature to the soil. In addition, the solar-wind-implanted particles, notably protons (hydrogen), helium, and carbon, introduce exogenous components into the soil. These particles and meteorite and micrometeorite impacts, with their associated shock metamorphism, including complete melting, ultimately produce one of the distinctive aspects of lunar soil, namely the presence of "agglutinates" (aggregates of rock and mineral fragments and glass) with their myriad minute iron metal (i.e., Fe^0) grains.

The formation conditions of lunar rocks, most notably the volcanic ones, are different from those on Earth in two basic aspects: (1) temperatures of formation and (2) the oxygen partial pressures prevailing during formation. Largely because of the lack of water and its great "fluxing" ability and the paucity of other mineralizers (e.g., F, Cl), the crystallization temperatures of the mineral components of the rocks are about 100° - 150°C higher than corresponding ones on Earth. The conditions of oxygen

partial pressure (called oxygen fugacity; abbreviated as fO_2) are distinctly different (Fig. 1) and have a pronounced effect on the mineralogy. Because of the low oxygen fugacity, there is no Fe^{3+} present in any of the minerals. Indeed, because the formation conditions are at and below the iron/wüstite buffer curve, native Fe is ubiquitous in lunar samples of all kinds. Likewise, some of the elements in the minerals are present in a reduced state with unusual valence states compared to Earth situations (e.g., Ti^{3+} vs. Ti^{4+} ; Cr^{2+} vs. Cr^{3+} ; Fe^0 vs. Fe^{2+} ; P^{3+} vs. P^{5+}).

ROCKS

Most U.S. Apollo (manned) and Russian Luna (unmanned) missions landed within maria, areas of comparatively young basalt flows. Some missions were to areas consisting largely of highland rocks. Several excellent review papers have been written concerning the lunar rock, among them *Papike and Bence* (1979), *Papike and Vaniman* (1978), *Smith and Steele* (1976), *Taylor* (1975, 1982), and *Wilhelms* (1984). Therefore, the discussion presented here will be brief. An additional reason for this shortened portion on rocks is that it is the minerals that are of most importance for lunar base endeavors, not the rocks per se.

Representative portions of the ancient highlands have been sampled by Apollo 14, Apollo 16, and Luna 20. However, every mission brought back some samples identified as originating in the highlands. Although it appears that the darker maria make up a substantial portion of the surface, mare basalts only constitute between 15% and 20% of the Moon. The rocks on the Moon consist of two basic types: igneous rocks, formed through processes of crystallization of minerals from a silicate melt, and breccias, created as a result of meteorite impacts whereby preexisting rocks are broken and mixed with other rocks and soil and shock metamorphosed into coherent, cemented aggregates. Indeed, few of the highland samples returned to Earth are simple igneous rocks. Most consist of complex metamorphosed breccias, remelted regolith, or fine-grained soil.

The igneous rocks consist of mare basalts, iron-rich lava flows that filled the great impact basins, and the plutonic rocks of the highlands, composed of anorthosites, norites, and troctolites. In addition, there is a chemical component called KREEP (an acronym for the elements K, REE, and P) that is present in some basalts and that dominates trace-element patterns of most highland polymict breccias.

The mare basalts have been classified into various types based upon their mineralogy and bulk chemistry. There are three general mare basalt types, high-Ti, low-Ti, and very-low-Ti (VLT) basalts, and some less abundant varieties such as very-high-potassium (VHK) basalt. Figure 2 shows the variations in chemistry for the three main types. These can be seen best in the TiO_2 vs. Mg' [called "magnesium number" and equal to atomic $Mg/(Mg+Fe)$]. These rocks possess low contents of the volatile elements Na and K, a distinction from most terrestrial basalts. Pyroxene makes up about 50% by volume of the basalts, regardless of type, with 20-30% plagioclase, and 0-20% olivine. The opaque oxide phases, ilmenite and chromite-ulvöspinel, vary from a few percent to over 20%. The ubiquitous native Fe is present in amounts less than 1%. (Note: "modal percent" refers to the volume percent actually present in the rock; "normative percent" refers to a "calculated," theoretical mineralogy, starting with the bulk composition of the rock, and commonly expressed in weight or volume percent.)

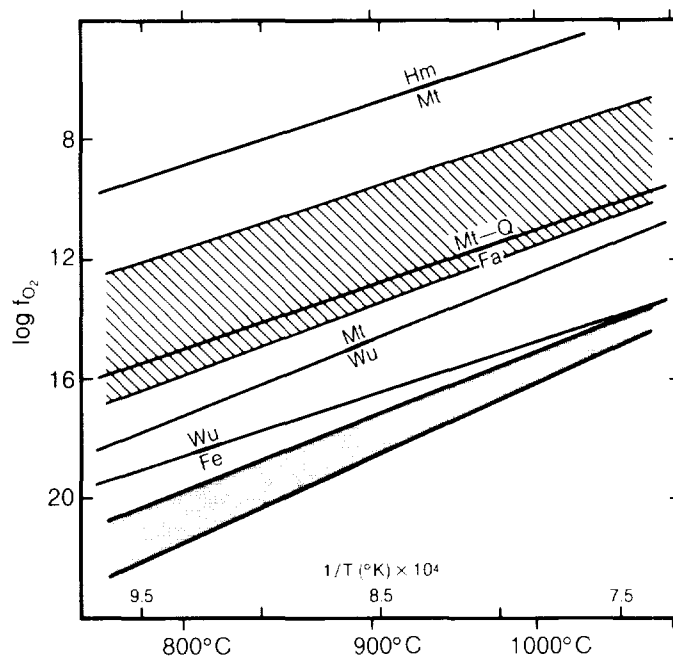


Fig. 1. Partial pressure of oxygen (fO_2) vs. temperature plot depicting the regions for terrestrial (upper shaded area) and lunar (lower area) magmatic activity. The terrestrial region centers around the fayalite/quartz + magnetite buffer curve, whereas the lunar activity is located entirely below the Fe/wüstite curve, in the field where metallic Fe is stable. No highly oxidized Fe (i.e., Fe^{3+}) is stable within this lunar area.

Anorthositic rocks are abundant in the ancient, heavily cratered highlands. Anorthosites are composed mainly of plagioclase feldspar. However, in addition to plagioclase, other highland rocks contain varying amounts of orthopyroxene, clinopyroxene, and olivine; norite is composed of unequal amounts of plagioclase and orthopyroxene, gabbro contains plagioclase and clinopyroxene, while troctolite is made up of plagioclase and olivine. Compositions of these highland rocks are shown in Fig. 3.

Breccias are present at all sample sites, but are particularly abundant at those sites with a large highland component (e.g., Apollo 14, 16, and Luna 20), as well as at Apollo 15 and 17. After much turmoil associated with many schemes of complex nomenclature for brecciated lunar rocks, the working classification of *Stöffler* (1980) has been generally accepted. Breccias are complex rocks and consist of fragments of rock, mineral, and meteorite fragments welded together by a fine-grained matrix. The amount of glass in the matrix depends upon the degree to which a given rock has been shocked during meteorite impact. Breccias range from poorly indurated aggregates of debris, all the way to complete impact-melt rocks. These melt rocks texturally resemble igneous rocks, but generally have compositions either similar to the soil or intermediate to the compositions of the soil and the lunar, plutonic, "pristine" rocks. It is not always easy to identify some of these rocks as melt products. The least ambiguous means for identifying "pristine" rocks is by analysis of siderophile elements (Ir and Au). Most meteorites have high siderophile contents, and melt rocks formed by impacting meteorites retain a signature of the impactor in the form of these siderophile elements.

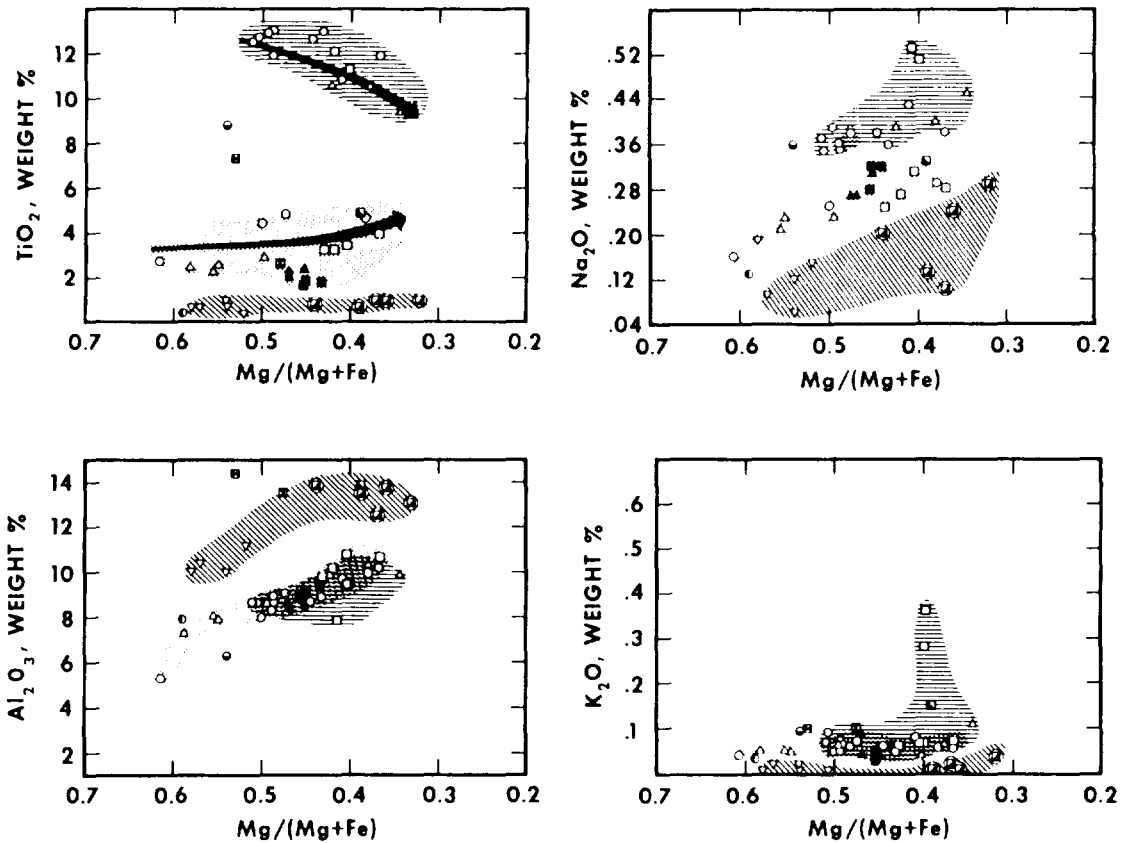


Fig. 2. Oxide variations vs. Mg' for mare basalts (adapted from BVSP, 1981). Horizontal line shadings are for high-Ti basalts; dot shadings are for low-Ti basalts; diagonal line shadings are for very low-Ti (VLT) basalts.

