# PETROLOGY

A total of 48 rocks were returned along with fines material in the three sample return containers. Pieces smaller than 10mm are classified as fines.

## SURFACE FEATURES

During preliminary examination one surface feature of the rocks that was most noticeable was the rounding of one or more edges and corners. Many of the rocks had one flat surface, with the remaining sides rounded. This rounding appeared to be more pronounced in the softer, more friable breccias than in the crystalline rocks (LSPET, 1969).

Two other types of surface features occur on the Apollo 11 rocks. These are glass-lined pits and glassy spatters not necessarily associated with pits.

Most glass-lined pits are less than one millimeter in diameter, but they have been found as large as 4mm (10063,1). Impacts that would produce the larger pits usually break the rocks apart and the pits are not preserved. The rocks generally show pitting in the rounded surfaces but not on the flat sides. The glass lining the pits is bright-reflecting and commonly uneven and botryoidal.

The pits are generally surrounded by whitish haloes which are at least partially attributable to intense micro-fracturing of minerals. This whitening does not appear to penetrate more than mm below the surface of the rock (LPSET, 1969) and tends to give the surfaces of the crystalline rocks a lighter color than the interiors.

In addition to glassy pits, thin glass crusts occur that appear to be the result of spattering. These crusts are generally less than 1mm thick. Taken together, these features make up what is know as patina.

## BASALTS

All of the basalts returned are volcanic in origin and probably represent surface or near surface lavas. The term “volcanic” carries no connotation regarding impact generated or triggered volcanism versus volcanism in the common terrestrial sense.

The rocks contain pryogenic mineral assemblages and gas cavities suggestion that they crystallized from melts. The major minerals can be assigned to known rock-forming mineral groups. The unique chemistry of the magmas has resulted in mineral ratios different from known terrestrial volcanic liquids, yet not significantly different (at least in the major elements) from some terrestrial cumulates (LSPET, 1969).

The Preliminary Examination Team (LSPET, 1969) divided the crystalline rocks into fine-grained (Type A) and coarse-grained (Type B). Grain sizes of Type A rocks (fine-grained) range from 0.05 to 0.2mm. A typical mode (10017) is pyroxene, 44%; plagioclase, 24%; opaques (mainly ilmenite), 24%; mesostasis, 8%. Grain sizes of Type B rocks (coarse-grained) vary from 0.2 to 0.3 mm. A typical mode (10044) is pyroxene, 47%; plagioclase, 34%; opaques, 12%; cristobalite, 3%; and, mesostasis, 4%.

James and Jackson (1970) and James and Wright (1972) have classified the crystalline rocks as ilmenite basalts following the rather loose definition of basalt by Holmes (1920). They divided these further, on the basis of texture, into three sub-groups. These are 1)intersertal; 2)fine-grained ophitic; and, 3)medium-grained ophitic.

Basically, the intersertal basalts correspond to some of the LSPET (1969) fine-grained (Type A) rocks. The fine-grained ophitic basalts correspond to the remainder of the fine-grained rocks. The medium-grained ophitic basalts correspond to the coarse-grained (Type B) rocks.

Tera et al. (1970 and others have classified the crystalline rocks chemically on the basis of potassium content. Generally, the high-K (>0.20%K) rocks have intersertal textures and the low-k (<0.20%K) have ophitic textures.

The Apollo 11 Re-examination Team classified the crystalline rocks according to the following scheme: All crystalline rocks observed were called basalts. When the accessory materials olivine or cristobalite were found in the samples, respective modifiers were prefixed (i.e. cristobalite, basalt, olivine basalt). If neither was observed, the presence of abundant vesicles was noted (vesicular basalt). If a particular sample was non-vesicular, the grain size (fine or medium) was used as a modifier.

A summary of the Apollo 11 crystalline rock classification is shown in Table 3.

## BRECCIAS

The breccia samples returned by Apollo 11 are mixtures of fragments, various kinds of rocks, minerals, and glass, and are grey to dark grey in color. Most breccias are fine-grained, with fragments smaller than 1 cm in diameter The term "matrix" refers to material that is too fine-grained to be resolved by whatever optical means are employed, be it a petrographic microscope, a binocular microscope or the unaided eye. Clasts are those fragments that can be resolved from the matrix through differences in color, texture, or composition. The types and abundances of clasts found in the Apollo 11 breccias are summarized in Table 4. It can be seen from Table 4 that many clast types (white, brown, salt & pepper, brown & white) are dissimilar to the crystalline rocks collected at the Apollo 11 site and probably represent ejecta from distant impact sides.

The matrix consists largely of glass particles and mineral fragments. Much of the glass has undergone some devitrification, which gives the matrix an overall turbid appearance in thin section.

