Petrologic history of the moon inferred from petrography, mineralogy, and petrogenesis of Apollo 11 rocks

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Abstract—The mineralogy and petrology of the Apollo 11 rocks are consistent with impact melting of ilmenite and pyroxene crystals plus liquid derived from fractional crystallization of basaltic magmas. The complementary plagioclase accumulate should exist in the highlands. The ferrobasaltic magma is derived from a differentiated hot moon of modified chondritic composition. The one-sided distribution of large irregular seas is explained by tidal attraction of the last fraction of liquid to the near side of the moon and release of liquid by meteorite impact.

The vesicular ferrobasalt lavas contain ilmenite, clinopyroxene and plagioclase and have textures similar to some terrestrial basalts. Delayed appearance of plagioclase indicates an unusual source of the magma. The iron-enrichment of the coarser microgabbros is extreme at the end of crystallization resulting in a new iron metasilicate, pyroxferroite.

The oxygen fugacity at 1050°C of these rocks indicated by the composition of opaque oxides and titanite-iron intergrowths is 10^−14−10^−16 compared to 10^−11 for terrestrial basalts and about 10^−16 for ordinary chondrites. Absence of hydrous minerals indicates loss of volatiles at some stage in the moon’s history.

The breccias and soil have the same mineralogy modified by shock. Plagioclase vitrophyres are probably melted cumulates and may derive from the highlands. Lithification of the breccia results principally from welding of debris discharged from a hot gas cloud created by meteorite impact. Small glass spheres have surface features consistent with a fiery rain of boiling silicate liquid rounded by surface tension and later impacted by high-velocity micrometeorites.

Melting experiments of synthetic material of mean Apollo 11 rock composition revealed low liquidus temperature, delayed appearance of plagioclase and narrow crystal–liquid interval. These support the concept of advanced fractional crystallization of a basaltic liquid under reducing conditions leading to high iron enrichment. Flotation of plagioclase and sinking of ilmenite and pyroxene should occur in the liquid basalt.

We propose that meteorite impact blasted away a plagioclase-rich crust, melting a mixture of fractionated basalt liquid and ilmenite plus pyroxene crystals. The new liquid formed the Sea of Tranquillity and yielded the near-surface lava flows represented by the ferrobasalts and microgabbros. This new liquid could yield plagioclase only after the extra ilmenite and pyroxene had crystallized.

We propose that the original basalt liquid was derived by fractional crystallization of a molten moon of modified chondritic composition yielding a metallic core surrounded by pressure-stable Mg-rich olivine and pyroxene. The fractionated liquid became Fe-rich resulting in an inverse density stratification. Primitive ultrabasic crust should occur in the highlands, along with dominant plagioclase-rich cumulates.

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The temperature-time relations of the model are discussed qualitatively. Key factors are early removal of radioactive material from the center by fractional crystallization and possible enhancement of radiative heat transfer in volatile-free silicates. The moon rocks should be more refractory and rigid because of the low volatile content.

1. INTRODUCTION

The preliminary findings of the Lunar Sample Preliminary Examination Team published in Science (LSPET, 1969) were supplemented by the short papers presented at the Houston Meeting in January, 1970 (published in Science, 167, No. 3918, 1970). Here we present a review of the lunar rocks aimed specifically at the petrological history of the moon. This is based almost entirely on the results in our previous, abbreviated paper (Anderson et al., 1970a) and specifically references only those results presented by other investigators at the Houston conference that extend ours. Because of space limitations, we present in full only those sections dealing with the Apollo 11 rocks, and publish elsewhere Sections 7, 9 and 10 which have more general implications for the crystallization of lunar rocks. Very brief summaries are given in place of these sections.

We studied samples 10022, 10057 and 10072 of Type A (LSPET numbers) fine-grained crystalline igneous rocks hereafter termed "ferrobasalt"; microgabbros 10044 and 10047 of Type B, medium-grained vuggy crystalline rocks; breccia 10061 of Type C; and fines 10084 and 10085 of Type D.

One of us (A.T.A.) surveyed thin sections of other samples in Houston, finding considerable variability in the proportions of minerals, and in texture, from one specimen to another. The rock samples available to us, however, appear to illustrate the main trends exhibited by the assemblage of Apollo 11 specimens.

Particles from the fines were studied with single crystal X-ray diffraction and electron microscope techniques. The thin-sections were studied by optical microscopy using reflected and transmitted light. Our chemical analyses were made with an ARL electron probe X-ray microanalyser. Analyses are corrected for background and instrument drift and for deadtime, matrix absorption and atomic number effects according to procedures given by Smith (1965). A phase equilibrium study was made of a synthetic material of lunar ferrobasalt composition in stoppered Fe metal containers in evacuated and sealed SiO₂ glass tubes.

2. Petrography of the Crystalline Rocks

Ilmenite, augite and plagioclase are dominant in Apollo 11 crystalline rocks, breccias and fines (LSPET, 1969). Their relative proportions vary from rock to rock as well as within individual rocks. Figure 1 illustrates the range of textural variations.

(i) Ferrobasalts

The ferrobasalts (Figs. 1 a, b, c, f) are microcrystalline volcanic rocks containing vesicles up to a millimeter in diameter. The order of abundance of the major minerals is clinopyroxene, plagioclase and ilmenite. Many vesicle walls are lined by ilmenite, a feature also characteristic of experimentally melted ferrobasalts at near-liquidus temperatures. In most ferrobasalts, patches of relatively coarsely crystalline ilmenite
Fig. 1. Large scale textural features of Apollo 11 rocks. (a) Ferrobasalt 10022: Note platy habit of ilmenite in plagioclase rock region compared to tabular ilmenite in pyroxene rich portion; (b) Ferrobasalt 10072: Note grain size intermediate between (a) and (c); (c) Microgabbro 10044: Large arborescent ilmenite, dark, turgid residuum region containing diamond-shaped plagioclase; (d) Breccia 10061: Note 2 large fragments of ferrobasalt, fine grained, dark matrix, other rock fragments and glass spheres; (e) Breccia 10061: Note fragments of vesicular glass (lower left), plagioclase vitrophyre (lower right), ferrobasalt fragment (center left); (f) Ferrobasalt 10057: Transmitted light, 1 cm = 0.22 mm. (a) through (e): Plagioclase light, pyroxene medium gray, ilmenite black. Scale: 2 cm = 1.48 mm.

and pyroxene surround finer grained regions rich in plagioclase, pyroxene and interstitial glass (Fig. 1a). The interstitial glass constitutes 5–10 per cent of the ferrobasalts, is invariably devitrified, and locally contains tiny high refractive index spheres interpreted by ROEDDER and WEIBLEN (1970) as quenched droplets of an immiscible iron-rich residual liquid. Although rare olivine has been reported in some of the ferrobasalt samples (LSPET, 1969), no olivine phenocrysts were observed in our ferrobasalt samples. Olivine was found in some ferrobasalt fragments in the breccia.
(ii) Microgabbros

The microgabbros contain the same major minerals. They are coarser-grained, with irregular cavities lined with small crystals (Fig. 1c). There are no phenocrysts. Interstitial patches of fine grained iron-rich and silica-rich minerals take the place of the glass in ferrobasalt. A striking residual symplectic intergrowth of two moderate-reflectivity minerals and one very low-reflectivity mineral forms an apparent continuation of some large pyroxene grains. This texture was interpreted by Ware and Lovering (1970) as a breakdown product of a pyroxene or pyroxenoid mineral. Other as yet unidentified minerals occur in these residuum regions together with ilmenite and ulvöspinel, and probably include some of the rare earth and zirconium minerals mentioned by others.

3. Petrography of the Breccia

The Apollo 11 breccia sample is a well-indurated detrital rock composed of a spectacular array of glass particles and small mineral and rock fragments set in a dark matrix of extremely fine-grained glass and mineral dust (Fig. 1d, e). The agency of lithification is not immediately apparent: although the LSPET (1969) report states that some of the breccias are as hard as any of the crystalline rocks, at least breccia 10061 shows little evidence of strong post-depositional compaction. The bulk compositions of breccias given in LSPET (1969) indicate to us that they contain somewhat more plagioclase than the crystalline rocks. The possibility that some of the breccia material is derived from a plagioclase-rich highlands source will be discussed below.

(i) Mineral fragments

Broken mineral fragments are a major component. The mineral species present are those of the ferrobasalts and microgabbros, variously altered by shock. Plagioclase is conspicuous both in abundance and in the range of shock features it exhibits. Nearly isotropic plagioclase with prominent birefringent cracks is common. Conversion to a nearly glassy state is produced in some plagioclase by moderately strong shock. One plagioclase fragment showed densely-spaced possibly shock-induced twin lamellae (as in Fig. 2, p. 511, of Bunch et al., 1969). A weakly birefringent particle of what is probably shocked plagioclase showed reduced refringence and birefringence and contained numerous inclusions of high relief. The granules may either be fresh plagioclase grown during annealing of the shocked host, or they may be a high pressure phase or phases produced by shock.