SILICATE MINERALS

Most of the minerals that comprise the lunar rocks are silicates and are essentially the same as those commonly found in mafic, igneous rocks on Earth, i.e., olivine, pyroxene, and plagioclase. It is the nonsilicate phases, most of which are "opaque" to transmitted light when viewed in thin section, that are most distinctive of the lunar rocks. The abundances of the minerals in mare basalts are depicted in Fig. 4. As mentioned above, the highland igneous rocks consist mostly of plagioclase, with lesser amounts of pyroxene and olivine. The chemistry of these three rock-forming silicate minerals is presented below.

Pyroxene

Pyroxene is the general name for a group of minerals that displays considerable solid solution (i.e., range in chemistry). The compositions of pyroxenes in terms of the major elements (i.e., Ca, Fe, Mg) are commonly represented by use of the "Pyroxene Quadrilateral" where the corners are diopside ($\text{CaMgSi}_2\text{O}_6$), hedenbergite ($\text{CaFeSi}_2\text{O}_6$), ferrosilite ($\text{Fe}_2\text{Si}_2\text{O}_6$), and enstatite ($\text{Mg}_2\text{Si}_2\text{O}_6$), as shown in Fig. 5. Pyroxenes with compositions near or on the enstatite-ferrosilite join have orthorhombic crystal symmetry and are termed "orthopyroxenes," whereas all other compositions represent pyroxenes with monoclinic symmetry and are termed "clinopyroxenes." Pyroxenes with 4-7% CaO are

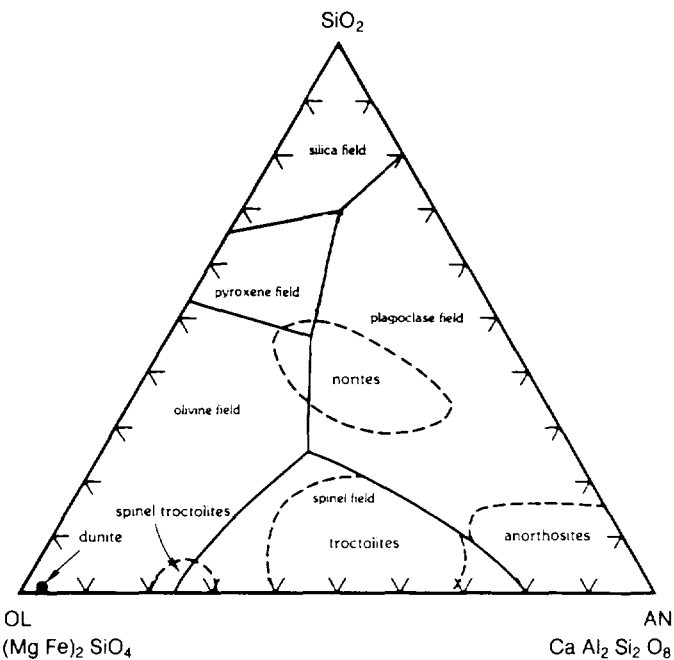


Fig. 3. Compositional fields of lunar highland igneous rocks plotted on the olivine (OL)-anorthosite (AN)-silica (SiO_2) pseudoternary diagram (adapted from Taylor, 1982).

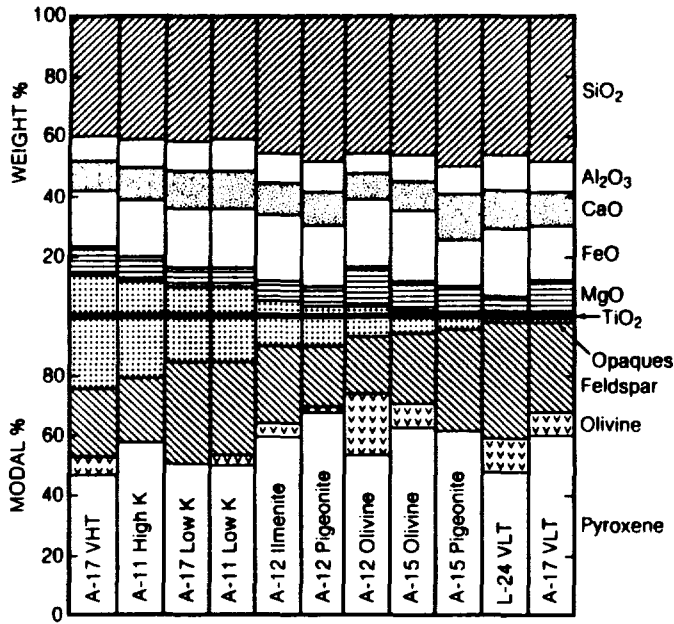


Fig. 4. Mare basalt major-element chemistry and modal mineralogy, ordered from left to right by decreasing TiO_2 (or opaque oxide) content (adapted from BVSP, 1981).

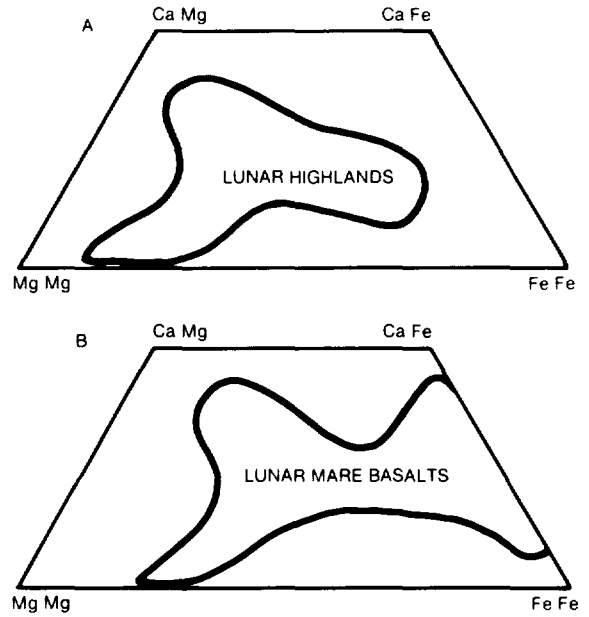


Fig. 5. Lunar pyroxene major-element chemistry plotted on the "pyroxene quadrilateral." The corners clockwise from the upper left are diopside ($CaMgSi_2O_6$), hedenbergite ($CaFeSi_2O_6$), ferrosilite ($Fe_2Si_2O_6$), enstatite ($Mg_2Si_2O_6$).

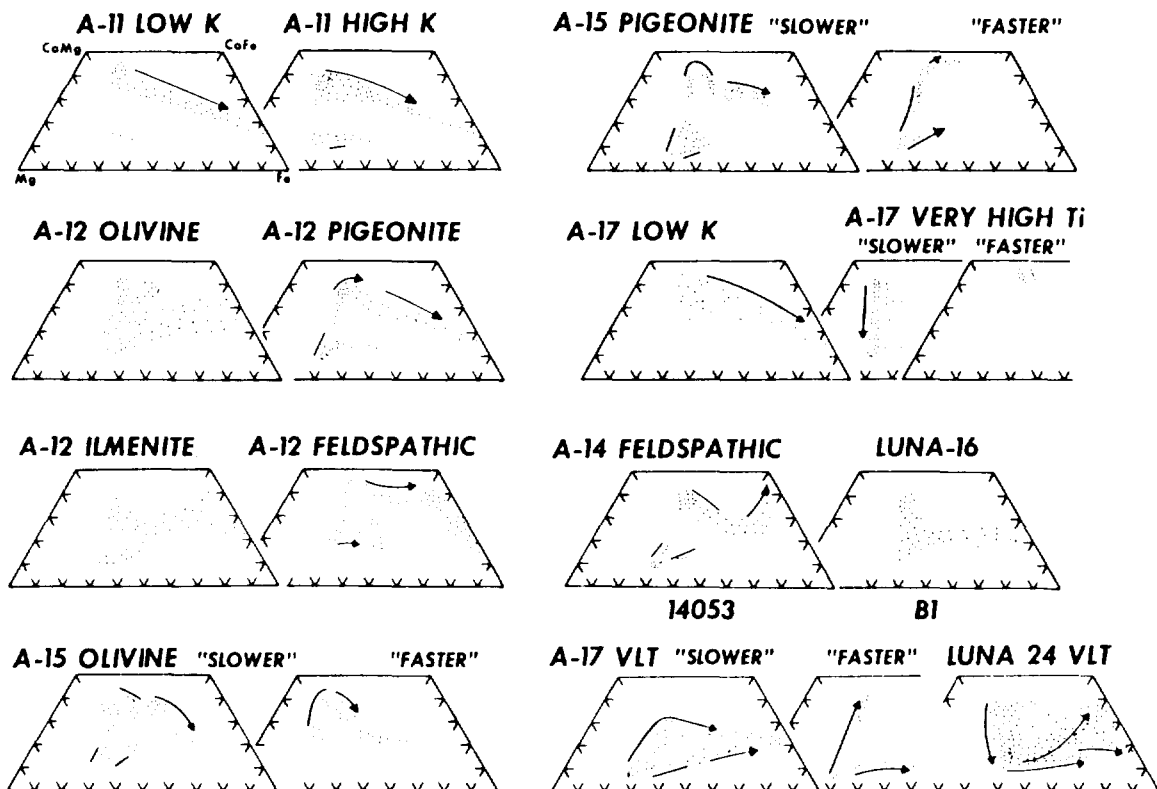


Fig. 6. Mare basalt pyroxene variations with arrows indicating important crystallization trends (adapted from BVSP, 1981).

called "pigeonites," those with 12-16% CaO are "subcalcic augites," and those with >16% CaO are augites. Pyroxferroite is a mineral that was first discovered in lunar samples and has a composition near the Fe-rich end of the hedenbergite-ferrosilite join. The minor elements in lunar pyroxenes include Al, Ti, Cr, and trace amounts of Na. Their use as discriminant parameters can usually be more effective for basalt petrogenesis than the major-element chemistry.

As shown in Fig. 5, the pyroxenes in the highland rocks do not range in composition to the high FeO contents so characteristic of the mare basalts. This is largely a result of (1) the higher MgO contents [usually expressed as Mg/(Mg+Fe) ratios] of the highland rocks and (2) the slower cooling rates that aid the attainment of equilibrium, thereby restricting chemical variation. The more extensive chemical zonation of the pyroxenes in mare basalts is commonly represented by their overall Fe enrichment and Ca depletion, frequently resulting in pyroxferroite. This zonation can be observed in the basalts, sometimes within a single grain, as orthopyroxene cores mantled by pigeonite, in turn mantled by augite, commonly grading to ferroproxenes, as shown in Fig. 6. The chemical trends in the pyroxenes are not only a result of the melt composition, but more importantly, the cooling rates (and associated kinetics) of the crystal-melt system. These effects are particularly well displayed by the Apollo 15 basalts (Fig. 6).