Because the chemical composition of the soils and breccias are similar (but not identical) it was assumed by LSPET (1969) that the breccias were some sort of lithified soil, and lithification by shock was put forward as a mechanism. This mechanism was favored by King et al. (1970), Mason et al. (1970), Quaide and Bunch (1970), Shoemaker et al. (1970), Wood et al. (1970). Other investigations have proposed lithification by thermal welding [Smith et al. (1970); Duke et al. (1970); McKay et al. (1970); and McKay and Morrison (1971)]. A third hypothesis proposed by Chao et al. (1971) suggests that breccias are formed by low level shock compaction of soil located some distance from the point of impact and near the base of the regolith.

TABLE 3
Apollo 11 Basalt Classification

| Sample | Re-Examination Team<br>Hand Specimen | James & Jackson (1970)<br>Thin Section | PET | K-Content* |
|---|---|---|---|---|
| 10003 | Cristobalite Basalt | Med. Grained Ophitic Basalt | B | Low-K |
| 10017 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10020 | Ves.Olivine Basalt | Fine Grained Ophitic Basalt | A | Low-K |
| 10022 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10024 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10029 | Med.Grained Basalt | Med. Grained Ophitic Basalt | B | -------- |
| 10031 | Vesicular Basalt | ------------------------------ | A | -------- |
| 10032 | Fine Grained Basalt | ------------------------------ | A | Low-K |
| 10044 | Cristobalite Basalt | Med. Grained Ophitic Basalt | B | Low-K |
| 10045 | Olivine Basalt | Fine Grained Ophitic Basalt | A | Low-K |
| 10047 | Cristobalite Basalt | Med. Grained Ophitic Basalt | B | Low-K |
| 10049 | Fine Grained Basalt | Intersertal Basalt | A | High-K |
| 10050 | Cristobalite Basalt | Med. Grained Ophitic Basalt | B | Low-K |
| 10057 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10058 | Cristobalite Basalt | Med. Grained Ophitic Basalt | B | Low-K |
| 10062 | Olivine Basalt | Fine Grained Ophitic Basalt | A | Low-K |
| 10069 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10071 | Fine Grained Basalt | Intersertal Basalt | A | High-K |
| 10072 | Vesicular Basalt | Intersertal Basalt | A | High-K |
| 10092 | Olivine Basalt | -------------------------------- | - | ------- |

*After Tera et.al., (1970) and others

.

SOILS

Soil samples were obtained from the Contingency, Documented and Bulk Samples, all of which were taken within 30m of the lunar module (Fig. 2).

The Contingency Samples soils were collected along with the rocks using the special Contingency Sampler (Fig. 9), in which rocks and soils were collected simultaneously by scooping. Except for the drive tube samples, the only soil present in the Documented Sample was what adhered to the rocks. This soil was admixed with material produced by the crumbling and spalling of the rocks. The soils present in the Bulk Sample were collected by scooping into the regolith using the large scoop (Fig. 7).

During Preliminary Examination, fines samples from the Contingency, Documented, Bulk and Core samples were sieved and the results plotted as cumulative-weight percent curve (Fig. 14).

Since apparently a scoop was not used in collection of the documented samples, the fines (10011) with the rocks probably consist of a mixture of soil that adhered to the rocks with material abraded from the rocks in transit, especially from the friable breccias. On the other hand,

