GENERAL PETROLOGY

Although systems of rock classification should not be based on sample genesis, their interpretation generally is based on some underlying model of how samples were formed. In the case of lunar samples, this model is relatively simple, but the resulting samples can be extremely complex. Primitive lunar crust is assumed to have been coarse-grained igneous material. Coarse-grained igneous lunar samples have old ages (most have crystallization ages older than 4.0 billion years ago), hypidiomorphic-granular texture with a grain size generally greater than 1 mm, anorthositic compositions or high Mg/Fe ratios suggestive of a cumulate origin, low rare-earth values and positive Europium anomalies, and have low-siderophile element concentrations (Warner et al., 1974).

This primitive coarse grained material is assumed to be older than most of the fine-grained igneous material. This fine-grained material includes mare flood basalts and volcanics with associated pyroclastics. These samples have igneous textures, lack mineral and lithic clasts, have low-siderophile concentrations, and contain relatively little metallic iron (Warner et al., 1974).

The primary geologic process acting on this primitive material has been meteroid bombardment. The major phase of this bombardment was accomplished before the emplacement of the flood basalts, but has continued up to present times. Meteoroid bombardment constitutes the major weathering and rock forming agent acting on the lunar surface. Lunar soils and breccias form as a result of meteoroid impact, but there has been much debate over the actual lithification process. Because of the close chemical and mineralogic resemblance LSPET (1969) believed lunar breccias to be shock lithified soil. Two schools of thought emerged, with investigators such as King et al. (1970),Mason et al. (1970),Quaide and Bunch (1970), Shoemaker et al. (1970), Wood et al. (1970) favoring shock welding and Smith et al. (1970), McKay et al. (1970), and McKay and Morrison (1971) preferring thermal welding as the lithification process responsible for breccia formation. Chao et al. (1971) believed breccias formed by low level shock compaction of the soil near the base of the regolith. He felt that this would occur at some distance from the impact. Studies of Apollo 14 breccias indicated thermal metamorphism to be the most reasonable model for breccia lithification (Warner, 1972; Jackson and Wilshire, 1972; Wilshire and Jackson,1972; Chao et al.,1972). More recently, using SEM techniques, Simonds et al. (1977) and Phinney et al. (1976) suggested that breccias form when hot silicate melt welds the relatively cool clastic fragments together during meteorite impact.

The collection of rocks returned by the Apollo 14 mission consists of breccias, most of which are compound (or polymict) in their nature, and a few basalt samples. This is consistent with the idea that the Apollo 14 landing site was on the Fra Mauro Formation. A breccia is a rock consisting of angular coarse-grained fragments in a fine grained matrix. Commonly, in the case of lunar breccias, there is no definite distinction between "matrix" and "clasts" because of the seriate texture of the rock. In these cases, we refer to fragments larger than 1 mm as clasts and those smaller than 1 mm as matrix to be consistent with the practices of the curatorial staff.

Breccias have a higher siderophile element concentration than do lunar rocks of igneous origin implying that they contain some admixed meteoritic material. They contain both mineral and lithic clasts and have more metallic iron than do either the fine-grained or coarse-grained igneous rocks.

The return of so many breccias as a result of the Apollo 14 mission made it important to devise a breccia classification scheme, and many investigators have done so. Wilshire and Jackson (1972) chose a simple descriptive means of classification which enables the rocks to be placed in categories (F1-F4) primarily on the basis of the color index of their clasts and the sample's coherence, a useful classification allowing the rocks to be categorized on the basis of hand specimen examination (Table 3).