Olivine

Olivine is a silicate material that displays a solid solution series (range in chemical composition without phase change) between Mg_2SiO_4 (forsterite, abbreviated as Fo) and Fe_2SiO_4 (fayalite, abbreviated as Fa). Compositions are given in terms of mole percent of Fo or Fa. All other elements are present in amounts <1 wt%. The most abundant of these minor elements in olivine are Mn, Ni, Ca, Cr, Co, and Al.

Olivine is a major mineral in many basalts where it may constitute 0-35% by volume of the rocks. As shown in Fig. 7, it has compositions ranging from 20% to 70% Fa (Fo 80 to Fo 30), with some near-pure fayalite in the late-stage mesostasis (final residue from crystallization) of the basalts. Olivine in basalts is always zoned from Mg-rich cores to more Fe-rich rims, e.g., from Fo 80 to Fo 30 (Fa 20 to Fa 70). This Fe-enrichment in olivine is similar to that observed in the pyroxenes, where continued crystallization of these phases results in Mg-depletion with subsequent Fe-enrichment in the melt. Olivine constitutes from 0% to 100% of highland rocks, where it has compositions from Fa 7 to Fa 18 (Fo 93 to Fo 82). Olivine is less than 10% by volume in anorthosite, 10-20% in troctolite, 0-15% in gabbronorite, and up to 100% in dunite.

Plagioclase Feldspar

The majority of lunar feldspars are calcic plagioclases ($CaAl_2Si_2O_8$; anorthite, abbreviated as An) in solid solution with sodic plagioclase ($NaAlSi_3O_8$; albite, abbreviated as Ab). Lunar plagioclase also contains trace amounts of K-feldspar ($KAlSi_3O_8$; orthoclase, abbreviated as Or) in solid solution. The compositions of feldspars are commonly given as mole percent of these three components, An, Ab, Or. As shown in Fig. 8, the compositions of plagioclase in mare basalts range from An 98 to An 74. The Or contents are minor (0-3%). Rare K- and Ba-feldspars are present in late-stage mesostasis in some of the mare basalts, particularly those rich in KREEP components. The compositions of feldspars

in highland rocks commonly contain even fewer alkalis, e.g., An 99 to An 90, Or 0 to 2. The low Ab and Or contents of lunar plagioclase are a consequence of the low alkali contents of the magmas that formed the lunar rocks.

Plagioclase commonly displays chemical zonation, with calcic cores grading outward to more Na- and K-rich compositions. In addition, Fe content of plagioclase, particularly in mare basalts, can range from as much as 0.5% in the cores to over 1% in the rims. Furthermore, the Fe content of mare basalt plagioclase is considerably higher than those of highland feldspars. Thus, based solely on the Fe content of the plagioclase, the mare vs. highland origin of a single particle can be determined.

The trace-element chemistry of lunar plagioclase is important for lunar evolutionary models. Plagioclase frequently contains relatively more Eu than other rare earth elements (REE). This

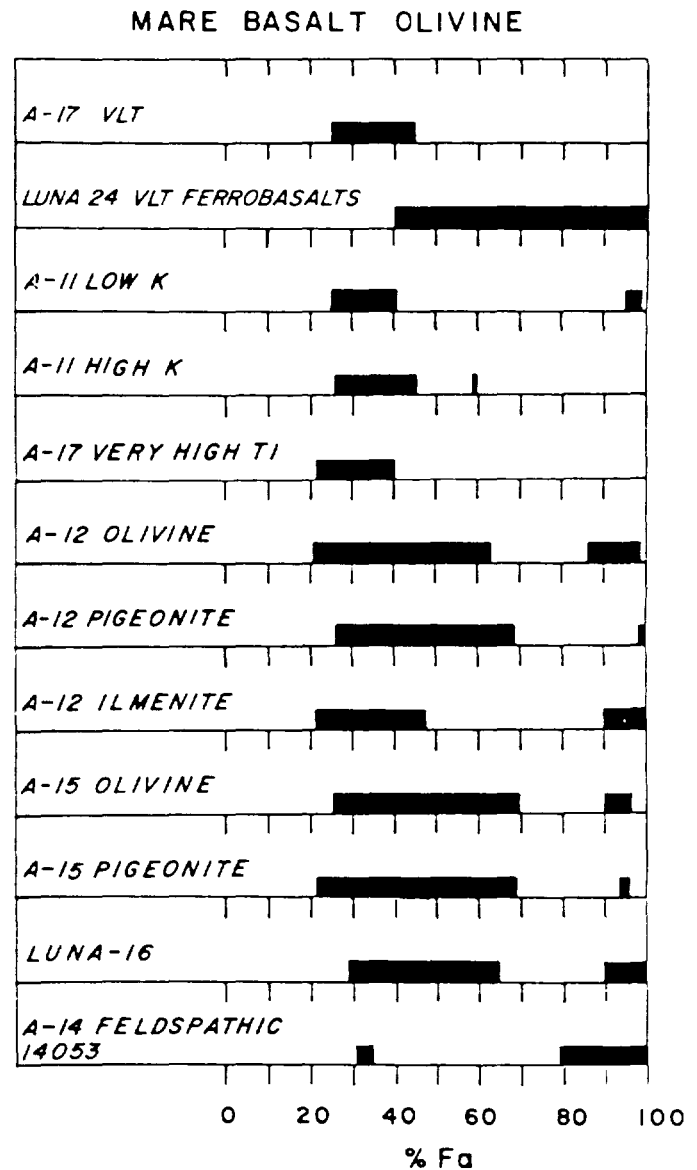


Fig. 7. Fayalite content along the join Fe_2SiO_4 - Mg_2SiO_4 for mare basalts (adapted from Pupike and Vaniman, 1978).

positive Eu anomaly, caused by the dual valance of Eu (2+, 3+) compared with the other REE, indicates that there are other minerals that must have negative Eu anomalies. The plagioclase in the anorthosites of the lunar highlands contains positive Eu anomalies. This led to the "magma ocean theory," which postulates that during the first 100 m.y. after the formation of the Moon, the outer portions melted to depths of 100 km or so, and as this magma cooled, plagioclase crystallized and floated to the top of the melt to eventually aggregate into large masses forming the early lunar crust, now referred to as the highlands. The other, more Mg- and Fe-rich, minerals settled to the depths of the ocean forming the residual from which basalts were later generated. However, this lower portion had a negative Eu anomaly as,

consequently, did the derivative basalts. From this brief narrative, it should be possible to realize that the recognition of these Eu anomalies is one of the important discoveries of lunar geochemistry, and that this signature has permitted major interpretations of lunar (and terrestrial) evolution.

OXIDE MINERALS

The nonsilicate minerals, which are minor yet important constituents of lunar rocks, include ilmenite, spinels of various chemistry, armalcolite, rutile, baddeleyite, fluorapatite and chlorapatite, whitlockite, troilite and other sulfide phases, and native FeNi metal phases. Schreibersite, cohenite, and niningerite, minerals largely of meteoritic origin, are present only in trace amounts. The first several minerals in this list, namely the oxides, are the most important phases in lunar rocks and soils.

The oxide minerals in lunar rocks are signatures of the conditions of formation (e.g., fO_2) of the rocks in which they occur. They also have tremendous potential for utilization with any future lunar base activities. Whereas lunar silicate minerals are basically the same as those of Earth, the oxide phases, most of which are "opaque" minerals, reflect the reducing conditions on the Moon that prevailed during their formation.

Ilmenite

Ilmenite is the most abundant opaque mineral in lunar rocks. It has hexagonal symmetry and compositions near $FeTiO_3$. Most lunar ilmenite contains some Mg, the result of the solid solution which exists between $FeTiO_3$ (ilmenite) and $MgTiO_3$ (the mineral geikielite). All other elements, including Cr, Mn, V, and Zr, are <1%. Although terrestrial ilmenite almost always contains some Fe^{3+} , lunar ilmenite contains none, a reflection of the general reducing state of the magmatic conditions on the Moon. The amount of ilmenite in a rock is largely a function of the bulk composition of the magma from which the ilmenite has crystallized. Effectively, the higher the TiO_2 content of the rock, the higher the ilmenite content. Indeed, ilmenite contents of 15-20% are common for Apollo 11 and 17 basalts.

The compositions of lunar ilmenite vary and plot along the $FeTiO_3$ - $MgTiO_3$ join (Fig. 9). The high magnesium contents of many ilmenites are similar to terrestrial ilmenites from kimberlites, which are of high-pressure formation. It was originally thought that the Mg content of lunar ilmenites was also a reflection of high pressure of formation; however, the lunar ilmenites with the highest Mg contents are from Apollo 17 mare volcanic rocks. Instead, the composition correlates with the bulk composition of rock, a reflection of the primary magma. Indeed, the distribution of Mg between ilmenite and silicates is related to the position of ilmenite within the crystallization sequence, which itself is a function of cooling rate and oxygen partial pressure (i.e., fO_2). However, it is doubtful that these MgO contents all represent equilibrium conditions, since the composition of ilmenite can vary significantly even within one rock (Fig. 10).

The stability curve of pure ilmenite is below that for ulvöspinel, the spinel phase with which it is commonly associated (Fig. 11). In fact, ilmenite is commonly formed as a product of subsolidus reduction of this high-Ti spinel (discussion below).

The production of oxygen on the Moon from lunar materials is important in establishing a lunar base. Ilmenite can be reduced to rutile plus iron with the release of oxygen (Williams *et al.*,

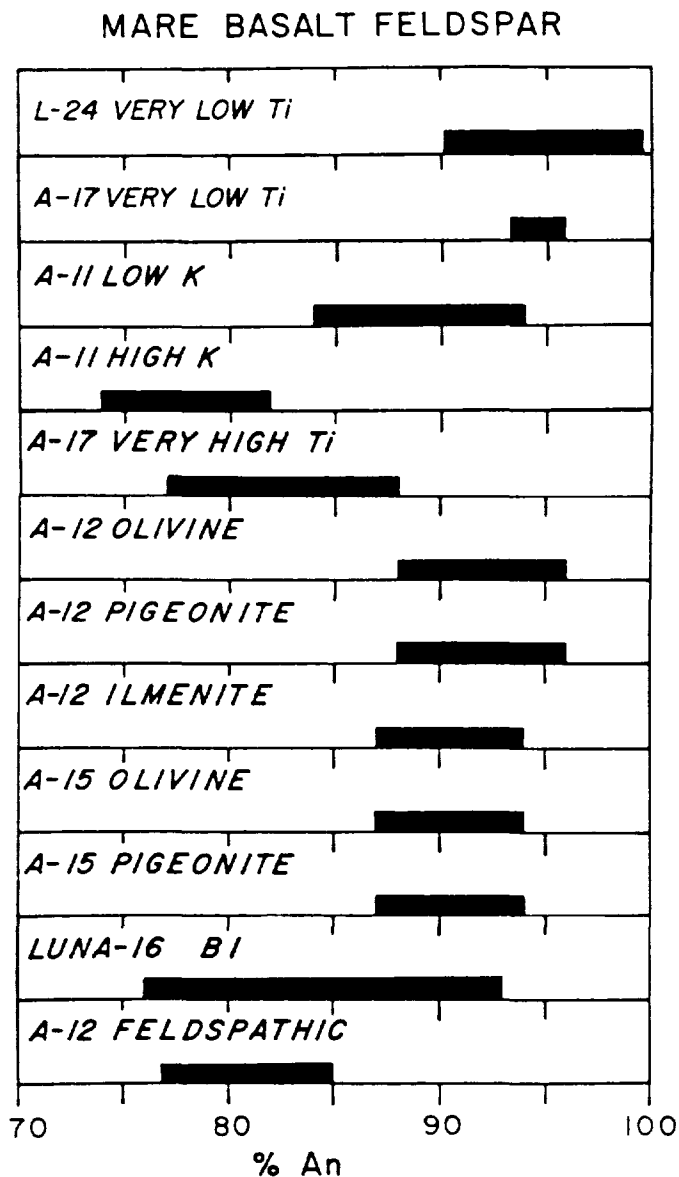


Fig. 8. Anorthite content ($CaAl_2Si_2O_8$) of mare basalt feldspars (adapted from Papike and Vaniman, 1978).