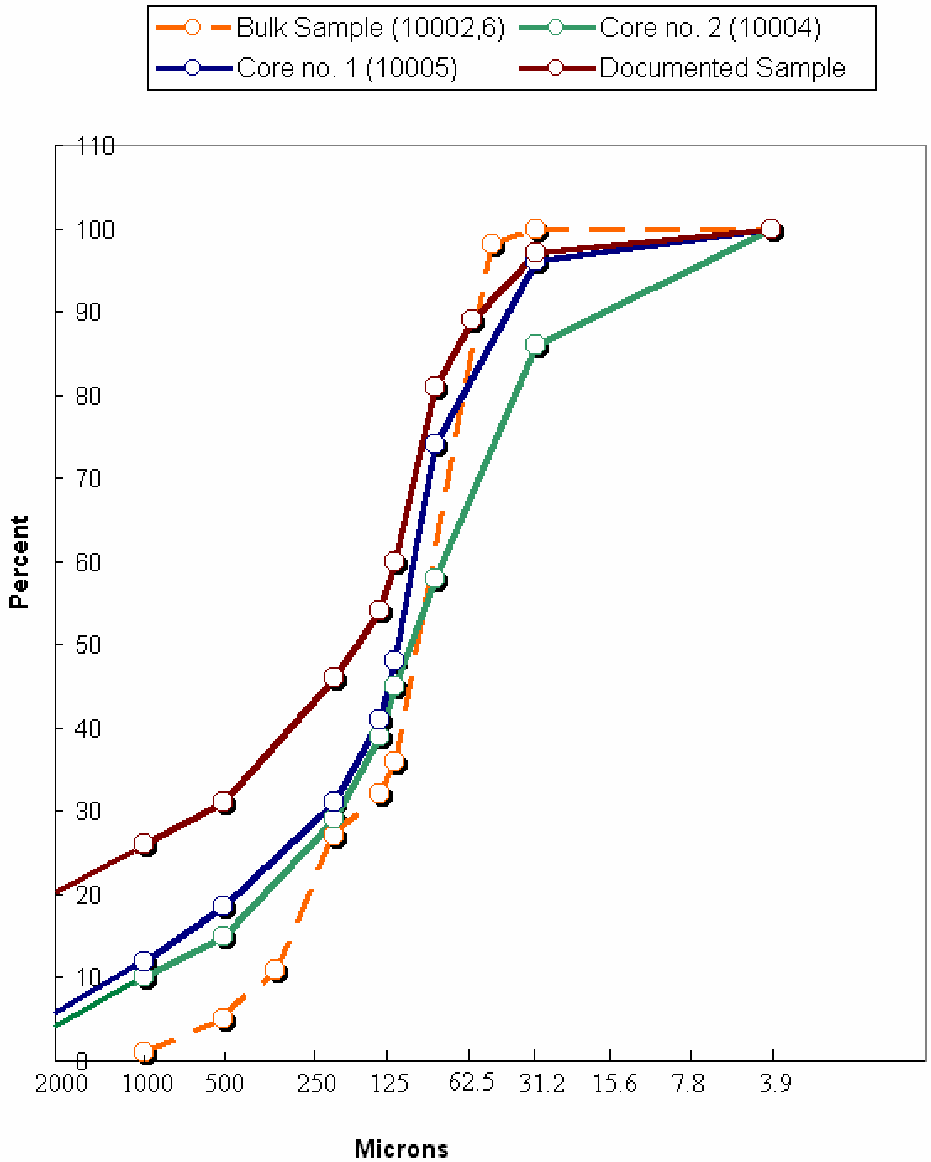


Figure 14. Cumulative Weight Percent of some AP-11 fines.

the bulk and contingency fines were collected by scooping and probably contain only a small proportion of rock material abraded in transit.

Soils from Apollo 11 contain the following components, given in order of abundance:

1) <u>Igneous rock and mineral fragments.</u> These occur as black to grey basalt fragments with densities of greater than 3.32 $gm/cm^2$ (Heiken, 1975). Mineralogically and textureally these fragments are similar to the basalts collected at the Apollo 11 landing site (LPSET, 1969). Most of the mineral fragments found in the soils are comminution products of the basalts: ilmenite, pyroxene, plagioclase, olivine and chrome spinel (Heiken, 1975). Small amounts of cristobalite and alkali feldspar have also been reported (Agrell et al., 1970; VonEngelhardt et al., 1970.)

2) <u>Breccia fragments.</u> These occur as tabular to equant, sub-rounded to subangular fragments with densities of 2.9-3.1 $gm/cm^3$ (Heiken, 1975). The breccia fragments are composed of basalt, glass, mineral and previous breccia fragments (LSPET, 1969). It has been proposed by Agrell et al. (1970), Chao et al. (1971), and others that the breccia fragments are a result of soil lithification, but there is not a direct correspondence of soil modes to breccia modes (Duke et al., 1970). It has been postulated by Heiken (1975) that the breccias are most probably a mixture of freshly comminuted rock and soil from impact craters.

3) <u>Glass spheres.</u> 1-mm to 3-mm-diameter glass spheres make up a minor (1-5%) but thoroughly studied soil constituent. Most are spherical, but some occur in ovoid to dumbbell shapes. Various colors are exhibited with a predominance of pale amber (2.2-2.6 $gm/cm^3$), dark amber (2.7-3.2 $gm/cm^3$), red brown (3.0-3.32 $gm/cm^3$), and pale yellow, pale green, or colorless (2.2-2.6 $gm/cm^3$) spheres (Duke et al., 1970; Agrell et al., 1970). Many spheres are devitrified; some of the larger spheres have the larger vesicles. Many spheres exhibit flare patterns. Some sphere surfaces are coated with imbedded particulate matter or spattered droplets of glass, Fe, Fe-Ni and troilite (McKay et al., 1970; Agrell et al., 1970) and some surfaces show evidence of micro-meteorite impacts (zap pits).

