Papike, J.J. and Merrill, R.B., eds.
Proc. Conf. Lunar Highlands Crust (1980), p. 51-70
Printed in the United States of America

Recommended classification and nomenclature of lunar highland rocks—a committee report

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Abstract—As a result of the work of the LAPST (Lunar and Planetary Sample Team) Nomenclature Committee the following recommendations for the lunar highland rock classification are made. The rocks should be classified into Groups, Subgroups, Classes, and Subclasses according to a series of textural and compositional properties and to the degree of shock. Root names should be given to the rock classes which are to be subclassified by means of modifying adjectives or prepositions. The proposed system of Groups, Subgroups, and Classes is as follows:

1 *Igneous Rocks.*
1.1 Volcanic rocks: 1.1.1 Basalts; 1.2 Plutonic rocks: 1.2.1 Anorthosites (Anorthosite, Noritic anorthosite, Gabbroic anorthosite, Troctolitic anorthosite); 1.2.2 Norites (Anorthositic norite, Norite, Gabbroic norite, Olivine norite); 1.2.3 Gabbros (Anorthositic gabbro, Gabbro, Noritic gabbro, Olivine gabbro); 1.2.4 Troctolites (Anorthositic troctolite, Troctolite); 1.2.5 Ultramafics (Pyroxenite, Peridotite, Dunite).
2 *Metamorphic (recrystallized) rocks.*
3 *Breccias.*
3.1 Monomict breccias: 3.1.1 Cataclastic rocks; 3.1.2 Metamorphic (recrystallized) cataclastic rocks; 3.2 Dimict breccias; 3.3 Polymict breccias: 3.3.1 Regolith (soil) breccias; 3.3.2 Fragmental breccias; 3.3.3 Crystalline melt breccias (impact melt breccias); 3.3.4 Glassy melt breccias ((impact) glass); 3.3.5 Granulitic breccias.

The classes of igneous rocks which are based on the modal or normative composition follow a system similar to that proposed by Prinz and Keil (1977).

1. INTRODUCTION

A number of different classification and nomenclature systems for lunar highland rocks are currently in use in lunar science. This greatly impedes an easy and unequivocal scientific communication on highland rock materials and their genetic interpretation. The reasons for this confusing situation and the needs for an improvement and unification of rock nomenclature have been discussed repeatedly in recent time (Prinz and Keil, 1977; Stöffler *et al.*, 1979 a,b). In view of this, a Nomenclature Committee was established in 1979 on the recommendation of the Lunar and Planetary Sample Team (LAPST) in order to define a new and unified classification and nomenclature system. This paper presents the results of the work of this committee.

2. CLASSIFICATION PRINCIPLES

2.1 First order classification criteria (texture, structure)

The lunar highland rock samples are fragments of impact displaced and metamorphosed lithic units which belong to texturally and compositionally complex, polygenetic breccia formations of the upper part of the lunar crust. Both magmatic and impact processes were important in the evolution of the crustal rocks. Because of their complex genesis such rocks cannot be classified on a single parameter such as mineralogical (or chemical) composition. Several independent parameters such as texture, modal and chemical composition, and grain size are required for an appropriate classification. In view of the dominance of impact processes in the formation of the sampled crustal rocks, we find it necessary to emphasize texture in the classification (see Stöffler *et al.*, 1979 a). Additional properties, such as composition which reflects the nature of the target and which inevitably affects the details of the texture, are treated as modifying terms. With regard to the importance of impact processes it appears reasonable to use the information on rock textures observed at terrestrial impact craters in crystalline bedrock for a first-order *textural classification* of the highland rocks. The present state of knowledge about terrestrial impact formations and their critical implications for the highland rock classification (and genesis) has been reviewed in detail recently (James, 1977; Stöffler *et al.*, 1979 a).

As discussed in some detail by Stöffler *et al.* (1979 a) three basic textural types of highland rocks are distinguished: *igneous rocks, metamorphic rocks,* and *breccias*. Breccias are either monomict, polymict or dimict. The *monomict breccias* are cataclastic rocks formed by in-situ brecciation of a single lithology *(monolithologic)*. *Polymict* or *polylithologic breccias* consist of two main textural components which are termed *matrix* and *clasts*. Such breccias result from the mixing of different lithologies formed under different conditions at different selenological locations. Polymict breccias may have either a *clastic matrix,* a *"melt" matrix* which is crystallized or glassy, or a *metamorphic matrix*. The *clastic matrix* consists of mineral clasts and, in some cases, of additional glassy particles. These clasts form the host for larger rock clasts. The grain size of all clasts is more or less seriate. We define the matrix arbitrarily as the grain size fraction which is smaller than 20–25μm. The *"melt" matrix* is characterized by a variety of textures ranging from holocrystalline (crystalline matrix) to glassy (glassy matrix).

Some crystalline and semi-crystalline textures appear to result from devitrification of glass. The *metamorphic matrix* is typified by a recrystallization texture which is granoblastic to poikiloblastic.

The breccia *clasts* are 1) mineral fragments and fragments of rocks with igneous, metamorphic, and breccia textures, and 2) glassy or partially recrystallized melt bodies or fragments thereof. Many of the clasts are themselves breccias, giving the rock a breccia-in-breccia texture.

Dimict or *dilithologic* breccias are characterized by an unusual structural feature in which a crystalline matrix is combined with a monomict cataclastic breccia texture in an *intrusive-* or *vein-like* relationship.

On the basis of the textural properties outlined above, lunar highland rocks are classified into textural groups, subgroups, and classes in Table 1. This classification has a number of characteristics which are considered to be important for its practical use, in that it

(1) allows the assignment of an unknown sample by standard microscopic examination of thin sections in conjunction with macroscopic observations,
(2) uses equivalent and consistent criteria for the whole classification system,
(3) uses textural and structural properties of a sample as the prime criteria for the classification,
(4) involves a minimum of genetic interpretation, and
(5) is compatible with the classification of terrestrial impact breccias.