ILMENITE

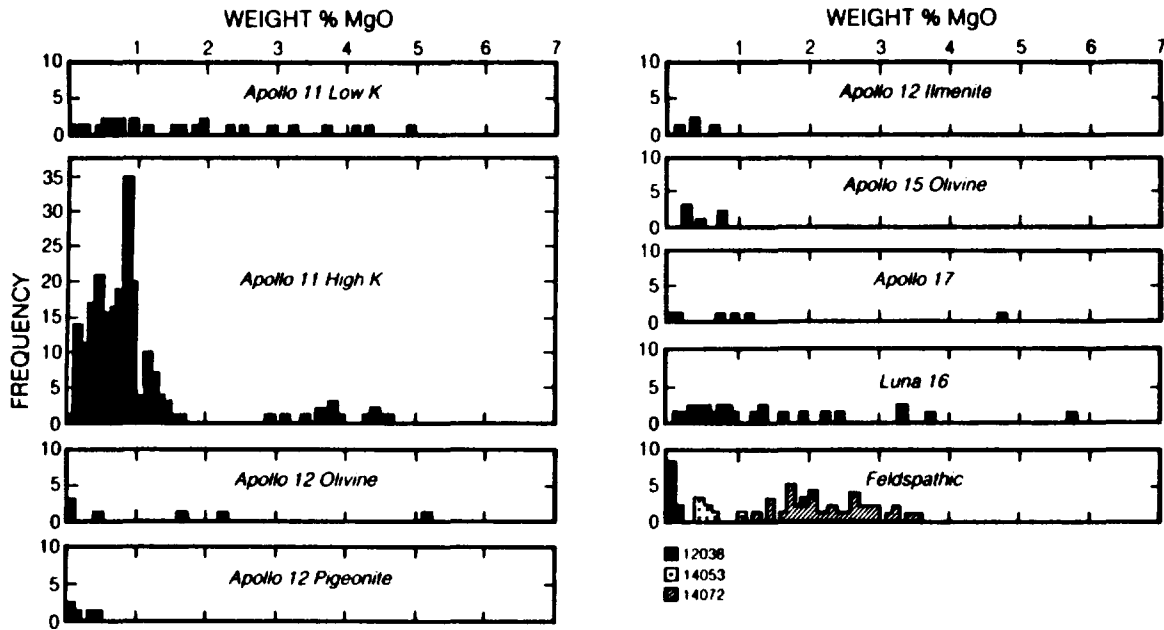


Fig. 9. MgO (wt%) content for various mare basalt ilmenites (adapted from Papike et al., 1976).

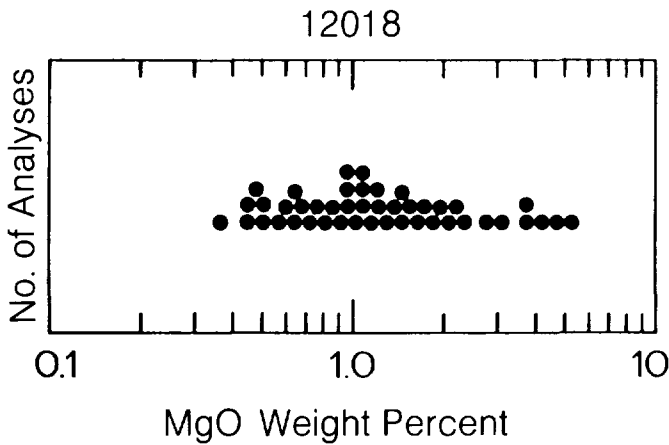


Fig. 10. MgO (wt%) variations in ilmenite from one rock (adapted from El Goresy et al., 1971).

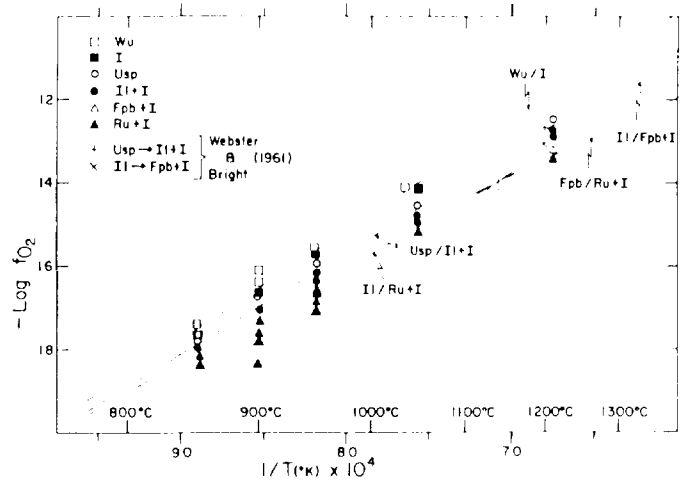
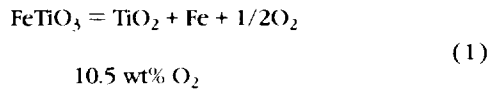


Fig. 11. Fugacity of oxygen vs. temperature plot of the univariant curves in the Fe-Ti-O system (adapted from Taylor et al., 1972). Abbrev.: Wu = wüstite; I = iron; Usp = ulvöspinel; Il = ilmenite; Fpb = ferropseudobrookite; Ru = rutile.

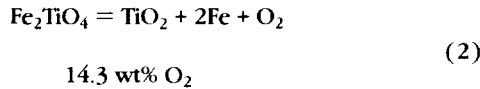
1979). This reaction is that associated with the lower univariant curve on Fig. 11, determined by Taylor et al. (1972)



The amount of oxygen produced by this reduction reaction is large. This reaction could be accomplished by the hydrogenation of ilmenite using indigenous solar-wind-implemented protons

(hydrogen), adsorbed and abundant on grains of the lunar soil. Preliminary studies have shown that oxygen production by this method is feasible (Williams, 1985; Gibson and Knudsen, 1985). These preliminary studies have been conducted largely with terrestrial ilmenite, which contains varying amounts of Fe³⁺. The complications associated with the Fe³⁺-free, high-MgO lunar ilmenite, particularly from Apollo 17, remain to be evaluated. Indeed, even the beneficiation of an ilmenite feedstock from lunar soil may not be a simple, one-step process (Taylor and Oder, 1990).

Another possible source of oxygen is the spinel phase, ulvöspinel (Fe_2TiO_4), according to the reaction



The O_2 yield from the reduction of ulvöspinel is greater than for the ilmenite reaction. However, even though this spinel phase is present up to several percent in basalts from Apollo 12, 15, and 17, its composition is quite variable compared with ilmenite (see "Spinel Group" section below), and ilmenite is generally more abundant. The compositional variability could introduce complications into its large-scale use for lunar oxygen production.

Spinel Group

Spinel is the name for a group of minerals with cubic symmetry that display extensive solid solution. The general structural formula for these minerals is $A^{iv}B_2^{vi}O_4$, where A typically represents 2+ cations in tetrahedral (iv) coordination (e.g., Fe^{2+} , Mg^{2+}) and B represents 3+ or 4+ cations in octahedral (vi) coordination (e.g., Cr^{3+} , Al^{3+} , Ti^{4+}). The various members of the spinel group of minerals (Fig. 12) include chromite ($FeCr_2O_4$), ulvöspinel ($FeFeTiO_4$, commonly written as Fe_2TiO_4), and spinel (*sensu stricta*) ($MgAl_2O_4$). Solid solution compositions between these end members are designated by the use of modifiers such as "chromian" ulvöspinel or "titanium" chromite. Some solid solution compositions have distinct names, such as pleonaste for compositions essentially between $MgAl_2O_4$ and $FeAl_2O_4$ (Fig. 12).

In lunar basalts, spinels have complicated and varied chemistry. As shown in Fig. 13, besides the major oxides FeO , Cr_2O_3 , and TiO_2 , chromites have higher contents of Al_2O_3 , MgO , and V_2O_3 than ulvöspinel, with V_2O_3 contents near 1%. In typical mare basalts, chromite is one of the first phases to crystallize, as evidenced by its inclusion in Fo-rich olivine. If the chromite is

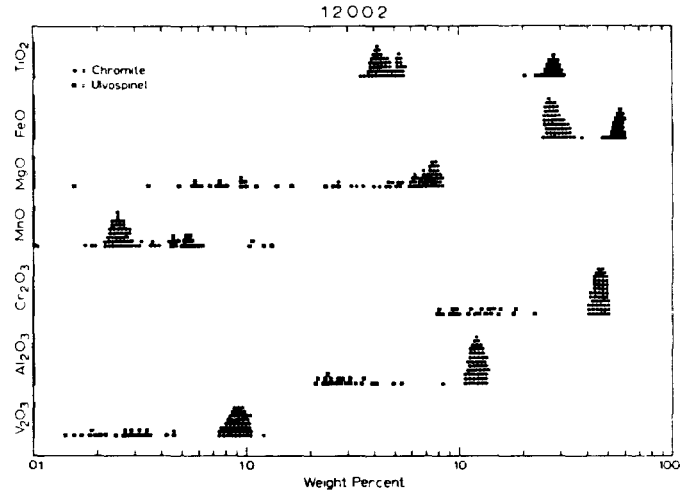


Fig. 13. Elemental distribution diagrams for chromites and ulvöspinel in typical Apollo 12 basalt (adapted from El Goresy et al., 1971).

completely included within the olivine, it is effectively isolated from the melt and undergoes no further growth or chemical change. However, if the chromite is in contact with the melt, it will continue to grow, increasing in TiO_2 and FeO and decreasing in Al_2O_3 , MgO , and Cr_2O_3 , the overall composition moving toward ulvöspinel (Fig. 14). Most of the basalts that contain both titanian chromites and chromian ulvöspinel possess the latter phase as overgrowths on the chromite. In reflected light, the ulvöspinel appears as brown to tan rims about the bluish chromite. The contact between the two is commonly sharp and is reflected in a discontinuity in the compositional trend from core to rim. This break probably reflects a cessation in crystallization, followed later by renewed growth in that the earlier chromite grains acted as the nuclei. Some rocks (e.g., 12018, Fig. 13) contain spinel grains that display diffuse contacts, also reflected in gradational changes in the chemistry of the solid solution. This could result from continuous crystallization of spinel or subsolidus reequilibration involving solid-state diffusion.