Bizarrely broken and bent pyroxene crystals are very abundant. Many show oscillatory extinction varying over 60° or more. Rare ilmenite grains laced with shock-induced twinning lamellae are found. Numerous small olivine chips are present. There are occasional small ragged pieces of iron, probably meteoritic.

(ii) Rock fragments

Several relatively large ferrobasalt chips, up to two millimeters across, are present in breccia 10061 (Fig. 1d). The ferrobasalt fragments in the breccia appear different
from the large ferrobasalt specimens brought back by Apollo 11. Glass and pyroxene-rich particles of ferrobasalt are present and some lack plagioclase (Fig. 2a). Many fragments show evidence of moderately strong shock. Some ferrobasalt fragments have a rind of non-vesicular or vesicular glass.

(iii) Glass fragments

A variety of glass and partially glassy fragments is found: (a) glass beads and “chondrules,” (b) irregular fragments of vesicular glass, (c) glass rims on rock fragments, (d) plagioclase vitrophyres and (e) olivine vitrophyre.

Fig. 2. Complementary ferrobasalt (a) and plagioclase vitrophyre (b). Reflected light, scale: 90 μm = width of fields of view. (a) Ferrobasalt fragment in breccia 10061 (glass analysis No. 4, Table 5). Troilite and iron—white, ilmenite—light gray, augite—medium gray, devitrified glass—mottled dark gray. (b) Plagioclase vitrophyre fragment in breccia 10061, (glass analysis No. 10, Table 5). Sputtered carbon in cracks—light gray, devitrified glass—mottled medium gray, plagioclase—dark gray.

(a) Glass beads of the sort described in the Tranquillity Base fines are abundant in the breccia. They vary from a fraction of a millimeter in diameter down to the lower limit of optical resolution. Some larger beads show irregular surface breakage. Colors range from colorless to deep reddish brown. Some beads are inhomogeneous in composition. One hollow thin-walled bead had three distinct colors. Many beads have small spheroidal cavities near the center; a few have very large cavities enclosed by thin walls of glass. The cavities presumably result from volatilization of
material within the liquid droplet. Some spherules have fine radiating crystal aggregates reminiscent of the structure of pyroxene chondrules of chondritic meteorites. An analysis of a "chondrule" verified that the composition is pyroxene-rich (Analysis 13, Table 5).

(b) Irregular fragments of vesicular glass, pale yellow to golden brown are abundant. Some are up to half a millimeter across. Vaguely defined crystal relics are characteristic, as if fast partial melting was arrested. Highly vesicular areas are devoid of crystal relics. Dim streaks of very small inclusions of bubbles give a wispy appearance. Abundant spherical blebs of metallic iron are ubiquitous in the irregular vesicular glass particles, especially concentrated towards the rims. Microprobe scanning of some of the larger blebs showed that nickel is quite minor (<4 wt. %), much less than would be expected if they were of meteoritic origin. The surrounding glass shows an iron depletion immediately adjacent to the blebs. These features suggest that some of the iron blebs may have formed by reduction of original iron during strong heating.

(c) Glass rims on lithic fragments in the breccia are conspicuous. One large particle had a thin clear yellow glass rim, but a more common rim type consists of vesicular glass speckled with tiny iron inclusions and containing dim relics of partially melted crystals. A small lithic fragment with a continuously enveloping glass jacket had a relic of pyroxene in the rim. Hence this rim cannot be splashed-on glass. The glass rims apparently formed by melting inward from the external surface during flight. Some rims, especially the more vesicular ones, have relatively sharp margins with the unmelted rock. Others are more diffuse. A strong but very momentary heating of impact-produced ejecta suggests itself.

(d) Plagioclase vitrophyres are largely glassy non-vesicular particles containing euhedral or dendritic plagioclase microlites (Fig. 2b). Several examples were found in the breccia. The plagioclase vitrophyres lack the minute iron blebs found in many other types of glassy particles.

(e) The single olivine vitrophyre fragment contains 70 per cent glass lacking vesicularity. Olivine crystals are elongate and skeletal. The tendency towards sub-parallel arrangement of olivine crystallites suggests a mode of origin in common with the barred-olivine chondrules of chondrites.

4. Components of the Soil

Brief optical and X-ray study of the soil indicated that the major part was composed of the same fragments found in the breccia, as described earlier.

The morphology of the glass spheres was studied by hard-vacuum scanning electron microscopy as described earlier [Crewe et al. in Anderson et al., (1970a)]. The complex surface features include: (a) Dimpled surfaces. The dimples do not overlap, and emission of gas is a possible explanation. (b) Deformed surfaces with small angular fragments sticking to them. This feature is consistent with collision of semi-viscous sphere with soil. (c) Broken edges. This indicates cracking of solidified spheres. (d) Minute, rubble-filled, circular lipped depressions. This indicates high-velocity impact of meteoritic origin.

All features are consistent with a cloud of liquid drops shaped by surface tension.
and vibration falling onto the moon's surface and colliding with the regolith at different degrees of solidification. Cold spherules lying on the surface were bombarded by micrometeorites and impact-generated projectiles.

Strong evidence of shock in the breccia and soil minerals indicates that at least much of the liquid forming the fiery rain was formed by meteorite impact. No estimate could be made of the extent of volcanic production.

Very rare fragments of iron meteorites accounted for at most about 0.1 per cent of the soil. No undoubted fragments of stony meteorites were identified, but they would be essentially indistinguishable from other components.

Fragments of plagioclase-rich materials were identified but not studied in detail. Other workers identified these as fragments of anorthositic rocks, possibly from the highlands (Chao et al., 1970a; King et al., 1970; Short, 1970; Wood et al., 1970).

5. MINERALOGY

We now describe in approximate order of crystallization the phases which we recognized in the Apollo 11 materials. Later we summarize the mineral paragenesis of Apollo 11 crystalline rocks.

(i) Troilitc and metal

In ferrobasalts 10022, 10057 and 10072 and in microgabbros 10044 and 10047 there is troilitc with inclusions of Fe metal. The troilitc-iron grains are spherical to irregular and up to about 100 μm in diameter. The iron inclusions are subspherical to euhedral and up to 20 μm in dia. Magnified 1200 diameters some iron crystals are internally heterogeneous and contain at least one phase with a reflectivity lower than that of troilitc. Microprobe analysis of the large iron crystals gave 97% Fe, 0.3% Ni and less than 0.1% S. Possibly the low reflectivity phase is an oxide, phosphide or carbide. The composition of the troilitc is about Fe1.05S, with the apparent excess of Fe possibly due to an iron crystal below the plane of polish. The bulk composition of the troilitc-iron grains is about Fe1.3S as indicated both by microprobe analysis and by modal analysis of the troilitc-iron composite grains.

Iron-troilitc grains in impact glasses of the soil and breccia 10061 vary widely in iron/troilitc ratio, but most are more than 90% iron. Most grains are spherical, but some grains larger than 50 μm are irregular. Analyses of three small spherical grains and two large irregular grains of metal revealed up to 4% Ni in a small sphere.

The largest metal fragment (500 μm by 200 μm) contained less than 0.5% Ni. Other investigators reported variable and in part higher Ni contents of metal phases than we encountered. The small iron metal spheres in irregular vesicular impact glasses are surrounded by haloes of low iron glass suggesting a local (not meteoritic) origin of the iron. The origin of the large fragment of metal low in Ni is uncertain.

(ii) Armalcolite

Two large crystals of moderately anisotropic magnesium-rich armalcolite (cf. Anderson et al., 1970b) occur in thin section 29 of rock 10022. Both have rims of ilmenite about 100 μm wide. A representative chemical composition is listed in Table 1 and plotted on Fig. 3. The composition varies slightly from the centers of
Table 1. Lunar Fe–Ti oxides

<table>
<thead>
<tr>
<th></th>
<th>Ferrobasalt 10022</th>
<th>Ferrobasalt fragments in breccia 10061</th>
<th>Microgabbrro 10044</th>
</tr>
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<tr>
<td></td>
<td>B11-3</td>
<td>010-6</td>
<td>F19-1</td>
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<tr>
<td>MgO</td>
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<td>43.8</td>
</tr>
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<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>TiO2</td>
<td>53.1</td>
<td>51.5</td>
<td>52.3</td>
</tr>
<tr>
<td>Al2O3</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MnO</td>
<td>0.29</td>
<td>0.32</td>
<td>0.36</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>0.54</td>
<td>1.11</td>
<td>0.48</td>
</tr>
<tr>
<td>Total</td>
<td>99.6</td>
<td>97.9</td>
<td>98.8</td>
</tr>
</tbody>
</table>

Microprobe standards: natural ilmenite K13-131-8 (Mg, Fe, Ti, Mn), chromite 61-1436 (Al, Cr) cf. (Anderson, 1968). Some sums are low possibly due to problems of electrical conductivity of the carbon-coated thin section mounts.