TABLE 3
Basic Breccia Classification Scheme
of Wilshire and Jackson (1972)

	FRIABLE	COHERENT
LIGHT CLASTS	F_1	F_2
DARK CLASTS	F_3	F_4

Following more extensive observations, it was possible to invent more elaborate schemes, and a debate arose over the classification as well as over the origin of these breccias. Much of the debate stemmed from the lack of agreement on the stratigraphic history of the landing site (see General Geology). Most researchers had accepted the Fra Mauro Formation as being an ejecta blanket associated with the Imbrium event, and, there is undoubtedly a sizable contribution of material from the many post-Imbrium cratering events. This contribution could be merely a thin veneer, mixed with Imbrium ejecta or it could even be a thick regolith developed on Fra Mauro basalts as was suggested by Schonfeld and Meyer (1973). Many workers now accept the arguments of Chao (1972), Morrison and Oberbeck (1975), and Head and Hawke (1975) that the high degree of thermal effects in the rocks is more consistent with their origin by nearby smaller, pre-Imbrium events. This has recently been reviewed by Hawke and Head (1977).

Almost as many methods of classifications of these breccias were developed as there were articles written about them. Some, such as Chao et al. (1972), formed groups on the basis of the clasts, thereby deriving genetic relationships. Chao's classification system is based on fragment population, nature of matrix, grain size and porosity, metamorphic history, and bulk chemical composition. He divided the Apollo 14 breccias into regolith microbreccias, Fra Mauro breccias, and spherule-rich microbreccias (Table 4).

TABLE 4

Breccia Classification System
of Chao et al. (1972)

1. Regolith microbreccias
   a. Unshocked, porous
   b. Compact, nonporous
   c. Shocked
2. Fra Mauro breccias
   a. Unannealed or slightly annealed, feldspathic breccias
   b. Moderately annealed breccias
   c. Strongly annealed (thermally metamorphosed) breccias
      Unshocked
      Shocked
3. Spherule-rich, transported microbreccias

This classification is roughly comparable to that of Jackson and Wilshire (1972). Their F_1 is equivalent to the unshocked, porous regolith microbreccia of Chao et al. (1972); F_2 resembles the compact or shocked regolith microbreccia; F_3 is analogous to unannealed (Fra Mauro) friable feldspathic microbreccia, and F_4 resembles the strongly annealed (Fra Mauro) breccias of Chao et al. (1972).

The distinction between shocked and unshocked samples in the classification of Chao et al. (1972) is mainly on the basis of the presence or absence of microfractures that cause the microbreccias to break across, rather than around, grain boundaries. Other shock features include shock-induced lamellar twinning in ilmenite grains, low porosity, and glass coating on the microbreccia chips. Compact regolith microbreccias that show no evidence of shock features were also observed (14313).

The gradation between unannealed to annealed breccias is analogous to that of Warner's (1972) low to high metamorphic grades. This model included three metamorphic grades, low, medium, and high. He was able to form eight groups (1-8) corresponding to these grades. These were formed on the basis of abundance of matrix glass, abundance of glass clasts, and matrix texture. It was suggested that with increasing temperature, glass clasts and spherules devitrify and lose identity, while pyroxene and feldspar recrystallize developing more euhedral crystals, until, at the highest temperatures, the matrix melts. These 8 groups were correlated with temperature by Williams (1972) who found the range from 500°-1100°C to be sufficient to produce the observed features. Magnetic properties of the Apollo 14 samples correlate well with the metamorphic classification of Warner (1972). All observed magnetic characteristics can be attributed to the increase in grain size of interstitial iron from the 100 Å range in Warner's lowest metamorphic grade samples to grains larger than 1 um in the highest grade samples (Gose et al., 1972).

Quaide and Wrigley (1972) saw three groups: regolith breccias, white rock breccias, and annealed breccias. Others believed the matrix provided a good classification standard. Von Engelhardt et al. (1972), using glass content as a criterion, divided breccias into 3 groups, each matched by a proposed origin:

i. Glass-rich breccias- produced by meteorite impacts on regolith

ii. Glass-poor breccias - produced by impacting solid rock

iii. Glass-poor breccias with a crystalline matrix - produced by recrystallization of a base surge deposit or an impact melt

Christie et al. (1973) emphasize textural features, forming two groups (A & B) on the basis of the presence or absence of evidence of recrystallization, and Lindsay (1972) formed two groups, I and II, on the basis of the presence or absence of glass.