The spinel compositions of lunar rocks are typically represented within the ternary system: $FeCr_2O_4$ - Fe_2TiO_4 - $FeAl_2O_4$. The addition of Mg as another major component (actually, $MgAl_2O_4$) provides a third dimension to this system (Figs. 12 and 14). The principal cation substitutions of the solid solution in these lunar phases can be represented by $Fe^{2+} + Ti^{4+} = 2(Cr,Al)^{3+}$. The generalized compositional trends of the spinels in lunar mare basalts are shown in Fig. 14. Spinels are ubiquitous in mare basalts where they display various textures and associations. They are second in abundance only to ilmenite as the opaque mineral in basalts. They make up to 10-12% of some basalts (e.g., those from Apollo 12).

Spinels also occur in nonmare rocks such as anorthosites, anorthositic gabbros, and troctolites, although in much lower abundance than in mare basalts. The spinels in the anorthositic rocks tend to be chromites with lesser amounts of MgO , Al_2O_3 , and TiO_2 than those in basalts. Certain highland rocks, notably troctolites, contain a spinel phase called pleonaste (slightly Fe- and Cr-rich of the midpoint along the $MgAl_2O_4$ - $FeAl_2O_4$ join, Figs. 12 and 14). This spinel is not opaque, but it stands out in thin section because of its pink color, high refraction index, and isotropism.

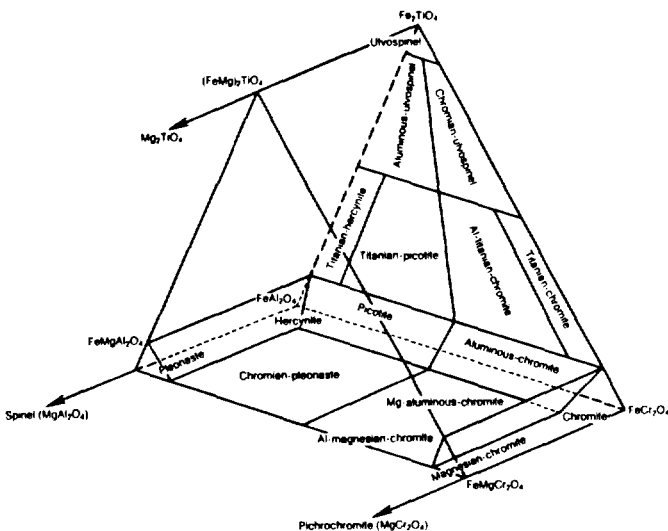


Fig. 12. Nomenclature for lunar spinels (adapted from Haggerty, 1972).

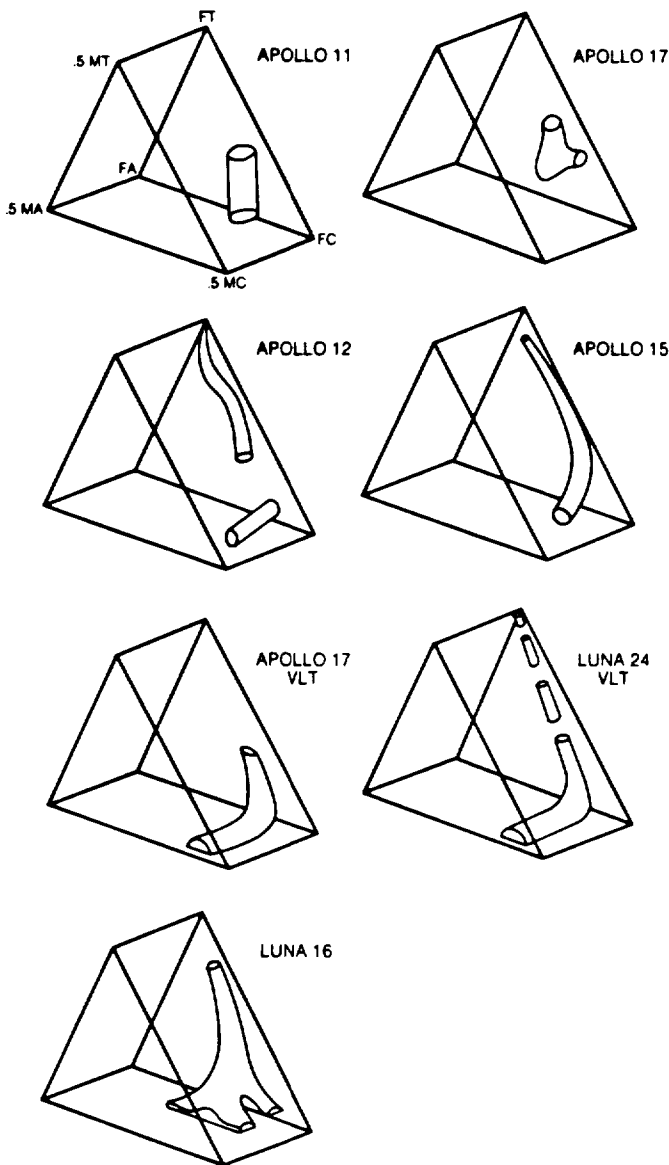


Fig. 14. Perspective views of the 3-D system $\text{FeCr}_2\text{O}_4\text{-Fe}_2\text{TiO}_4\text{-FeAl}_2\text{O}_4\text{-MgAl}_2\text{O}_4$ for mare basalt spinel compositions (modified from Haggerty, 1972).

Normal processes accompanying and subsequent to crystallization in terrestrial rocks involve oxidation; however, in lunar rocks and soil, the normal situation involves reduction. Ulvöspinel grains are often reduced to ilmenite + native Fe and sometimes to rutile + native Fe. This is the normal paragenetic sequence with lunar rocks and involves these subsolidus reactions (Fig. 15). In a few rocks (e.g., 14053, 14072), the Ti-rich spinel, ulvöspinel, is reduced to a Ti-poor spinel, titanian chromite, ilmenite, and native Fe. Figure 15 addresses this type of reaction. During normal crystallization of spinel from a melt, the spinel typically begins as chromite and changes its composition toward ulvöspinel as growth continues. The effect of the later subsolidus reduction on the last-formed ulvöspinel is to "exsolve" ilmenite + native Fe with the residual components enriching the remaining spinel, such that

its composition moves toward chromite. As well as being evidence for reduction of spinel, this secondary generation of the native Fe is important as a lunar base raw material. In fact, spinel in the soil readily undergoes reduction when shock metamorphosed by impacting micrometeorites. This reduction is driven by the presence of solar-wind-implanted particles, notably the elements hydrogen and carbon, which impart a reducing environment when heated to the high temperatures caused by the impacts.

Armalcolite

Armalcolite was first recognized as a mineral in samples from the Apollo 11 site where it occurs as an accessory mineral in Ti-rich basalts. Although its composition is strictly defined as $(\text{Fe}_{0.5}\text{Mg}_{0.5})\text{Ti}_2\text{O}_5$, the name is also used in a broader sense to describe the intermediate portions of the solid solution series $\text{FeTi}_2\text{O}_5\text{-MgTi}_2\text{O}_5$ (Fig. 16). Detailed chemical analyses of

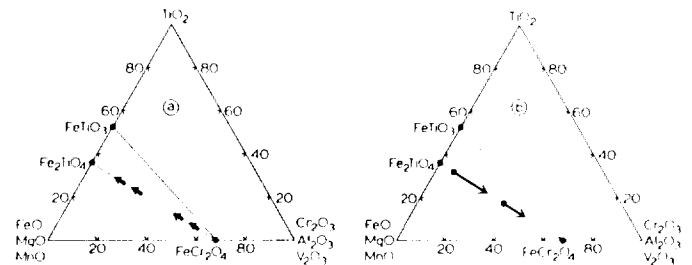


Fig. 15. Spinel compositional variations during (a) crystallization from a silicate melt and (b) subsolidus reduction (adapted from El Goressey et al., 1972).

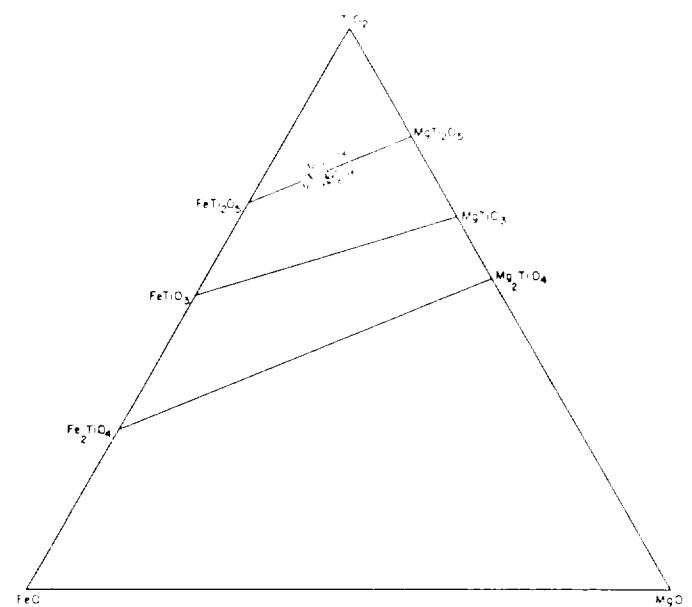


Fig. 16. Armalcolite compositions (wt%) plotted in the system FeO-MgO-TiO_2 (adapted from Anderson et al., 1970).

armalcolite, with crystal-chemical considerations of charge balance within the structure, have shown the presence of appreciable amounts of Ti^{3+} (Fig. 17). This is another result of the distinctly reducing environment that prevailed during the formation of lunar igneous rocks. This presence of Ti^{3+} in lunar armalcolite is noteworthy since it sets off the lunar varieties from armalcolites subsequently found on Earth.