* 0.5 wt. % TiO2.

Key to analyses of Fe–Ti Oxides

Ferrobasalt 10022. B, 11-3 ilmenite rim on armalcolite; O, 10-6 ilmenite lining vesicular cavity; F, 19-1 interior of large tabular ilmenite in pyroxene-rich, plagioclase-poor region; B, 11-25 small platy ilmenite about 100 µm away from large armalcolite; E, 19-5 small platy ilmenite in plagioclase-rich region adjacent to devitrified residual glass. B11-5 Large phenocryst of armalcolite jacketed by ilmenite.

Ferrobasalt fragments in breccia 10061. 21, 31, 41, 51 are ilmenites in corresponding fragments 2, 3, 4, 5 glass analyses reported in Table 5.

Microgabbrro 10044. PQ-7 interior of large arborescent ilmenite. PQ-8 margin of same crystal. S-16B tiny ilmenite in residuum. ST-17 ulvöspinel in residuum.

The armalcolite crystals toward their contacts with ilmenite: Cr2O3 and MnO decreasing, Al2O3 and MgO increasing. Although armalcolite in rock 10022 had negligible ferric iron (assuming R3O8 stoichiometry) its composition is otherwise similar to material in Hawaiian basalts.

Breccia 10062 contains armalcolite rimmed by ilmenite in a fragment of ferrobasalt and in a tiny grain composed of rutile (or other TiO2 polymorph), ilmenite and armalcolite. The three-phase assemblage: rutile, ilmenite and armalcolite (seen also

Fig. 3. Compositions of Fe–Ti oxide minerals in Apollo 11 rocks and range of phenocryst oxides in terrestrial basalts.
In rock 10022) is noteworthy because of the breakdown of FeTi₂O₅ to TiO₂ and FeTiO₃ below 1140°C in the pure FeO–TiO₂ system (LINDSLEY, 1965).

(iii) Ilmenite

Ilmenite in ferrobasalt decreases in Gi content (Gi = mol. % MgTiO₃) with crystallization. Rims on armalcolite have 13% Gi, early crystals lining vesicles 11% Gi, tabular crystals in ilmenite-pyroxene rich areas 6% Gi, platy crystals in plagioclase–glass rich areas 3–0·3% Gi (Table I). With crystallization and decrease in Gi the ilmenites in ferrobasalt contain less Cr₂O₃ but variable MnO (Table I).

![Diagram](image)

Fig. 4a. Compositions of minerals from Apollo 11 rocks. End members and minor element data which apply to different minerals are: plagioclase (CaAl₂Si₂O₈, NaAlSi₃O₈, KAlSi₃O₈, 0·5–1·3 FeO, 0·2 MgO, 0·1 TiO₂), pyroxenes and pyroxmangite (renamed pyroxferroite) (Ca₂Si₂O₆, MgSiO₃, FeSiO₃, 0·15–0·7 MnO, 0·6–0·1 Cr₂O₃, 8–1 Al₂O₃, 4–1 TiO₂, data for augites only, Al and Ti are highest in augites from ferrobasalts), olivine (Ca₃SiO₄, Mg₃SiO₄, Fe₃SiO₄, 0·00–0·03 Ni, 0·14–0·29 Mn, 0·2 Ca, and in fayalite: 0·8–0·9 Mn, 0·2–0·4 Ca, 0·1–0·3 Ti, 0·00–0·01 Cr) ilmenite (Fe₃O₅, MgTiO₃, FeTiO₃, 0·5–0·0 Al₂O₃, 0·8–0·3 Cr₂O₃, 0·4–0·9 MnO). Comparison curves for Shiant Isles and Skaergaard pyroxenes and plagioclases from BROWN (1957), MURRAY (1954) and WAGER and DEER (1939).

Fig. 4b. Iron, magnesium, alkali diagram of glasses from Apollo 11 rocks. Arrows on lines of liquid variation point toward increasing solidification. Comparison curve for estimated Skaergaard liquids from BROWN (1957).

The ilmenites in microgabbro 10044 are less variable in composition than those in ferrobasalt 10022 and range from Gi 3 in the center of a large arborescent crystal to Gi 0·4 in a tiny crystal in the microcrystalline residuum (Table I). Whereas the ilmenites in ferrobasalt have 0·3–2·7 wt. % Fe₂O₃ (which increases with decreasing Gi content, Figs. 3 and 4a, Table I) those in microgabbro 10044 have less than 0·5 wt. % Fe₂O₃ and possibly contain up to 1 wt. % of Ti₂O₅, assuming ideal R₂O₃ stoichiometry.
Ilmenite which rims armalcolite in ferrobasalt 10022 and a few armalcolite grains in ferrobasalt fragments in breccia 10061 contains lamellae of rutile (or other TiO₂ polymorph) up to about 5 μm wide and wisps of spinel up to about 2 μm wide. Their thinness prevented complete resolution with the microprobe. Analyses revealed more than 74% TiO₂ in rutile (?) and a positive correlation between Al₂O₃ (up to 12 per cent) and Cr₂O₃ (up to 9 per cent) for the spinel phase with one value of 21% Al₂O₃ and 0.5% Cr₂O₃.

(iv) Ulvöspinel

Microgabbros 10044 and 10047 contain ulvöspinel subhedra up to 40 μm in diameter in the finely crystalline residuum. Microprobe analyses reveals the ulvöspinel to be nearly pure Fe₂TiO₄ with a small amount of Al₂O₃ and MnO (Fig. 3, Table 1). In microgabbro 10047 the ulvöspinel is commonly intergrown with ilmenite whereas in 10044 it occurs principally as isolated grains.

Table 2. Olivines in lunar breccia 10061

<table>
<thead>
<tr>
<th></th>
<th>P10-6</th>
<th>P10-B</th>
<th>1-J, 12-13</th>
<th>14</th>
<th>O, 12</th>
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<td>82</td>
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<td>Ni</td>
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* Fo—mol. % Mg₅SiO₄ based on a calibration curve of Mg counts vs. Fo, accuracy ±2%.

P10-C, B: isolated crystals in breccia 1-J, 12-13; microphenocryst in ferrobasalt fragment. 14: microphenocryst in olivine vitrophyre (Table 5, No. 14). Poor resolution, Fo possibly appreciably greater. O, 12: phenocryst in ferrobasalt fragment. DE, 14: large crystal in ferrobasalt fragment. Microprobe standards: analyzed olivine Fo 88.5, 0.32% Ni, 0.118% Mn, diopside glass.

(v) Olivine

Two fragments of ferrobasalt in breccia 10061 contain subhedral crystals of olivine up to 200 μm long. One glassy fragment contains dendritic olivine microphenocrysts and possibly is a fragment of quenched picritic lava. Figure 4a shows and Table 2 reports compositions of olivine crystals in breccia 10061. The moderate Mn and Ca contents are usual for terrestrial volcanic olivine (Simkin and Smith, 1970), but the Ni contents are low compared to most terrestrial olivines of similar Mg₅SiO₄ content (about 70 mol per cent). A microprobe analysis of residuum fayalite is given in Table 3.

(vi) Pyroxenes and pyroxenoid

Figure 4a illustrates the range of compositions encountered in pyroxenes from the three rock types. Chemical analyses for the pyroxenes and pyroxenoid are listed in Table 3.

(a) Subcalcic augite. The dominant mineral in both ferrobasalt and microgabbro is a subcalcic augite exhibiting extreme zoning, the range being from Ca₉₄Mg₄₅Fe₂₁ to Ca₂₉Mg₂₀Fe₅₈. The range of zoning in individual crystals in Fig. 4a is shown by the two groups of open circles connected by lines; each group was measured for a single crystal. The range of zoning measured in the augites from the ferrobasalt did not
Table 3. Lunar pyroxenes, pyroxenoid and fayalite

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3PX-A, B, C: center of small and large microphenocrysts and margin of microphenocryst in ferrobasalt fragment 3 (Table 5).
4PX: center of microphenocryst in ferrobasalt fragment 4 (Table 5).
7PX-A, B: center and margin of crystal adjacent to rhyolitic glass in ferrobasalt fragment 7 (Table 5).
10022-1-9-12-14: spot analyses of zoned pyroxene in ferrobasalt 10022: 1 and 9 interior, 14 margin, 12 pigeonite inclusion.
10044-2-3-4: zoned pyroxene in microgabbro 10044: 2 margin, 3 intermediate, 4 center.
10044-7-9: pyroxferroite (7) surrounded by pyroxene (9) in residuum of microgabbro 10044.
10044-5-6₁-6₁₁: bulk and individual analyses of symplectite phases in residuum: 6₁ and 6₁₁ are approximately CaFeSi₂O₆ and Fe₂SiO₄ respectively.
10044-16B: Small fayalite crystal in residuum.
Microprobe standards: analyzed hedenbergite, basalt glass, chromite, ilmenite, apatite, diopside, synthetic ferrosilite.
extend quite so far in iron enrichment. The types of zoning range from sharply defined hour-glass zoning in the ferrobasalts, to poorly defined hour-glass zoning in the microgabros, with much irrational planar sector zoning. The pyroxene in the microgabbro zones discontinuously into almost Mg-free metasilicate, which may be iron-rich pyroxferroite. The augite in the ferrobasalt is further distinguished from that in the microgabbro by small patches of pigeonite within it.