Later, more detailed studies of the matrices of the Apollo 14 breccias using the SEM indicated that the texture of Warner's group 1-7 is "heterogeneous and intermingled on a scale of millimeters" (Simonds et al., 1977). Based on these studies Simonds et al. (1977) have identified 3 breccia groups, which bear some resemblance to the groups of von Engelhardt et al. (1972). The three groups they propose are:

Crystalline matrix breccias (CMB) - those with coherent holocrystalline matrices, at least vestiges of clasts, and meteorite contamination (evidenced by high siderophile content).

Vitric matrix breccias (VMB) - impactites with a definite fragmental texture and abundant glass, glass-bearing clasts, and low melting point clasts.

Light matrix breccias (LMB) - friable, porous, fragmental breccias, with little glass, lacking in recrystallization effects, and more feldspathic than the other two categories.

Simonds et al. (1977) further subdivide their crystalline matrix breccias into 3 subgroups:

1) Clast-free impact melts (14310, 14276)
2) Clast-bearing impact melts - 1-15% clasts (14068)
3) Fra Mauro breccias - more than 15% clasts (all other Apollo 14 CMB's)

Indeed, many of the Apollo 14 breccias are described by them as being crystalline matrix breccias of the Fra Mauro type.

Table 5 contains a list of Apollo 14 rocks and their classification by various investigators. The following observations can be made based on samples classified by the various schemes suggested:

- All CMB's are F4 except 14171 (F3)
- All LMB's are F3
- All VMB's are FI or F2 except 14264 (F4)
- Twice as many VMB's are F2 as FI
- All CMB's are Warner's grade 4 or higher except 14171 (3)
- All LMB's are Warner's grade 3
- All VMB's are Warner's grade 3 or lower

TABLE 5
COMPARISON OF VARIOUS BRECCIA CLASSIFICATION SCHEMES

Sample	Mass (g.)	Wilshire and Jackson (1972)	Warner (1972)	Chao et al. (1972)	Quaide and Wrigley (1972)	von Engelhardt et al. (1972)	Simonds et al. (1972)
14006	12	C	high (6)	2c unshocked	Annealed Breccia	Glass poor crystalline matrix	CMB
14066	510	F4	high (7)	2c shocked	Annealed Breccia	Glass poor crystalline matrix	CMB
14169	78.66	F4					CMB
14171	37.79	F3	med (4)	2c shocked			CMB
14172	32	F4					CMB
14270	25	F4	high (7)	2c unshocked			CMB
14274	15	C					CMB
14303/304	3397	F4	high (6)	2c shocked	Annealed Breccia		CMB
14305/302	2497	F4	high (6)	2c shocked			CMB
14311/308	3200	F4	high (5)	2c unshocked 2c shocked	Annealed Breccia	Glass poor crystalline matrix	CMB
14312	299	F4	high (7)	2c shocked			CMB
14314	116	F4	high (7)	2c shocked			CMB
14319	211	F4	high (7)	2c shocked			CMB
14320	64.9	F4	high (6)	2c shocked	Annealed Breccia	Glass poor crystalline matrix	CMB
14321	9000	F4	med (4)	2b	Annealed Breccia	Glass poor crystalline matrix	CMB
14306	872	F4	med (4)	2c shocked	Annealed Breccia		CMB
14063	135	F3	med (3)	Fra Mauro Breccia 2a	White Rock Breccia	Glass poor with fragmental matrix	LMB
14064	107	F3					LMB
14082/82	79	F3	med (3)	2a		Glass poor with fragmental matrix	LMB