The occurrence of armalcolite is restricted to high- TiO_2 -content rocks that have cooled relatively rapidly; slow cooling results in the reaction of early-formed armalcolite and liquid to form magnesian ilmenite. In practice, there are three distinct compositional types or varieties of armalcolite in lunar samples (Fig. 18). The first and most abundant type (>95% of observed) is represented by compositions intermediate to the solid solution series described above. This is the typical occurrence in Apollo 11 and 17 basalts, although it is found in samples returned from all missions. Two varieties of this first type have been characterized as gray and tan in color. These have overlapping compositions but appear to be present in different petrographies, with the most common type being the gray variety, which has rims of high-Mg ilmenite. Although it was suggested that these varieties were polymorphs, the crystal structures have been determined to be identical. Because the compositions are not distinctly different either, these are simply varieties, not polymorphs of armalcolite.

The second compositional type of armalcolite is characterized by having high ZrO_2 (3.8-6.2 wt%), Cr_2O_3 (4.3-11.5 wt%), and CaO (3.0-3.5 wt%) contents. This type is called Cr-Zr-Ca-armalcolite. The third type has a composition between the first, Fe-Mg titanate, and the second, Cr-Zr-Ca titanate. This armalcolite is termed Zr-armalcolite and has definitive amounts of ZrO_2 (2.0-4.4 wt%), Y_2O_3 (0.15-0.53 wt%), and Nb_2O_5 (0.26-0.65 wt%). These last two types of armalcolite are potentially important as resources of ZrO_2 .

Other Oxide Minerals

The only other oxide minerals of any volumetric significance in lunar rocks and soils are rutile (TiO_2) and baddeleyite (ZrO_2). Rutile is generally associated with ilmenite and most commonly

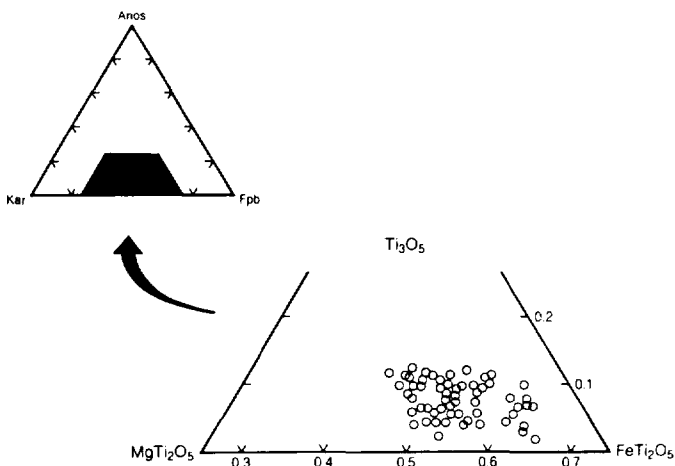


Fig. 17. Armalcolite compositions from mare basalts depicting the amount of Ti^{3+} as anosovite (Ti_3O_5) as calculated from electron microprobe analyses (adapted from Papike *et al.*, 1976).

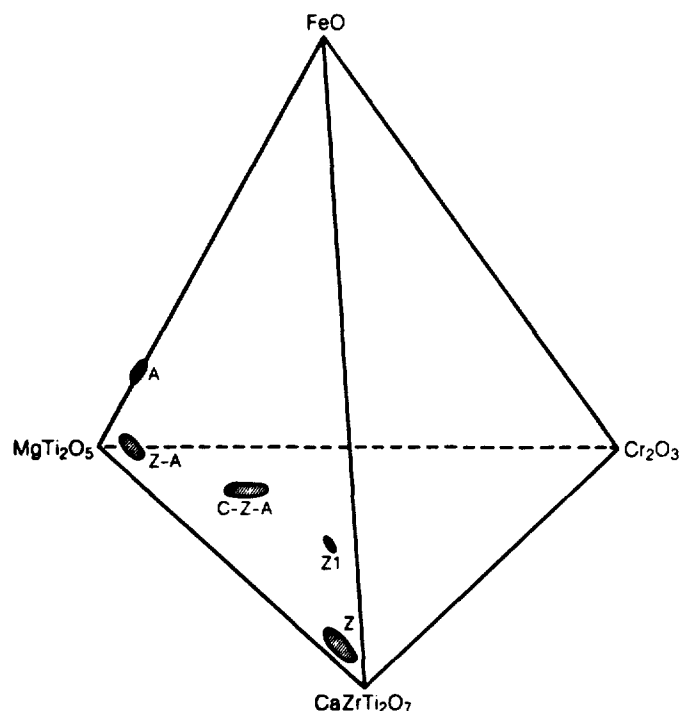


Fig. 18. Compositions (wt%) for armalcolite (A), Zr-armalcolite (Z-A), Cr-Zr-Ca-armalcolite (C-Z-A), Phase Z1, and zirconolite (Z) (adapted from Haggerty, 1973).

occurs as a reaction product from the reduction of ilmenite and/or armalcolite. In such cases, this rutile is secondary, forming after the initial formation of the rock. Primary rutile is rare and occurs as discrete, euhedral grains, typically associated with ilmenite. This rutile often contains Nb, Cr, Ta, and REE. Baddeleyite commonly occurs in "melt rocks," which are formed by large meteorite impacts that effectively melt the soil into a silicate magma that subsequently recrystallizes into an igneous rock, not much different from the other normal igneous rocks. However, it does have various amounts of meteoritic constituents. An example is Apollo 14 rock 14310, which contains abundant baddeleyite and schreibersite $[(Fe,Ni)_3P]$, both, most likely, residual from meteorites. Where baddeleyite occurs, the ilmenite commonly contains appreciable zirconium (i.e., up to 0.6% ZrO_2), and the Zr-bearing forms of armalcolite may also be present.

SULFIDE MINERALS

Troilite is the most common of the sulfide minerals in lunar rocks. It is ubiquitous and commonly associated with native Fe and/or ilmenite and/or spinel. It was originally thought that the troilite was always associated with native Fe in a texture reminiscent of the $988^\circ C$ eutectic between Fe and FeS. This is undoubtedly one of the origins of troilite in the lunar rocks; however, there are several others. In all occurrences, the amount of troilite is usually less than 1% by volume.

The most common occurrence of troilite is as an accessory phase in mare basalts, where it is usually a late-stage crystallization product. It is commonly associated with ilmenite and spinel, but also with native Fe. Its formation is a result of the bulk

composition of the melt, in particular, the S content. The volatility of S controls the formation of secondary troilite during meteorite-induced shock metamorphism. Some of the Apollo 16 rocks, notably 66095, "Rusty Rock," contain troilite that most likely formed as a direct result of the remobilization of sulfur during the impact process. The chemistry of troilite is essentially that of FeS with <1 wt% of all other components.

Other sulfides that have been positively identified include chalcopyrite, cubanite, and sphalerite. These phases have only been found as small (<10-15 μm) grains in some Apollo 12 basalts. Sphalerite was observed in some Apollo 16 breccias where it was probably formed as a result of mobilization of Zn and S during shock metamorphism. It is only present as small (<20 μm) grains and in minor quantities (<0.01 vol%).

NATIVE IRON

Iron present as Fe⁰ is not common in terrestrial rocks; however, in lunar rocks, it is an extremely common phase largely because of the low oxygen fugacities prevailing at the time of magma crystallization (Fig. 1). Native Fe is present as two phases in various proportions that are usually intergrown, kamacite (0-8% Ni) and taenite (8-50% Ni). Native Fe occurs in lunar samples as (1) indigenous, normal igneous metal, (2) Fe formed by reduction of certain minerals (e.g., ulvöspinel), (3) fragments of meteoritic metal, and (4) metal crystallized from lunar soil impact metamorphism formed during the normal crystallization of lunar highland and mare igneous rocks. In practice, it is the native Fe in the lunar soil that is the most common and easiest to recover.

Figure 19 shows a plot of Co vs. Ni contents for native Fe metal. The diagonal lines outline the "meteoritic field" that Goldstein and Yakowitz (1971) mistakenly designated as unique to metal from meteorites. The composition of metal within this field does not imply that it is of meteoritic origin. It may be indigenous lunar. Here, these boundary lines are used simply for reference.

The Ni and Co contents of native Fe metal can vary considerably, from 0% to over 50% Ni and from 0% to 4% Co. Figure 20 shows the chemical variation of native Fe for several Apollo 16 highland samples. Of all lunar samples, it is reasonable to sup-

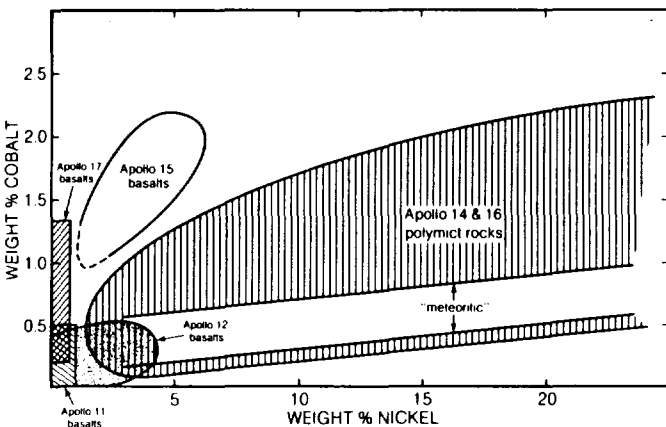


Fig. 19. Native Fe metal compositions by mission as compiled from the literature. The region labeled "meteoritic" is not necessarily indicative of metal originating from a meteorite, but is used for reference (see Misra and Taylor, 1975).

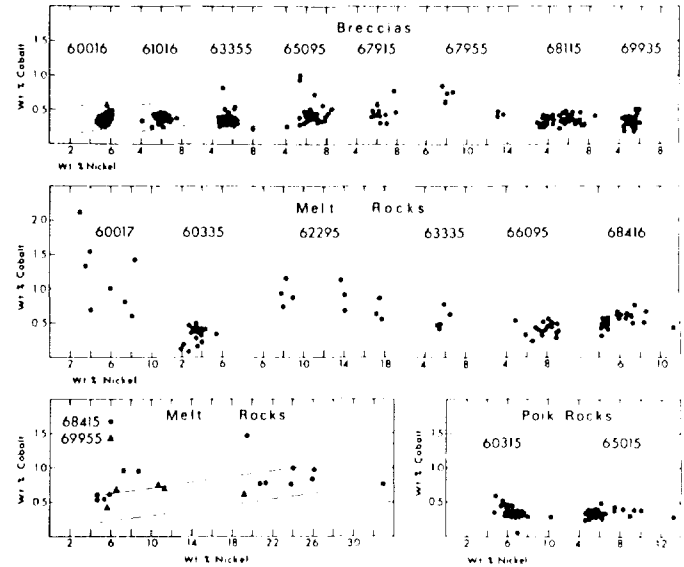


Fig. 20. Nickel and Co contents (wt%) of native Fe grains in numerous Apollo 16 rocks (adapted from Misra and Taylor, 1975). The diagonal parallel lines are used for reference (see Fig. 19 caption).

pose that the highland rocks contain the most meteoritic metal. In practice, the contents of certain siderophile elements in the soil, notably Ir, W, Re, Au, etc., are meteoritic signatures that have been used to estimate the influx of this type of extralunar matter. Using such signatures, the amount of meteoritic material in the highland soils has been estimated to be only 1-3%.