(b) *Pigeonite.* Pigeonite was found only as small patches within the subcalcic augite of the ferrobasalt. Exsolution lamellae of pigeonite were sought but not found in the subcalcic augites.

(c) *Pyroxferroite.* The unidentified yellow mineral of the microgabbro (LSPET, 1969) is pyroxferroite. With stereomicroscopy, yellow pyroxferroite clearly abuts cinnamon pyroxene, but in thin section identification is more difficult. The composition of the mineral is shown in Fig. 4a and listed in Table 3. More detailed data are given elsewhere in this volume in a summary paper combining the results of many investigators (Chao et al., 1970b).

(d) *Comparison with terrestrial pyroxene trends.* The iron-enrichment of the crystalline rocks and the depletion in calcium, shown by the general crystallization trend of the pyroxenes, contrasts with the alkali (Shiant Isles) and subalkalic (Skaergaard) trends developed in standard terrestrial basic magmas by fractional crystallization.

Subcalcic augites in lunar ferrobasalt contain variable but generally greater amounts of Al$_2$O$_3$, TiO$_2$ and Cr$_2$O$_3$ than in microgabbro. MnO is lower in ferrobasalt than microgabbro augite (Table 3). Individual microphenocrysts of augite in ferrobasalt fragments have borders rich in TiO$_2$, Al$_2$O$_3$ and MnO and poor in Cr$_2$O$_3$ compared to the interiors.

Except for augites from some alkaline basalts, most terrestrial augites from volcanic rocks contain less TiO$_2$ and Al$_2$O$_3$ than those in lunar ferrobasalts (Deer et al., 1965). Probably both bulk compositional and kinetic factors contribute to this difference.

(vii) *Plagioclase*

In ferrobasalt 10022 and fragments of ferrobasalt in breccia 10061, rod-shaped plagioclase grains contain cores of pyroxene and devitrified glass with ilmenite micro- lites. Such plagioclase is weakly zoned from 77 to 71 mol% An (Table 4). Adjacent to rhyolitic residual glass the plagioclase composition is An$_{92}$. The absence of plagioclase in fragments of ferrobasalt containing more than 40% glass and its concentration in patches rich in residual glass in rock 10022 demonstrate it to be a late crystallizing phase. This late appearance is remarkable since plagioclase invariably commences to crystallize prior to ilmenite in terrestrial basalts and gabros.

In microgabbro, plagioclase is coarsely crystalline with or without pyroxene cores and is weakly zoned from An$_{92}$ to An$_{88}$ (Table 4). It is slightly more calcic than that in the ferrobasalts (Fig. 4a).

Plagioclase microphenocrysts in plagioclase vitrophyre have compositions similar to plagioclase in ferrobasalt (An$_{81}$, Fig. 4a, Table 4), compared to An$_{90-98}$ for crystalline anorthosite (Chao et al., 1970a; Wood et al., 1970).
Table 4. Plagioclase in lunar rocks

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9PI Microphenocryst in plagioclase vitrophyre 9 (Table 5).
10PI Microphenocryst in plagioclase vitrophyre 10 (Table 5).
7PI Crystal adjacent to rhyolitic residuum in ferrobasalt fragment 7 (Table 5).
10022-4-8 Interior of large crystal and exterior of small crystal next to residual glass in lunar ferrobasalt 10022.
10044-13-9 Interior and exterior of medium sized crystal near residuum in lunar microgabbro 10044.
Microprobe standards: An 80 synthetic glass, diopside glass, analyzed ilmenite, apatite, K-feldspar.

(viii) Cristobalite and tridymite

Cristobalite and tridymite occur in the microgabbros 10044 and 10047. Cristobalite is euhedral to intergranular and owes its cracked appearance to the transition from high to low cristobalite. Both cristobalite and tridymite are associated with the microcrystalline residuum in the microgabbros and crystallize only at the end.

(ix) Residuum material

Ferrobasals 10022, 10057 and 10072 and microgabbros 10044 and 10047 contain up to 10 per cent of glassy to microcrystalline interstitial material which is the solidified residual liquid. The residuum in rock 10022 is devitrified and microvesicular and has an andesitic composition (Table 5). In ferrobasalt 10057 the residuum contains numerous minute high index spheres similar to those attributed to silicate liquid immiscibility by Roedder and Weiblen (1970). The residual in microgabbros 10044 and 10047 are microcrystalline and contain pyroxferroite, hedenbergite(?), fayalite, ulvöspinel, ilmenite, troilite, iron, one or more silica minerals, and minerals optically similar to the zirconium-bearing minerals described by others. A single fragment of ferrobasalt in breccia 10061 contains 10 per cent of devitrified rhyolitic residual glass.

6. Compositions of Glasses

The compositions of the glasses already described reveal directly the effect of crystallization on the chemical differentiation of the magmas represented in the Apollo 11 rocks. Analyses of representative glasses listed in Table 5 are compared in Figs. 4b and 5. Figure 4b also shows the chemical variation trend calculated for successive magmas developed during the fractional crystallization of the Skaergaard intrusion in East Greenland (Wager, 1960), and the range of compositions for the Apollo 11 crystalline rocks.
Table 5. Microprobe analyses of lunar glasses

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1. Dense, angular fragment of devitrified ferrobasalt glass in breccia.
2. Devitrified glass in ferrobasalt fragment in breccia containing by volume 11% ilmenite, 2% pyroxene, 0.2% troilite.
3. Devitrified glass in ferrobasalt fragment in breccia containing by volume: 54% pyroxene, 10% ilmenite, 0.3% troilite.
4. Devitrified glass in ferrobasalt fragment in breccia containing by volume 54% pyroxene, 12% ilmenite, 0.3% troilite.
5. Devitrified glass in ferrobasalt 10022 containing by volume 50% pyroxene, 10% ilmenite, 35% plagioclase, 0.6% troilite.
6. Same as 5 except different patch of devitrified glass.
7. Devitrified glass in ferrobasalt fragment in breccia containing by volume: 67% pyroxene, 6% ilmenite, 14% plagioclase, 1.4% troilite.
8, 9, 10. Devitrified glass in plagioclase vitrophyres in breccia.
11, 12, 13. Brown glass sphere, clear glass sphere and radiating crystallite sphere in breccia.

(i) Glasses in ferrobasalts

The proportion of glass can be estimated in two ways: (1) by analysis of the amounts of phases present, as listed in Table 5; and (2) by calculating the fractional enrichment of K$_2$O in the glass compared to that of the initial liquid, which is taken as 0.43 per cent, the value in analysis 1 of Table 5 for a wholly glassy fragment in the breccia. The second parameter is used in Fig. 5 to show the chemical variation of glasses in the ferrobasalts. Comparison of the two methods shows agreement within 20 per cent absolute of the amount of glass observed and the amount predicted from the potash ratio, even though the initial magmas of the ferrobasalt rocks and the
Fig. 5. Variation of chemical composition of Apollo 11 lunar ferrobasalt with crystallization. Per cent of crystallization (horizontal axis) deduced on the basis of potassium assuming 100% storage in the liquid and an initial $K_2O$ content of 0.43% (analysis 1 of Table 5).

Breccia fragments of ferrobasalt probably differed in composition. Considering the small size and possibly unrepresentative mineralogy of several of the fragments in the breccia the agreement is encouraging, and quite justifies the use of both methods to outline the crystallization history of the ferrobasalt magmas.

Glasses in ferrobasalts (Table 5, Figs. 4b and 5) are low in $Na_2O$ and high in $TiO_2$ but otherwise similar to: (a) segregation veins (Tilley et al., 1963; Kuno, 1965) and residual glasses (Evans and Moore, 1968) in terrestrial basalts; (b) the calculated successive liquid fractions of the Skaergaard intrusion, East Greenland (Wager, 1960); and (c) the TiO$_2$-rich rocks associated with anorthosite massifs (Buddington, 1939).