4) <u>Micro-anorthositic fragments.</u> Small, angular fragments of plagioclase ($An_{95}$) with small ilmenite and rutile inclusions are described by Agrell et al., (1970) and Wood et al., (1970).

The origin for these fragments may be the lunar highlands or mare regions with anorthite-rich basalt flows (Heiken, 1975).

5) Meteoritic material. Only a trace of identifiable meteoritic material has been identified in the Apollo 11 soils. Rare metal grains, some with micro-cratered surfaces, are present. They are composed of some single-crystal kamacite and taenite and a hexahedrite with kamacite and zoned taenite. (Agrell et.al., 1970; Goldstein et al., 1970).

There is an agreement among investigators that the Apollo 11 soils were formed by meteorite comminution of fine-grained basalt and coherent breccia. Agglutinate grains and most glassy particles were formed by melting of rock and soil by impact processes. It is possible that some of the glass spheres have a pyroclastic origin, but they are very minor soil constituents (Heiken, 1975).

CORES (from LSPET, 1969)

Two core samples, each 2 centimeters in diameter, were returned: core tube 1 (10005) contained 10 centimeters, and core tube 2 (10004) contained 13.5 centimeters of material. The cores are composed predominantly of particles with diameters from 1 millimeter to 30 micrometers, with admixed angular rock fragments, crystal fragments, glass spherules, and aggregates of glass and lithic fragments in the coarser-sized fraction. Both the material in the tubes and the fines in general are medium to dark grey with tinge of brown. When prodded with a small spatula, the material disintegrates particle by particle or forms extremely fragile ephemeral units of subangular blocky shapes.

Neither core sample shows obvious grain-size stratification. The core from tube 2 has a slightly lighter zone about 6 centimeters from the top surface which is 2 to 5 millimeters thick with a sharp upper boundary and a gradational lower boundary. This lighter zone is not megascopically different in grain size or texture from the dark material.

MINERALOGY

Clinopyroxene – Clinopyroxene occurs in all of the rocks examined. The most widespread variety is cinnamon brown to resin brown in hand specimens and pale reddish brown to pinkish brown to nearly colorless in thin section. Little or no pleochroism is associated with the crystals. The habit of clinopyroxene in the crystalline rocks is generally stubby prismatic or anhedral, with some sheaf-like intergrowths with feldspar also being present. Some crystals are strongly zoned from the center outward as indicated in increasing positive optic angle from near $0^o$ to near $50^o$ together with increasing refractive index and intensity of color.

Rare pale yellow crystals of pyroxferroite occur as overgrowths and interstitial crystals to the pyroxene crystals, and in cavities in several of the more coarsely crystalline rocks.

Olivine – Olivine from $Fo_{65}$ to $Fo_{75}$ is a subordinate phenocryst constituent of several of the finer crystalline rocks, and occurs sporadically as crystal fragments in the breccias and dust. It is clear pale greenish yellow in the crystalline rocks but may range in color from greenish yellow through honey yellow and orange yellow in the breccias and dust. Much of the olivine occurs as anhedral cores in pyroxene.

Plagioclase – Plagioclase is likewise widespread but generally subordinate in amounts to the ferromagnesian minerals. It is calcic, mostly between $An_{70}$ and $An_{90}$, with some compositional zoning in some rocks. The habit is commonly tabular and plate-shaped, with lamellar twinning parallel and transverse to the plates. Interstitial, anhedral, poorly twinned crystals also occur in many of the basaltic rocks.

Ilmenite – Ilmenite is present in relatively large amounts in the crystalline rocks. It occurs as lathes and well-formed skeletal crystals. Ilmenite is also common in the breccias and soil as a constituent of the lithic fragments and as isolated crystal fragments. Many of the larger crystals show exsolution of chromite, rutile and many have armalcolite cores or inclusion.

Cristobalite – Cristobalite is present as thin clear coatings, and occurs in cavities and fills interstices between plagioclase plates in some of the coarser crystalline rocks. Microscopically it is characterized by a crackly surface and complex twinning.

Troilite – Troilite occurs in small amounts as rounded masses in interstices between plagioclase, clinopyroxene, or ilmenite of some coarser crystalline rocks. Most masses contain small blebs of native iron.

Native iron – Native iron occurs as scattered blebs up to 10 microns diameter within the troilite masses. Occasional isolated masses of iron are also present.

Other minerals – Several other accessory minerals occur in crystalline rocks which include chromian ulvospinel, ulvospinel, apatite, K-feldspar, whitlockite, tranquillityite, zirconolite, and baddeleyite.

For further description and reference, see Frondel, J.W. Lunar Mineralogy. New York, (1975) 323 pp.