With the return of the first lunar samples, it was noticed that the ferromagnetic resonance (FMR) signal from the lunar soil samples was greater than that from rock samples. Therefore, there must be considerably more metallic Fe (i.e., Fe⁰) in the soils than in the rocks. Since the soils were composed of disaggregated rock material, this pointed to something unique occurring during the process of soil formation. Indeed, unraveling the origin of this additional native Fe in the soils led to our understanding of the complicated processes inherent in lunar soil formation (discussed below).

LUNAR SOIL FORMATION AND THE ORIGIN OF SINGLE-DOMAIN NATIVE IRON

As mentioned above, the lunar soil contains several times more native Fe than the rocks from which the soil was derived. This apparent paradox has given us important clues toward understanding lunar soil formation. The following discussion on the origin and significance of this free Fe in the lunar soils is taken largely from Taylor and Cirlin (1986).

What is inherently different between the lunar rocks and soils? Without the shielding atmosphere that the Earth possesses, meteoritic particles impinge upon the lunar surface with velocities on the order of 40,000-250,000 km/hr, thereby causing considerable damage, with craters ranging in size from thousands of kilometers to <1 μm. The size of the particles that produced these smallest of craters ("zap pits") is about 10% of the diameter of the crater. The flux of the small particles (i.e., micrometeorites)

was always greater than the flux of the large meteorites. The larger impacts smash large rock material into smaller pieces and move material great distances from its origin, but the soil development is largely a function of micrometeorite impacts.

Two basic processes form the lunar soil: (1) simple comminution, disaggregation or breaking of rocks and minerals into smaller particles and (2) agglutination, the welding of lithic and mineral fragments together by the glass produced by the quenching of micrometeorite-produced impact melt. These two processes compete to decrease and increase, respectively, the grain size of soil particles. Figure 21 depicts the comminution and agglutination of the lunar soil particles at a small scale. The glass-welded particles are called "agglutinates."

Ferromagnetic resonance studies of the rocks and soils detected a characteristic resonance that was only associated with agglutinates and regolith breccias (larger samples of impact-produced material). This characteristic resonance is produced by large numbers of "single-domain (SD) Fe⁰," that is, metallic Fe in the size range of 40-300 Å. It seems that the abundant agglutinates, the presence of which in the lunar soil was not anticipated before Apollo, are the carriers of much of the single-domain Fe⁰ in the soil. Transmission electron microscopic (TEM) studies of the glass in some of the agglutinates provided the first direct determination of the actual sizes of the numerous single-domain Fe⁰ (Fig. 22). The majority of the grains are in the range of 100-200 Å, well within the single-domain size range. Subsequent FMR Curie point measurements showed that these particles are essentially pure elemental Fe in composition.

What is the origin of this abundant single-domain Fe⁰? The soil on the Moon is continually bombarded with solar wind and has effectively become saturated with solar-wind-implanted elements, notably H and C. When a portion of the soil is melted by micrometeorite impact, these elements impose a very reducing environment such that Fe²⁺ in the silicate melt is effectively reduced to elemental Fe⁰ that precipitates as myriad tiny Fe⁰ spheres that are disseminated within the quenched melt (i.e., the glass). The melting and cooling process is so fast that it prevents

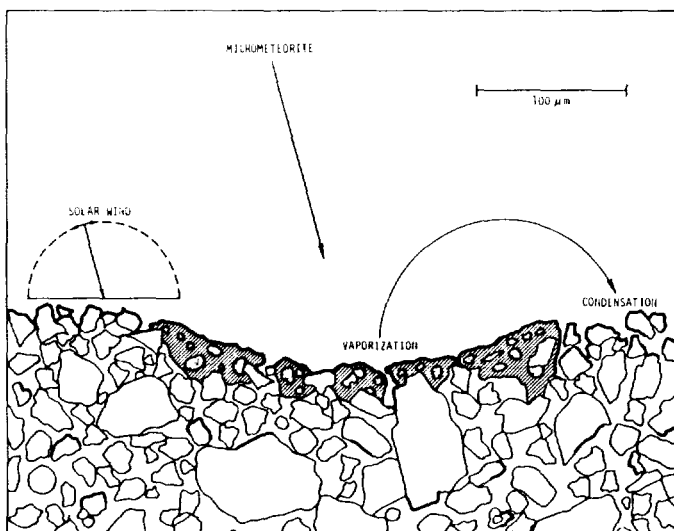


Fig. 21. Schematic representation of lunar soil formation.

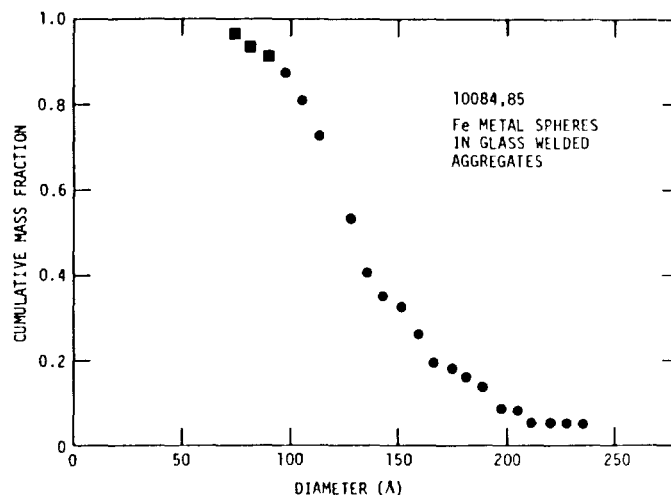


Fig. 22. Size distribution of Fe⁰ metal spheres in agglutinitic glass from Apollo 11 sample 10084. Data are from TEM photographs. The squares are for sizes <40 Å, which are too small to be counted with any certainty. Modified from Housley *et al.* (1974).

the native Fe from diffusing and aggregating into larger sized particles. This "autoreduction process" is responsible for the production of the additional Fe⁰ that resides in the agglutinates and distinguishes the soils from the rocks.

It was suggested that the variations in Fe⁰ contents of individual soils might be due to differences in exposure time to the solar wind and to meteoritic flux. That is, the amount of solar-wind-implanted reducing gases and impact reworking was a function of time. This was based upon rough correlations of Rb-Sr and Pb²⁰⁷-Pb²⁰⁶ ages vs. Fe⁰ content of soils. Although this apparent correlation was not real, it prompted other workers to study the origin of Fe metal particles in lunar samples. Thus, the concept of "exposure age" for a lunar soil was established as a function of the length of time of reworking at the lunar surface. To sedimentologists, this can be correlated with soil maturity.

I_s/FeO AS A MEASURE OF SOIL MATURITY

The ferromagnetic resonance spectra of all lunar soils are dominated by a signal due to fine-grained Fe⁰ particles (40-330 Å). The intensity of this signal is designated as I_s. It was suggested that this FMR intensity, normalized to the total Fe content (I_s/FeO), might be a measure of the relative surface exposure age of lunar soils. It is necessary to include FeO in this index because the amount of Fe⁰ generated by micrometeorite-impact autoreduction is a function, to some extent, of the FeO of the silicate liquid formed from the melting of the soil.

Effectively, as the duration of exposure at the lunar surface increases, so does the amount of solar-wind-implanted species, and the agglutinate content increases with an accompanying increase in the Fe⁰ metal (reflected in the increase I_s/FeO). Thus, the range of I_s/FeO for immature, submature, and mature levels of soil development is roughly equivalent to the same classification in terms of petrographic agglutinates, as well as mean grain size, for Apollo 17 soils. As explained above, an increase in I_s/FeO is a function of agglutinate content (Fig. 23), which in turn is a function of maturity (exposure) of a soil. This concept of

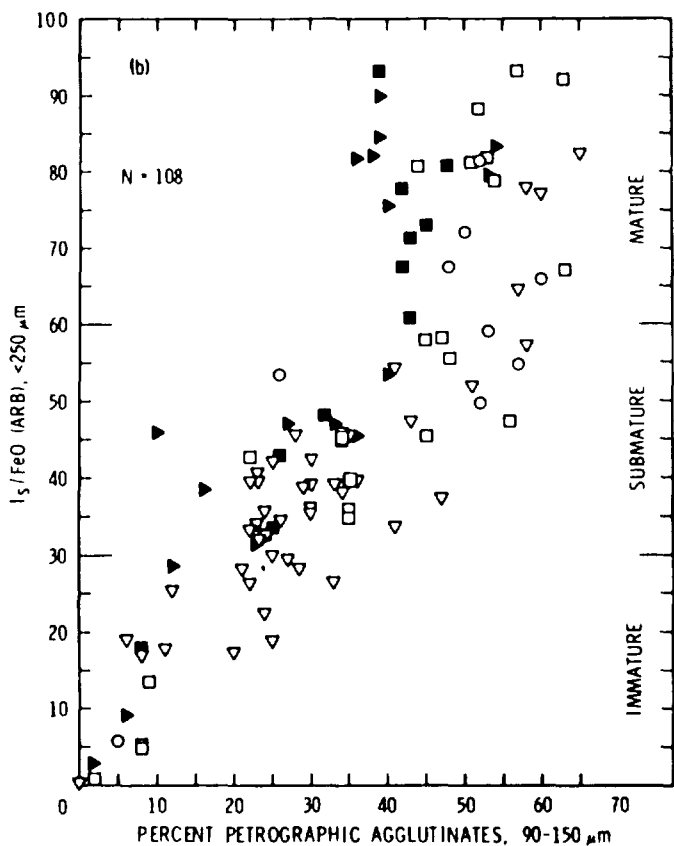


Fig. 23. Correlation of I_v/FeO with agglutinate contents of soils as determined by point counting with a petrographic microscope. Samples are from all Apollo missions. The legend for the symbols used here is given in Fig. 24. Figure modified from Morris (1976).

exposure age showed that for some soils, I_v/FeO correlates with trapped ^{36}Ar . Thus, the parameter I_v/FeO is an effective index of soil maturity, which is a function of surface exposure age.

I_v/FeO AS A MEASURE OF SOLAR-WIND ELEMENTAL CONCENTRATIONS IN LUNAR SOILS

Morris (1976) measured I_v/FeO for the $<25\text{-}\mu\text{m}$ -size fraction of 152 soils and for the $90\text{-}150\text{-}\mu\text{m}$ -size fraction of 88 soils. With this large suite of samples, it was possible to correlate I_v/FeO with a variety of other indices of surface exposure. For example, implanted N, C, and the gases ^3He and ^{36}Ar were shown to increase in concentration with increasing I_v/FeO values. Figure 24 shows the direct correlation of I_v/FeO (i.e., exposure age) with the contents of C and ^4He . However, of what practical use are the I_v/FeO values of lunar soils?