Sample	Mass (g.)	Wilshire and Jackson (1972)	Warner (1972)	Chao et al. (1972)	Quaide and Wrigley (1972)	von Engelhardt et al. (1972)	Simonds et al. (1972)
14041/42	270	F1	low (1)	Regolith microbreccia unshocked Ia Porous			VMB
14045	65	F1					VMB
14047	242	F1	low (1)	Regolith microbreccia unshocked Ia Porous			VMB
14049	200	F1	low (2)	Regolith microbreccia unshocked Ia Porous		Glass rich regolith breccia	VMB
14055	111	F1	low (1)	Regolith microbreccia unshocked Ia Porous	Regolith Breccia	Glass rich regolith breccia	VMB
14255	22	F2					VMB
14264	117	F4					VMB CMB clasts
14265	66	F2					VMB
14269	17	F2					VMB
14271	97	F2					VMB
14275	13	F2					VMB
14301	1360	F2	low (2)	Regolith microbreccia unshocked Ia Porous			VMB
14307	155	F2	low (1)	1c shocked		Glass rich regolith breccia	VMB
14313	144	F2	low (1)	1b compact	Regolith Breccia		VMB
14315	115	F2	med (3)	3 spherule			VMB
14318	600	F2	med (3)	3 rich	Regolith Breccia	Glass rich regolith breccia	VMB

In fact, the groups formed by von Engelhardt et al. (1972) contain the same members as the groups proposed by Simonds et al. (1977) without exception (Tables 5 and 6).

TABLE 6

Comparison of the Classifications
Simonds et al. (1977) and von Engelhardt et al. (1972)

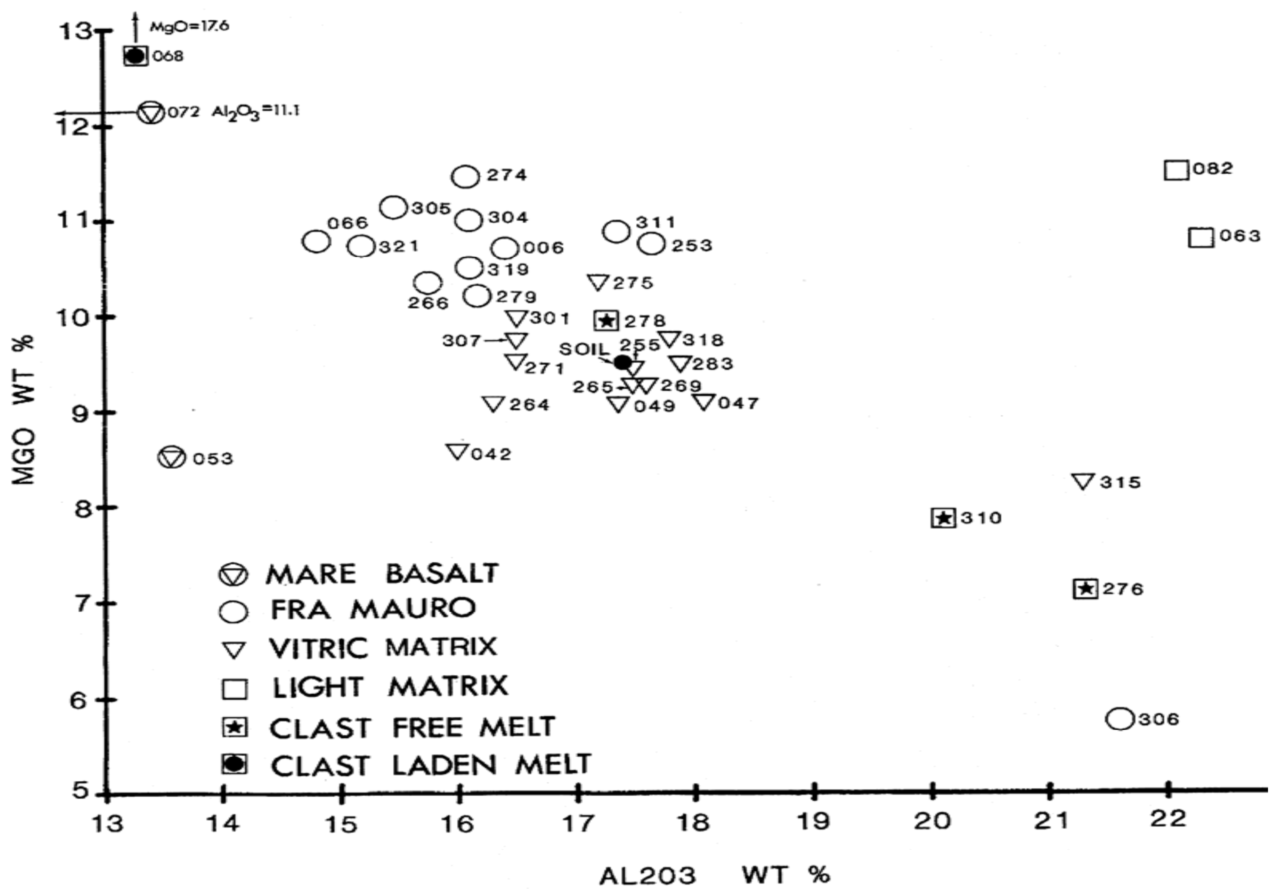
Simonds et al., 1977	von Engelhardt et al., 1972
CMB	Glass poor with crystalline matrix
LMB	Glass poor with fragmental matrix
VMB	Glass rich regolith breccia