Segregation veins form in basaltic lava flows from residual liquid rich in FeO and TiO$_2$, which migrates into cracks opened by thermal contraction, plastic creep and escaping gases. There it crystallizes to a comparatively coarse-grained, vuggy to vesicular rock, similar to ferrobasalt and microgabbro. The successive liquids of the Skaergaard intrusion formed as the early crystals sank to the floor of the magma chamber and became isolated from the liquid, which gradually was enriched first in iron and titanium and later in sodium. Differentiation of the Skaergaard intrusion produced rocks and liquids exceptionally high in total iron and in the Fe/(Mg + Fe) ratio, features interpreted as arising from exceptionally dry, reducing conditions (Osborn, 1959). High alumina basaltic lavas with bulk compositions close to that of the Skaergaard intrusion follow a similar pattern of chemical variation with crystallization (Kuno, 1965). The high Fe/(Fe + Mg) ratios of the lunar ferrobasalts and microgabbros shown in Fig. 4b correspond to an advanced stage of fractionation of the Skaergaard magma, attained only after crystallization of 75–90 per cent of the
original basaltic magma. The TiO$_2$-rich ferрогabbros associated on earth with anorthosite massifs are structurally young compared to the anorthites, but there is insufficient evidence to establish that these ferрогabbros are derived as liquid fractions of a parent magma from which the anorthosite was also derived.

The three groups of terrestrial rocks which show chemical similarities with the glasses in the lunar ferробasalts, namely the Fe–Ti-rich segregation veins, the Fe-rich Skaergaard liquids and the Ti-rich ferрогabbros associated with anorthosites, all form during the late stages of consolidation of liquids initially rich in Al$_2$O$_3$.

Analyses 1–7 in Table 5 give the compositions of glasses (or devitrified glasses) in ferробasalt, arranged in the sequence of increasing K$_2$O content, which corresponds to the sequence along the abscissae in Fig. 5. Rock 1 in Table 5 consists of 100 % glass and it plots with the crystalline rocks in Fig. 4a, as does the glass in the olivine vitrophyre (about 70 % glass). Analyses 2, 3 and 4 are from rocks containing about 79 %, 30 % and 28 % of glass by weight, respectively, and these cluster towards the top of the diagram. Compared to analysis 1, they show enrichment in iron and alkalis relative to Mg. Analysis 7, of rhyolitic glass in a fragment in breccia containing 9 % glass, illustrates marked enrichment in K$_2$O. Analyses 5 and 6 of the 4 % residual glass in ferробasalt 10022 plot in about the same position. Fig. 4b thus shows, for material with ferробasalt bulk composition, the variation in composition as the proportion of glass is reduced from 100 per cent to 4 per cent. The line through these points shows a chemical variation effectively similar to that of the successive liquids of the Skaergaard intrusion, with respect to the ratios of Fe, Mg and Na + K. The initial trends of marked increase in Fe/(Fe + Mg) and lesser increase in (Na + K)/Mg are replaced during the late stages of crystallization by marked enrichment in (Na + K)/(Fe + Mg). The late-stage trend develops only after crystallization of more than 95 per cent of the original magma for the Skaergaard intrusion, and apparently only after crystallization of about 80 % of the ferробasalt magma.

Figure 5 shows the absolute variation in composition of the glasses representing successive liquids during the crystallization of the ferробasalt magma, as they follow the general trend depicted in Fig. 4b. The FeO and TiO$_2$ contents of the successive liquids decrease as crystallization proceeds. In successive liquids in the Skaergaard intrusion, there was absolute enrichment of iron until 98 per cent of the liquid had crystallized, and then the iron content decreased with the Fe/(Fe + Mg) ratio remaining almost constant. The TiO$_2$ content increased to about 3 per cent by the time about 80 per cent of the original magma had crystallized, and then the TiO$_2$ content of the residual liquids decreased with continued crystallization. Figure 5 also shows a marked enrichment of Al$_2$O$_3$ in the successive liquids developed during crystallization of the ferробasalt magma, in contrast with the steady decrease in Al$_2$O$_3$ content of the Skaergaard liquids. The contrasting behaviors of FeO, TiO$_2$ and Al$_2$O$_3$ with crystallization shown by lunar ferробasalt and terrestrial basalt magmas suggest ilmenite enrichment and plagioclase depletion of lunar ferробasalt magma [see section 8(i)(d)].

Despite the detailed differences in behavior of TiO$_2$, FeO and Al$_2$O$_3$ the general differentiation trends exhibited by the ferробasalt and the Skaergaard magma show striking similarities (Fig. 4b). It is therefore reasonable to conclude that the differentiation trend developed in the ferробasalt magma resulted from effective separation
of crystals from the liquid through armoring by successive shells or zones of changing composition.

(ii) Glasses in plagioclase vitrophyres

Glasses in plagioclase vitrophyres (in bulk 80 per cent normative plagioclase) vary in composition in accordance with crystallization of plagioclase (Table 5, analyses 8–10; Fig. 4b) and trend towards the ferrobasalt composition on the FAM diagram, but distinct differences in composition remain (MgO too high, TiO$_2$ too low). Notably FeO, TiO$_2$, K$_2$O and P$_2$O$_5$ maintain nearly constant proportions in the

![Fig. 6. Lower diagram: hybrid summary of crystallization sequence in Apollo 11 ferrobasalts and microgabbros. Key: Sp titanian chromite spinel; Ol olivine; Fpb armalcolite; Il ilmenite; S sulfide melt (troilite plus iron); Pl plagioclase feldspar; Pf pyroxferroite; Ap apatite; Cr and Tr cristobalite and tridymite. Upper diagram results from phase equilibrium study showing temperature as a function of percentage of crystallization. The appearances of minerals and cessation of olivine crystallization are marked.]

glass and increase by a factor of 4 as crystallization increases, and the amount of glass decreases from 90 per cent to 30 per cent. This geochemical coherence is strong evidence of a common origin from a rather large and uniform source. The chance impact melting of small plagioclase-rich volumes within ferrobasalt would be an improbable explanation.

(iii) Glass spheres

The compositions of three glass spheres found in a breccia, one colorless, another brown and the third devitrified into radial fibers, have extremely low amounts of Na$_2$O and K$_2$O compared to ferrobasalt glass (Table 5, analyses 11–13, Fig. 4b).

7. EXPERIMENTAL PHASE EQUILIBRIA OF SYNTHETIC FERROBASALT

A full account of an experimental study of synthetic ferrobasalt, earlier briefly described by Anderson et al. (1970b), will be published elsewhere. Figure 6 shows the temperature at which the minerals appear based upon 15 temperatures investigated...
between 1185 and 1075°C. Note that ilmenite precedes pyroxene, and plagioclase crystallizes only after one third the liquid has gone.

8. PETROGENESIS

Working out the petrogenesis of the lunar rocks is not so speculative as it might at first seem in view of the small sample available. Interpretation of the data obtained from the rocks comprising the sample is based not merely upon these rocks, but it builds upon the vast reservoir of data and interpretations gathered during a century of petrogenetic study of meteorites and terrestrial rocks. The rock samples returned by the Apollo 11 mission, including the anorthosite fragments within the soil and the plagioclase vitrophyres within the breccia, support the remote analyses by alpha scattering (Patterson et al., 1969) and the two sets of information relate to each other and the geological maps of the moon in a most encouraging fashion. We therefore begin by considering the chemical analyses of lunar rocks, and comparing them with other materials both lunar and terrestrial. The major part of this section, however, is devoted to determining the conditions of crystallization of the ferrobasalt and microgabbro magmas. This leads to conclusions about the origin of the magmas and thence to the petrological history of the moon.

(i) Chemistry of lunar rocks

Here we discuss those chemical features which bear directly upon the geochemical differentiation of the moon. The oxides and ratios discussed are (1) K₂O and K₂O/P₂O₅, (2) Na₂O, (3) TiO₂, (4) Cr₂O₃, (5) V₂O₅, (6) Al₂O₃ and (7) europium and rare earths.

(a) K₂O and K₂O/P₂O₅. The ratios of K₂O to P₂O₅ in glasses of 2 out of 3 plagioclase vitrophyres and glass in ferrobasalt are equal to 3 within analytical error (Table 5). Since the K₂O/P₂O₅ ratio of plagioclase in ferrobasalt is at least 10 (Table 4), plagioclase vitrophyre and ferrobasalt probably are frozen aliquots of genetically related, differentiated liquids rather than fusion products of mineral fragments chanced-selected by impact. However, the detailed relations of the Apollo 11 crystalline rocks may be complex as indicated by the results of Compston et al. (1970), who distinguished two groups with high and low concentrations of K, Rb and P. In these groups, K₂O/P₂O₅ = 1.5 and 0.7, respectively. Although other data substantiates this twofold grouping, only one ferrobasalt has a low K₂O content; this is number 10020, which is also olivine rich. According to our data for rocks 10057, 10022, 10072, 10044 and glassy fragments in the breccia, the finer-grained and richer in glass the rock, then the higher the K₂O content and the K₂O/P₂O₅ ratio. In terrestrial basalts, fractional crystallization leaves unchanged the K₂O/P₂O₅ ratio until apatite begins to crystallize. In the Apollo 11 rocks apatite does not crystallize until the residuum forms, but the K₂O/P₂O₅ ratio drops from one rock to another. This might suggest preferential loss of potassium relative to phosphorus during cooling, but there is not enough stratigraphic control of the samples. The low K₂O may result from a superficial redistribution rather than a lesser extent of fractional crystallization or a greater extent of partial melting.