Nuclear fusion is a highly desirable source of energy because of its small amounts of radioactive products, and lunar soils are an extremely important source of ^3He , the most highly prized of the fusion reactants. This solar-wind-implanted species can be correlated with the more abundant ^4He . Figure 24 shows I_v/FeO vs. ^4He contents of several soils. At first glance, the ^4He correlation

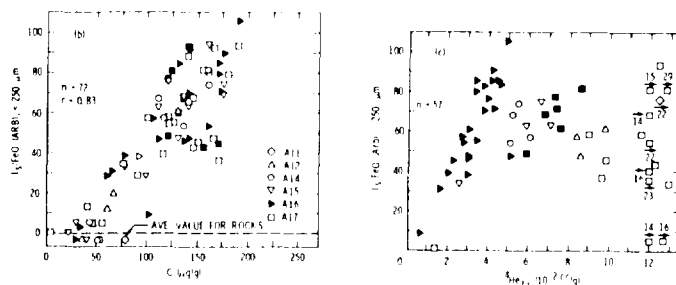


Fig. 24. Correlation of I_v/FeO with solar-wind gases. Figure has been modified from Morris (1976).

does not appear to be very good, but when the Apollo 17 soils are omitted, the correlation is good; in fact, it is almost the same as for C vs. I_v/FeO (also Fig. 24). The Apollo 17 soils are derived from high-Ti basalts and contain up to 14% ilmenite (FeTiO_3). Ilmenite appears to be a "sponge" (sink) for ^4He . Therefore, even immature Apollo 17 soils have enough exposure to solar wind to pick up and retain appreciable amounts of ^4He . The Apollo 17 soils with higher FeO contents (open squares on Fig. 24) have the highest ^4He contents; thus, the FeO content would seem to be indicative of the ilmenite content (Taylor, 1990).

Correlations also exist for $^{40}\text{Ar}/^{36}\text{Ar}$ and exposure age of soils. The trapped rare gases ^4He , ^{20}Ne , ^{36}Ar , ^{34}Kr , and ^{132}Xe are those gases that originate directly from the solar wind and not from nuclear reactions. Various studies have attempted to quantify the absolute rate of soil formation. These include use of cosmogenic radionuclides ^{22}Na , ^{26}Al , and ^{53}Mn , as well as "track densities." Based upon isotopic data, it is generally agreed that the rates of fine-grained lunar soil ($<1\text{ mm}$) formation are much less than 1 cm/yr .

The most detailed investigations applying I_v/FeO measurements on lunar soils were performed on core samples taken during the Apollo missions, particularly 15-17. Horizons of mature soil (high I_v/FeO) were discovered in these soil profiles. These mature soil layers are the result of slow formation with extensive reworking ("gardening") in the upper few centimeters or so of the regolith, a process termed "*in situ* reworking." However, large meteorite impacts obliterate or bury the "*in situ*" (i.e., mature) horizons so that the soil profile as revealed in cores does not represent continuous slow deposition, but sporadic events intermixed with periods of quiescent soil development. It was recognized that the units in the cores may be only discontinuous pods, rather than layers with horizontal extent and time significance. The unraveling of the secrets hidden within the soils is complicated and research continues today. However, the concept of I_v/FeO has proven to be one of the most useful in lunar science and will be of use for various commercial endeavors involved with a lunar base.

SUMMARY

The various constituents of the Moon, namely the rocks, minerals, and glasses, will be among the raw materials used to construct a lunar base. The lunar regolith, the fragmental material present on the surface, is composed mostly of disaggregated rocks and minerals, but also includes glassy fragments fused together by impacts. The finer fraction of the regolith (i.e., $<1\text{ cm}$),

informally referred to as soil, is probably the most important portion of the regolith for use at a lunar base. This soil can be used as insulation against cosmic rays, for lunar ceramics and abodes, for growing plants, for the extraction of valuable elements, etc. The soil contains abundant solar-wind-implanted elements, as well as various minerals, particularly oxide phases, that are of potential economic importance. For example, these components of the soil are sources of oxygen and hydrogen for rocket fuel, helium for nuclear energy, and metals such as Fe, Al, Si, and Ti, for construction. The peculiar impact-melt products in the soil called agglutinates are a function of the soil's maturity. These agglutinates contain tremendous quantities of metallic Fe. The FMR signature of a soil, I_2/FeO , measures the amount of agglutinates, which increases as maturity increases. As exposure at the lunar surface increases (i.e., maturity), the amount of absorption of solar-wind products also increases. Thus, the I_2/FeO signature is indicative of the relative amounts of solar-wind-implanted elements, notably He and H, in the lunar soil. It is obvious that a thorough knowledge of all aspects of the lunar regolith is requisite to any efficient plans for colonizing the Moon.

APPENDIX

Obtaining Lunar Samples

The lunar sample collection is a national treasure, and the samples must be preserved and curated with concern for their integrity. This entails the frugal use of samples for various purposes, usually scientific. Therefore, before samples are allocated, it must be determined that every attempt has been made to (1) use analog samples, either synthetic or natural (e.g., terrestrial or meteoritic specimens) and (2) design experiments such that the smallest amount of lunar material is needed without jeopardizing the quality of the results. In order to formally apply for allocation of lunar materials, it is necessary to write a short proposal to the Planetary Materials Curator. This proposal should address (1) the nature of the experiment to be conducted, particularly with respect to its scientific and/or engineering merits; (2) preliminary results obtained on analog samples; (3) consideration of the mass and size of the samples needed; (4) the specific sample number requested (as best as can be determined); (5) the credentials of the principal investigator and research associates; and (6) a description of the facilities necessary for conducting the experiment. Depending upon the individual situation, there may be some additional information needed; therefore, the Planetary Materials Curator should be contacted before submitting any request. Upon receipt of the sample request, the proposal will be reviewed by the Lunar and Planetary Sample Team (LAPST), who will make a recommendation to NASA concerning the request. It should be emphasized that the Planetary Materials Curator and his staff will make every effort to assist an individual in obtaining the proper sample, if the experiment merits its use.

Catalogs and Documents on Lunar Samples

There are many catalogs and documents about lunar samples that are not commonly known to the public. Following is a compilation of many of these publications, several of which are NASA publications and can be obtained by writing to

Planetary Materials Coordinator
NASA Johnson Space Center - Code SN2
Houston TX 77058
(713) 483-3274

Lunar Sample Documents

Apollo 11

- Preliminary Examination of Lunar Samples from Apollo 11. *Science*, 165, 1211-1227. (Lunar Sample Preliminary Examination Team, 1969.)
- Geologic Setting of the Lunar Samples Returned with Apollo 11. (Shoemaker E. M. et al., 1969.)
- Apollo 11 Preliminary Science Report. NASA SP-214, 1969.
- Lunar Sample Information Catalog Apollo 11. Lunar Receiving Laboratory, Science and Applications Directorate, MSC, NASA, 1969.
- Apollo 11 Organic Contamination History. (Flory D. A., Simoneit B. R., and Smith D. H., 1969)
- Lunar Surface Closeup Stereoscopic Photography on the Sea of Tranquility. NASA TMX-58077. (Greenwood W. R. et al., 1971.)
- Apollo 11 Lunar Sample Information Catalog (Revised). JSC 12522. (Kramer F. E. et al., 1977.)

Apollo 12

- Preliminary Examination of Lunar Samples from Apollo 12. *Science*, 167, 1325-1339. (Lunar Sample Preliminary Examination Team, 1970.)
- Apollo 12 Preliminary Science Report. NASA SP-235, 1970.
- Apollo 12 Lunar-Sample Information. NASA TRR-353. (Warner J., 1970.)
- Electron Microprobe Analyses of Minerals from Apollo 12 Lunar Samples. *Univ. New Mexico Spec. Publ. No. 3*. (Busche E. D. et al., 1971.)
- Apollo 12 Coarse Fines (2-10 mm): Sample Locations, Description, and Inventory. NASA JSC 14434. (Marvin U. B., 1979.)

Apollo 14

- Preliminary Examination of Lunar Samples from Apollo 14. *Science*, 173, 681-693. (Lunar Sample Preliminary Examination Team, 1971.)
- Apollo 14 Preliminary Science Report. NASA MSC SP-272, 1971.
- Apollo 14 Lunar Sample Information Catalog. NASA MSC TMX-58062. (Lunar Sample Curator's Office, 1971.)
- Lunar Surface Closeup Stereoscopic Photography at Fra Mauro (Apollo 14). NASA JSC TMX-58072. (Carrier W. D. and Heiken G., 1972.)
- Description, Classification, and Inventory of the Comprehensive Sample from Apollo 14. NASA JSC. (Phinney W. et al., 1975.)
- Apollo 14 Coarse Fines (4-10 mm) Sample Location and Classification. NASA JSC 12922. (Kramer F. E. and Twedell D. B., 1977.)
- Geology of the Apollo 14 Landing Site in the Fra Mauro Highlands. *U.S. Geol. Surv. Prof. Pap. 880*. (Swann G. A. et al., 1977.)
- Lithological Maps of Selected Apollo 14 Breccia Samples. NASA JSC 13842. (Twedell D. et al., 1977.)
- Apollo 14 Rock Samples. NASA JSC 14240. (Carlson I. C. and Walton J. A., 1978.)

Apollo 15

- Apollo 15 Preliminary Science Report. NASA MSC SP-289, 1972.
- Apollo 15 Lunar Samples—Collection of Papers. *Science*, 175, 1972.

- Apollo 15 Coarse Fines (4-10 mm): Sample Classification, Description, and Inventory. *NASA MSC 03228*. (Powell B. N., 1972.)
- Documentation of Apollo 15 Samples. *U.S. Geol. Surv. Interagency Rept. 47*. (Sutton R. L. et al., 1972.)
- Lunar Sample Information Catalog Apollo 15. *NASA MSC 03209*. (Lunar Receiving Laboratory, 1972.)
- Apollo 15 Rake Sample Microbreccias and Non-Mare Rocks: Bulk Rock, Mineral and Glass Electron Microprobe Analyses. *Univ. New Mexico Spec. Publ. No. 11*. (Hlava P. F. et al., 1973.)
- Electron Microprobe Analyses of Spinel Group Minerals and Ilmenite in Apollo 15 Rake Samples of Igneous Origin. *Univ. New Mexico Spec. Publ. No. 10*. (Nehru C. E. et al., 1973.)
- Apollo 15 Deep-Drill-Core: Classification, Description, and Inventory of Separated Particles. *NASA JSC*. (Drake M. J., 1974.)
- Catalog of Apollo 15 Rocks: Parts 1, 2, and 3. *Curatorial Branch Publ. No. 72, JSC 20787*. 1296 pp. (Ryder G., 1985.)
- Workshop on the Geology and Petrology of the Apollo 15 Landing Site. *LPI Tech. Rpt. 86-03*. 126 pp. (Spudis P. D. and Ryder G., 1986.) Lunar and Planetary Institute, Houston.
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