It is not so easy to relate the classification of Chao et al. (1972) to the others because his was based on clasts, but all CMB's studied by Chao were placed in his group 2c except 14321, which was classified as a 2b. Moreover, all the 2c breccias are CMB's and F4's except 14171 which is a F3. An interesting feature noted by our group in observing clast populations is the association of chondrules or chondrule-like bodies with the larger samples of the 14300 series. Smaller samples contain more amorphous "glassy" masses and matrix glass.

It is interesting to note the numerous similarities that must exist among those groups of breccias for there to be so few exceptions when attempts are made to correlate different classification schemes. This suggests that there are natural groupings of breccias and/or there might be something fairly unusual about samples that are exceptions to these groupings, such as 14171, 14264, and 14321. For the purposes of this booklet, we will rely on criteria recognized by von Engelhardt et al. (1972) and Simonds et al. (1977) as being effective in forming groups among the lunar breccias. Differences among these groups are relatively uncomplicated and distinctive. In addition, the small but important difference in chemical composition (Mg and AI) noticed by Simonds et al. (1977) (figure 3) for CMB, VMBand LMB types is persuasive ewidence of their basic difference. Unlike Simonds et al. (1977), howeve'r, we will tend to refer to samples such as 14310 and 14276 as melt rocks rather than "clast-free impact melt crystalline matrix breccias." A basalt is a fine grained, usually dark colored, igneous rock which commonly is extrusive in origin. It is composed primarily of calcic plagioclase, pyroxene, and other mafic minerals such as olivine. Lunar basalts differ from terrestrial basalts chiefly in their minor element composition. Lunar basalts typically contain more $Ti0_2$, rare earth elements, and zirconium, and less nickel than their terrestrial counterparts. The plagioclase is more calcic in lunar basalts, being An_{80} or more in composition while terrestrial basalts are more likely to be in the labradorite range of plagioclase composition.

It was anticipated from early data on the large ion lithophyle (LIL) element-rich or KREEP basalts from the Apollo 12 site that Fra Mauro samples would have similar characteristics. Hubbard et al. (1972) establish the similarities among other KREEP basalts and Apollo 14 basalts. Using Al_20_3 and FeO as discriminating factors Hubbard et al. (1972) show that mare basalts are distinguished from non mare basalts (KREEP and low-k) by higher FeO (> 14%) and lower Al_20_3 (< 12%) concentrations.

Figure 3. MgO vs Al_2O_3 plot for Apollo 14 samples. [After Simonds et al., 1977.]



Some disagreement exists regarding the classification of crystalline lunar rocks. Of the crystalline rocks returned during the Apollo 14 mission, very few are regarded as basalts by virtually all investigators. As we pointed out previously, samples 14310 and 14276 are classified as crystalline matrix breccias of the clast-free impact melt variety by Simonds et al. (1977).

When we can recognize remnant clasts or other criteria suggesting that a sample was once a soil or a breccia, we will simply refer to it as a melt rock. Obviously, many samples duplicating basaltic texture and composition may have had their origins as something other than extrusive or intrusive melts, but we do not feel that the name "basalt" must necessarily carry genetic connotations. These samples are referred to merely as crystalline rocks.