(b) Na₂O. The content of Na₂O in all the crystalline rocks is 0.3-0.9 wt.%. In the plagioclase vitrophyre the Na₂O content is 0.9 wt.%, and in the anorthosite
fragments of the fines it is 0·4 per cent (Wood et al., 1970). The low Na$_2$O content might be an overall feature of the moon resulting either from an initial bulk composition low in sodium or from volatile loss from the Moon's surface as suggested by Keays et al. (1970).

Alternatively, the low Na$_2$O content might result from plagioclase crystallization from a more Na$_2$O-rich magma. This would require that plagioclase was the dominant crystallizing phase for an appreciable crystallization interval. Occurrence of anorthosite zones in layered igneous intrusions on earth (Hess, 1960) testifies to such a process. On the moon, the low Na$_2$O of the plagioclase of the Sea of Tranquillity region makes it difficult to reduce Na$_2$O by plagioclase crystallization of the source magma. Deeper in the moon, a liquid with a high Al$_2$O$_3$/Na$_2$O ratio might have been produced. In the low-pressure lunar situation, Al$_2$O$_3$ would concentrate in the liquid thereby favoring formation of plagioclase, rather than being incorporated in high pressure phases, as on earth.

(c) TiO$_2$. The most striking feature of the Surveyor V analysis from the Sea of Tranquillity, the extraordinarily high TiO$_2$ content, is now supported by analyses of the crystalline rocks from the Apollo 11 collection. In contrast, the TiO$_2$ content of the Apollo 12 collection is much lower, so that this is not a characteristic feature of all rocks in all maria. The Surveyor VII analysis of the highlands material is low in FeO and TiO$_2$. According to Tuthill and Satto (oral presentation at Houston Conference), experiments at 1 atm show that it is impossible to derive a liquid containing 10 per cent TiO$_2$ by fractional crystallization of basalt even at low values of $f_{O_2}$. However, the bulk composition and extent of fractionation may be critical. Possible explanations for the high TiO$_2$ content of the rocks include: (1) partial melting of clinopyroxene at moderate pressure (O'Hara et al., 1970; Ringwood and Essene 1970); (2) fractional crystallization at moderate pressure, such as might be produced by crystal–liquid reactions at the base of a deep convecting lava lake; and (3) mechanical accumulation of ilmenite or asmalcolite into a more normal basaltic magma.

(d) Cr$_2$O$_3$. We have measured distribution factors for pyroxene and ilmenite with respect to the liquid, and Haggerty et al. (1970) reported data for olivine from which a factor may be estimated. The values are:

\[
\frac{(\text{Cr}_2\text{O}_3) \text{ augite}}{(\text{Cr}_2\text{O}_3) \text{ liquid}} = 13, \quad \frac{(\text{Cr}_2\text{O}_3) \text{ ilmenite}}{(\text{Cr}_2\text{O}_3) \text{ liquid}} = 30 \text{ to } 60, \quad \frac{(\text{Cr}_2\text{O}_3) \text{ olivine}}{(\text{Cr}_2\text{O}_3) \text{ liquid}} = 0.5.
\]

Crystallization of olivine thus enriches the liquid in Cr$_2$O$_3$, whereas crystallization of augite and ilmenite depletes the liquid very rapidly in Cr$_2$O$_3$. The crystalline rocks from the Apollo 11 collection contain about 0·3% Cr$_2$O$_3$, and those from the Apollo 12 collection contain slightly more, about 0·5 per cent. These relationships are consistent with the following processes for the formation of the rocks: (1) the magmas were derived by fractional crystallization of a magma with modified chondritic composition with the Apollo 11 rocks being more fractionated than the Apollo 12 rocks, or (2) the magmas were derived by partial melting of Cr$_2$O$_3$-rich clinopyroxenite with the Apollo 11 and Apollo 12 magmas being successively greater fractions of the parent rock.
(e) \(V_2O_3\). In the lunar rocks, \(V\) is low compared with Cr. In terms of cosmic abundances (Goles, 1969), \(V/\text{Cr}\) is about 1/30, whereas in the Apollo 11 collection, \(V/\text{Cr}\) is about 1/100. The Apollo 12 rocks contain somewhat more \(V\). The low \(V\) in the Apollo 11 rocks may result because \(V\) is more easily reduced than Cr, and because \(V^{2+}\) is chalcophile; the Apollo 11 rocks are relatively sulfur-rich, and \(V^{2+}\) could be depleted by the separation of a sulfide phase. The higher \(V\) in the Apollo 12 rocks is consistent with either: (1) fractional crystallization of \(V\)-rich sulfide, with the Apollo 11 rocks being more fractionated, or (2) partial melting of pyroxenite, with the Apollo 11 rocks representing a smaller melt fraction.

(f) \(Al_2O_3\). The \(Al_2O_3\) content of the Apollo 11 specimens is successively higher from rocks, to breccia, to soil. This could reflect addition of other parts of the lunar surface to the soil, and associated breccia, which implies that other parts of the lunar surface, specifically the highlands, are more \(Al_2O_3\)-rich than the rocks of the seas.

(g) Europium and rare earth elements. Eu is strongly depleted relative to Sm in lunar crystalline rocks. Given even the most favorable (maximum) difference in the crystal/liquid distribution coefficients observed for terrestrial basalts, and starting with a chondritic ratio of Eu/Sm, more than 90 per cent crystallization of the system as plagioclase is needed to produce the observed Eu depletion (Haskin et al., 1970). Significantly, Philpotts and Schnetzler (1970) show that Eu is more heavily concentrated in lunar plagioclase (relative to pyroxene), suggesting that the difference between the plagioclase/liquid distribution factors for Eu and Sm may be larger for lunar ferrobasalt than for terrestrial basalt. This feature is consistent with a greater reduction of Eu to the divalent state in the more reduced lunar magmas.

(ii) Chemistry of the lunar highlands: plagioclase vitrophyres and anorthositic

The Surveyor VII chemical analysis (Patterson et al., 1969) fits well with typical analyses of terrestrial anorthosite rocks. This implication that the lunar highlands are composed of anorthosite is strengthened by the discovery of plagioclase vitrophyres in the breccia, and by others of anorthosite fragments in the fines. The calculated bulk compositions of the vitrophyres are very similar to those of gabbroic anorthosites, and these in turn are similar to the Surveyor VII analysis. We interpret these vitrophyres as the products of melting of plagioclase-rich rock by distant impacts on the lunar highlands.

(iii) Chemistry and origin of olivine vitrophyre

The composition of glass in the olivine vitrophyre (analysis 14, Table 5) is similar to the composition of lunar ferrobasalts and dissimilar to chondritic compositions. This is particularly true for the \(P_2O_5/TiO_2\) and \(K_2O/TiO_2\) ratios and the high contents of CaO and \(Al_2O_3\). Possibly this olivine vitrophyre is a fragment of the early crust of the moon formed prior to a plagioclase-rich crust.

(iv) Crystallization of ferrobasalt and microgabbro magmas

Here we discuss the evidence related to the crystallization of the Apollo 11 rocks. We then use this evidence to develop a petrogenetic scheme for the Apollo 11 rocks.
and possible lunar highland anorthosite, and finally we consider a source for the differentiated rocks.

(a) *Estimates of temperature of crystallization and cooling rate.* The phase equilibrium study referred to in Section 7 shows that the ferrobasalt composition has a relatively low liquidus temperature of 1160°C, and that most of the liquid crystallizes within a narrow temperature interval of about 75°C. Other workers have suggested similar crystallization temperatures. This compares with crystallization intervals, for most terrestrial basalts, from a liquidus of 1240–1160°C down to about 1050°C (135°–195°C range) (Yoder and Tilley, 1962, p. 382). Yoder and Tilley noted that all major silicate phases appear within a narrow temperature interval, less than 80°C. The low liquid temperature and narrow crystallization interval suggest strongly that the Tranquillity Base crystalline rocks are the products of advanced fractional crystallization of basic magma under reducing conditions.

Rhyolitic residual glass in young terrestrial basalts generally is fresh and not devitrified even from slowly cooled, partially oxidized and hydrated lava (Evans and Moore, 1968). Rhyolitic glass is known to hydrate and devitrify so sluggishly at temperatures below 100°C that negligible devitrification would occur during the history of the earth (Friedman et al., 1963; Marshall, 1961). The devitrification of the rhyolitic glass in the ferrobasalt fragment in breccia 10061, therefore, presents a puzzle: if the rock is rapidly crystallized, how did the temperature remain high enough long enough for the rhyolitic glass to devitrify? Was there prolonged annealing caused by high surface temperatures on the Moon?

Fernandez-Moran et al. (1970) found that the Mg, Fe site distribution in augites corresponds to an equilibrium temperature below 675°C, indicating very slow cooling in the range 600°C to approximately 480°C.

(b) *Gas and water content, and redox conditions.* The vesicularity of ferrobasalts indicates that gases were present during the crystallization of the liquid. Burlingame et al. (1970) concluded that there may be some CO in the gas bubbles. Despite the presence of vesicles none of the rocks shows obvious evidence of alteration. All investigators have noted the extreme dryness of the rocks.

The oxygen fugacity at 1050°C for most terrestrial basalts is about 10⁻¹⁰ bars (Sato and Wright, 1966; Anderson, 1968). In the lunar rocks, the presence of native iron indicates that these rocks crystallized under conditions of considerably lower oxygen fugacity than do terrestrial basalts.

The first of several calculations uses the fact that ilmenite plates containing thin rutile lamellae coexist either with native iron or with sulfide liquid nearly saturated in iron. The iron is isolated within troilite–iron droplets, hence the system is not fixed necessarily on an ilmenite–rutile–iron buffer. At a temperature of 1050°C, the oxygen fugacity of this buffer is found to be 10⁻¹⁵·⁷ bars, using the thermochemical data for the phases given in Robie and Waldbaum (1968). If the iron precipitated from the sulfide melt only at a somewhat lower temperature, its activity will be less than unity at 1050°C, although it should be a substantial fraction of unity. Thus the real \( F_O \) could conceivably be as much as an order of magnitude higher than the calculated value.

Secondly, blebs of metallic iron may be in equilibrium with clinopyroxene having a large mole fraction of FeSiO₃ and with olivine having a large mole fraction of Fe₂SiO₄.
The calculated buffer curve for the reaction:

$$\text{Fe}_2\text{SiO}_4 = \text{Fe} + \text{FeSiO}_3 + \frac{1}{2}\text{O}_2$$

passes through $10^{-14.4}$ bars at $1050^\circ\text{C}$ if the high-pressure experimental data for the stabilization of ferrosilite relative to fayalite + quartz of Akimoto et al. (1965) are used. The value of $10^{-14.4}$ bars, while in general agreement with the ilmenite–rutile–iron value, is less certain because of the uncertainty in $\text{Fe}_2\text{SiO}_4$ and $\text{FeSiO}_3$ activities.

Thirdly, the fayalite and cristobalite of the microgabbro residuum may be nearly in equilibrium with the iron precipitated from the sulfide-rich melt. The thermochemical data for the fayalite–cristobalite–iron buffer yield an $F_\text{O}_2$ of $10^{-15.4}$ at $1050^\circ\text{C}$.

Finally, depending on the oxygen content of the troilite–iron blebs, the oxygen fugacity at $1050^\circ\text{C}$ would range between $10^{-15.5}$ and $10^{-10}$ bars (NALDRETT, 1969, Fig. 13).

(c) **Immiscibility of sulfide liquid.** Blebs of troilite–iron are present in all the crystalline rocks and all the glassy ferrobasalt fragments in breccia 10061 except for the pure glass fragments. This confirms that an immiscible sulfide liquid commenced to form either at the magma liquidus or before the stage where the silicate magma was 30 per cent solidified. Blebs of troilite enclosing iron are present in the glassy portions of incompletely crystallized ferrobasalts at all stages of crystallization, including the late stage represented by the rhyolitic residuum. This indicates that the sulfide liquid continued to separate throughout the crystallization history of the ferrobasalt. However, troilite in the residuum of microgabbros 10044 and 10047 lacks the iron inclusions and probably crystallized directly from the silicate liquid without ever existing as an immiscible liquid.

(d) **Crystallization differentiation.** Petrographic study of the rocks indicates that the general crystallization sequence is as summarized in Fig. 6. The horizontal axis in Fig. 6 is an estimate of weight per cent of liquid crystallized, based largely upon the proportions of glass and crystals in ferrobasalt fragments in the breccia. The vertical axis gives the percentage of minerals crystallizing. The initial stage of crystallization is for the ferrobasalt, and the final stage is for the microgabbro. The intermediate stage is applicable to both rock types.

(a) 0–10 per cent crystallized: Olivine (Fo$_{66}$–Fo$_{78}$), magnesian armalcolite, and titanian chromite form in some rocks but cease to crystallize either due to changing liquid composition or temperature. Ilmenite (Gt$_{11.8}$) and an immiscible iron–sulfur (oxygen, carbon, phosphorus) liquid (bulk composition near Fe$_{1.1}$S) are the principal phases separating from the silicate melt. Possibly some augite commences to form during this interval.

(b) 10–50 per cent crystallized: Augite (Wo$_{29}$En$_{47}$ to Wo$_{31}$En$_{47}$) and ilmenite Gt$_{4.5}$ crystallize together. An immiscible sulfide liquid continues to separate. For some slow rates of crystallization and/or bulk composition (especially microgabbros) plagioclase may commence to crystallize during this interval. Also some magmas may continue to precipitate olivine. Minor amounts of pigeonite or an orthorhombic pyroxene may form in some systems.
Hypothetical Moon Just After
Creation of the Sea of Tranquility

- Thin crust (5-20 km) underlain by liquid
- Impacts create large lava lakes (seas)
- Pyroxene + Olivine Rock $\rho = 3.3-3.4 \text{ gm/cm}^3$
- Plagioclase-rich rock and basalts $\rho = 2.8-3.1 \text{ gm/cm}^3$
- Olivine-rich
- $\rho \approx 3.3 \text{ gm/cm}^3$
- (drawn to nearside by Earth’s gravity due to high density compared to overlying crust)
- Farside Thick crust, little or no underlying liquid
- Impacts create deep craters with little or no lava
- Thin layer of sulfide and ilmenite-rich rock $\rho \approx 5$

Fig. 7. Model of the moon just after creation of the Sea of Tranquility. Moon 95-99 per cent solid.

(3) 50–80 per cent crystallized: plagioclase ($\text{An}_{94}$ to $\text{An}_{75}$), augite ($\text{Wo}_{31}\text{En}_{47}$ to $\text{Wo}_{27}\text{En}_{33}$), ilmenite ($\text{Gt}_{5}$ to $\text{Gt}_{9}$), and sulfide melt separate from the silicate liquid in the approximate proportions 50:45:4:1.

(4) 80–100 per cent crystallized: plagioclase ($\text{An}_{75}$ to $\text{An}_{56}$), subcalcic ferroaugite ($\text{Wo}_{27}\text{En}_{33}$ to $\text{Wo}_{5}\text{En}_{13}$), pyroxferroite ($\text{Fs}_{75}\text{Wo}_{25}$), ilmenite ($\text{Gt}_{3}$ to $\text{Gt}_{0.1}$), and cristobalite and tridymite are the principal minerals. Minor amounts of potassium feldspar, apatite, ulvöspinel, hedenbergite(?), fayalite, baddeleyite, and two rare earth and zirconium bearing minerals crystallized in most microgabbros and a few ferrobasalts. Silicate liquid immiscibility produced iron oxide rich and silica rich liquids. Troilite crystallized directly from melt in microgabbro whereas an immiscible Fe–S melt continued to separate in ferrobasalts.

The status of olivine in the crystallization sequence is uncertain. Although the comparatively large size of olivine in one ferrobasalt fragment, presence of glass in two other olivine-bearing fragments in breccia 10061, indicates that some olivine is early, the data of CHAO et al. (1970a) on rock 10072 suggests that some olivine crystallizes at an intermediate stage. Olivine in anorthosite rock fragments is moderately magnesian ($\text{Fo}_{72}$: CHAO et al., 1970a; $\text{Fo}_{51}$; WOOD et al., 1970). Late crystallizing fayalite occurs in the residuum of microgabbros 10044 and 10047. Although most fayalite is symplectitic intergrown with another phase of composition near CaFeSi$_2$O$_6$, and may result from decomposition of a pyroxene or pyroxenoid precursor as suggested by WARE and LOVERING (1970), small subhedral of fayalite and rims of fayalite on troilite in the residuum are not part of the symplectite. A microprobe analysis of such fayalite is given on Table 3. In sum there is good evidence of early, middle and late olivine, but not all in the same rock.

Modal and chemical analysis of ferrobasalt fragments in breccia reveal that about 80 per cent of all the ilmenite in the rock crystallizes during the first 30 per cent of solidification, indicating that the early stages of crystallization of ferrobasalt are
heavily dominated by ilmenite. This contrasts sharply with terrestrial ferrobasalt liquids which crystallize ilmenite, pyroxene and plagioclase approximately in the proportions of 15:55:30 (Peck et al., 1966; Anderson and Greenland, 1969), such that the TiO$_2$ content of the liquid diminishes from 4-3 wt.% to 3-4 wt.% with a 45 per cent reduction in the amount of remaining liquid.

The subcalcic clinopyroxenes in the microgabbro have remarkable zoning, that is related to the fractionation of the magma. Hour-glass zoning indicates crystallographic control of zoning superimposed on the magma effect.

The plagioclase feldspar did not begin to crystallize until half of the magma had crystallized. Plagioclase in the microgabbro is more calcic than in the ferrobasalt: this probably results from the slower crystallization of the microgabbro such that less Al$_2$O$_3$ entered pyroxene than in the ferrobasalt. In addition the ferrobasalt 10022 has lower Al$_2$O$_3$ than the microgabbro 10044. The late role of plagioclase in ferrobasalts and microgabbros contrasts with the plagioclase-rich vitrophyres of the breccia fragments and with the anorthosite fragments found in the coarser fractions of the soil. The iron-enriched ferrobasaltic liquid and the plagioclase-rich fragments thus appear complementary, inviting speculation on the relation of the Apollo 11 rocks to the lunar highlands.

The possible products of crystallization differentiation of the ferrobasalt and, by inference, the microgabbro as well, are illustrated on the Fe–Mg–Na + K diagram in Fig. 4b, with the compositions of successive liquids given in Fig. 5.

The relative densities of the ferrobasalt liquid (3-2 g/cm$^3$), ilmenite (4-7), augite (3-3–3-6) and plagioclase (2-7–2-8) allow gravity separation leading to downward cumulates of ilmenite and pyroxene and upward cumulates of plagioclase. (These room temperature densities should preserve their relative values at high temperature). The iron sulfide liquid globules should sink unless buoyed up by turbulence.

(v) Petrogenesis of the lunar rocks

The ferrobasalts and microgabbros have compositions and temperatures of crystallization characteristic of strongly fractionated basaltic magma. We now consider the source of the ferrobasalt and microgabbro magmas.

The chemistry of the igneous ferrobasalt and microgabbro and related rocks suggested origins in terms of either partial fusion at depth, or of fractional crystallization. Such strongly fractionated rocks are unlikely to be derived by partial fusion of crystalline material, unless we make special assumptions, for example, that most lunar titanium occurs in accessory minerals which dissolve in early fusion fractions. A review of the chemistry with respect to crystallization differentiation leads us to conclude that the rocks represent liquids produced by advanced fractional crystallization of some parent magma.

The fractionation stage of the ferrobasalts and microgabbros depicted in Fig. 4b corresponds to the stage of strong Fe-enrichment and maximum Ti-enrichment of the Skaergaard residual magma. The TiO$_2$ content of the lunar rocks is far greater than that which could be dissolved in basaltic magma under terrestrial crystallization conditions, but the phase equilibrium experiments have demonstrated that this amount of TiO$_2$ is totally soluble at 1160°C in the ferrobasalt liquid under the redox
conditions inferred for the lunar rocks. Continued fractionation of the Skaergaard magma after this stage leads to decrease in TiO$_2$ content of the liquids, just as in the lunar ferrobasalts (Fig. 5). Crystallization differentiation of the ferrobasalt causes a decrease in the total Fe content of the residual liquids (Fig. 5); this occurs in the Skaergaard residual liquids after about 98 per cent of the original magma has crystallized.

If the ferrobasalt and microgabbros represented liquids tapped from a larger body of differentiating magma, all of the major phases crystallizing from the parent magma should precipitate simultaneously at the liquidus of the derivative.

Ilmenite precipitates abundantly within a narrow temperature interval before pyroxene joins it, and plagioclase feldspar does not begin to crystallize until about half of the liquid has crystallized to ilmenite and pyroxene. The early crystallization of ilmenite in the ferrobasalt composition could be explained if cumulus ilmenite had been added to the original liquid differentiate. If so, the very high TiO$_2$ content of the ferrobasalt and microgabbro could be explained in part by the process of fractionation of the parent magma, by analogy with the Skaergaard intrusion, and in part by the addition of ilmenite.

The delayed crystallization of plagioclase compared to pyroxene, revealed both by petrography and experiment, can be explained by selective removal of plagioclase from the parent magma, together with addition of pyroxene. Addition of pyroxene is required because removal of all the crystallized plagioclase would still leave a liquid saturated with plagioclase. The composition of the ferrobasalt and microgabbro is thus matched by a magma consisting of a strongly fractionated basaltic liquid, precipitating plagioclase feldspar which is rapidly removed by flotation, and containing suspended crystals of ilmenite and pyroxene.

What was the nature of the parent magma from which evolved the ferrobasalt and microgabbro magmas? What other products of differentiation might be expected from the parent magma? Our attention is drawn to the plagioclase vitrophyres in the breccia and the anorthosite fragments in the soil. The geochemical coherence of FeO, TiO$_2$, K$_2$O and P$_2$O$_5$ in the plagioclase glass vitrophyre fragments is strong evidence for their common origin from a rather large and uniform source, such as a large, differentiating magma. The K$_2$O/P$_2$O$_5$ ratios of these rocks and of glass in the ferrobasalts provide a strong case that these are all frozen aliquots of genetically related, differentiated liquids. The ferrobasalts are depleted in europium; concentration of europium in plagioclase crystallizing from the parent magma and separation by flotation of the plagioclase to produce anorthosite, would leave the residual liquids, such as the ferrobasalt magma, depleted in europium.

Our petrogenetic model is a large, differentiating body of parent magma. Plagioclase crystals float upwards to yield anorthosite cumulates, while olivine, pyroxene, ilmenite and an immiscible sulfide liquid sink downwards. This leaves a residual liquid fraction similar in composition to the ferrobasalt and microgabbro, but somewhat deficient in the components of ilmenite and pyroxene. The ferrobasalt and microgabbro compositions are represented by this residual liquid fraction together with crystals of ilmenite and pyroxene added by local processes. Comparison of these compositions with fractionation stages in the Skaergaard intrusion suggests that somewhere at depth below the exposed ferrobasalt and microgabbro there
should be cumulates amounting to at least four times the quantity of ferrobasalt and microgabbro developed. This draws attention to the significance for lunar history of large quantities of hidden rocks.

(vi) Origin of breccia and soil

The origins of the breccia and soil are strongly interrelated since the former consists largely of the components of the latter, while pieces of the former occur in the latter. The presence of features characteristic of shock metamorphism is consistent with the morphological data for high-speed impact of extra-lunar material.

Surely the most spectacular features result from high-velocity particles. The very small ones produce the lipped, circular craters found by electron microscopic study (see Anderson et al., 1970a). Larger craters are visible to the naked eye on the surface of rock fragments (LSPET, 1969). At the other extreme, large-bodies should produce upon impact a sequence of products ranging from fractured rocks through liquid to vapor. The extent of the changes should depend critically on the temperature of the impacted rock. Formation of a hot cloud composed of gas, liquid and solid can explain the formation of the great variety of products ranging from glass beads to crystalline fragments with partly melted surfaces. Some of the liquid strikes colder rock forming splatters, while some congeals in flight forming beads. Collisions in flight, together with accumulation while hot on the lunar surface lead to sintering.

The LSPET (1969) report stated that some of the breccias are as hard as any of the crystalline rocks. Much of the induration apparently results from thermal sintering: indeed if the process took place in a near-vacuum, welding should take place at quite low temperatures.

Our model of an impact-produced glowing cloud could apply to impacting bodies of a few cms to meters in size. Material from the regolith could be reworked without incorporation of the solid rock. Reworked clasts of breccia in breccia testify to repetition of processes.

Since the more moderate forces associated with volcanic processes produce effects which would be masked by the less extreme effects produced by impact, it was impossible to determine the volcanic contribution. Perhaps the low volatile content and low viscosity of the magma in the Sea of Tranquillity region precluded significant volcanic contribution to the shattering processes.

Although the presence of light-colored rays from the crater Tycho spreading over the Sea of Tranquillity indicates that highland material was ejected into the regolith, the source of plagioclase-rich material in the regolith must be tentative since a local origin is also possible.

Identification of iron meteorite fragments in the soil and breccia confirms the impact origin of some of the soil and breccia.

9. Implications for Meteorites

This matter will be discussed elsewhere. Although several types of meteorites have either chemical or textural resemblances to an Apollo 11 rock, none fit in all particulars.
PROPOSED PETROLOGIC HISTORY OF MOON

A detailed description of our view of the petrologic history of the moon will be published in another paper. In brief, from the crystallization and chemical properties of the Apollo 11 rocks, the density and moment of inertia of the moon, solar abundances of chemical elements and knowledge of the pressure-temperature stability of silicates, we proposed the model shown in Fig. 7. Fractional crystallization of a modified chondritic composition with gravity settling of metal (?), olivine and pyroxene produced a basaltic liquid. Floating of plagioclase augmented a primitive ultrabasic crust. The Sea of Tranquillity was produced by release of magma produced by meteorite impact: the magma was generated from existing magma plus pyroxene and ilmenite crystals.

Convection transferred radiogenic material to the surface. Latter radiative transfer might be especially efficient because of pressure welding of ultra-dry crystals.

Assuming that the moon was rotation-locked to earth, the final liquid was drawn to the earth side because of asymmetry in the tidal bulges. Radiogenic heat producers were transferred with the liquid prolonging the presence of liquid on the earth side and speeding up the crystallization on the far side. Meteorite impacts released large seas of magma on the earth side, but only blasted craters on the far side.

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