The classification system presented here is based on the clast-matrix relationships of the sample as a whole. Thus it is necessary to identify the last formed matrix for each sample considered. This may be difficult or impossible for small samples. Hence, as discussed by Stöffler *et al.* (1979 a), the determination of the parent macroscopic impact formation of any given rock sample may require a very large sample or knowledge of field relationships. Therefore, it is frequently impossible to trace the genesis of a breccia to any particular type of impact process or to a specific parent crater. A detailed discussion of the different textural highland rock classes in terms of their potential selenological provenance (type of parent crater deposit and type and size of parent crater) is given in a previous paper (Stöffler *et al.*, 1979 a).

2.2 Second order classification criteria (composition, texture, grain size, degree of shock)

The wide range of chemical and mineralogical compositions and textures observed in highland breccias make it desirable to supplement the main textural rock classes given in Table 1 by additional characteristics. In the case of breccias, it is most important to link the textural classification with a compositional classification. It is proposed that the same compositional classes as defined for igneous rocks (Table 1, Figs. 1 and 2) be used for the breccias and for the individual breccia components (matrix and clasts).

Table 1. Classification and nomenclature of lunar highland rocks.

Groups	Subgroups	Classes (root names)	Main textural characteristics
Igneous rocks (magmatic rocks)	Volcanic rocks	Basalt	Fine-grained to medium-grained, ophitic-subophitic-intersertal-porphyritic crystallization texture
	Plutonic rocks	Anorthosite Noritic anorthosite Gabbroic anorthosite Troctolitic anorthosite Anorthositic norite Norite Gabbroic norite Olivine norite Anorthositic gabbro Gabbro Noritic gabbro Olivine gabbro Anorthositic troctolite Troctolite Pyroxenite Peridotite Dunite	medium-grained to coarse-grained granular (mosaic) crystallization texture or cumulate texture
Metamorphic rocks (recrystallized rocks)		Granulitic rock[(1)]	granoblastic to poikiloblastic recrystallization texture
Breccias	Monomict or monolithologic	Cataclastic rock[(1)]	intergranular in-situ brecciation of a single lithology
		Metamorphic (recrystallized) Cataclastic rock[(1)]	intergranular in-situ brecciation of a single lithology and partial recrystallization
	Dimict or dilithologic	Dimict breccia	intrusive-like, veined texture of very fine-grained crystallized melt breccia within coarse-grained plutonic or metamorphic rock types

Table 1. *(Continued)*

	Polymict or polylithologic	Regolith breccia or soil breccia	clastic regolith constituents including glass spherules with brown vesiculated matrix glass
		Fragmental breccia	rock clasts in a porous clastic matrix of fine-grained rock debris (mineral clasts)
		(Crystalline) melt breccia or impact melt breccia	rock and mineral clasts in an igneous-textured matrix (granular, ophitic, subophitic, porphyritic, poikilitic, dendritic, fibrous, sheaf-like etc.)
		(Impact) glass or glassy melt breccia	rock and mineral clasts in a coherent glassy or partially devitrified matrix
		Granulitic breccia	rock and mineral clasts in a granoblastic to poikiloblastic matrix

(1) Use plutonic rock name or other rock name (from Figs. 1 and 2), if applicable, for subclassification (e.g., granulitic norite, cataclastic norite, etc.)

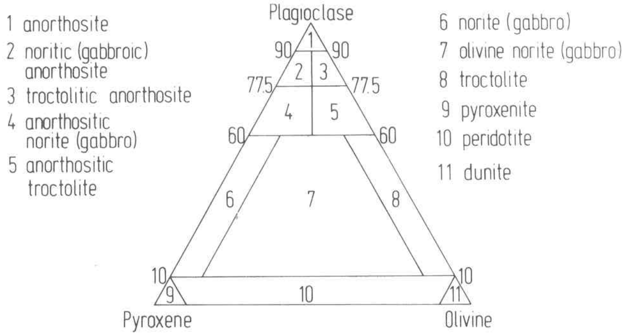

Fig. 1. Classification and names of plutonic lunar highland rocks based on the proposal of Prinz and Keil (1977). Composition in vol. %. The spinel-bearing troctolites are free of pyroxene. Note that the compositional fields are different from the IUGS-system (Streckeisen, 1974).

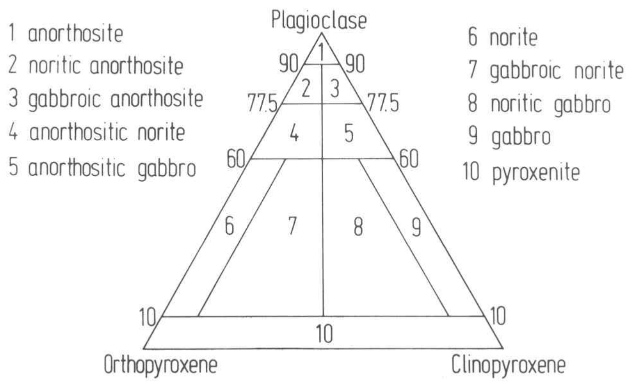

Fig. 2. Composition of noritic and gabbroic lunar highland rocks. Note that the compositional fields are different from the IUGS-system (Streckeisen, 1974).

In general, the following rules should be applied for the subclassification of highland rocks (see Tables 1, 2, 3, and 4):

Igneous rocks

The subclassification of plutonic highland rocks, according to their modal or normative composition, is based on the proposal of Prinz and Keil (1977). The mineralogical composition of the proposed plutonic rock classes in Table 1 is given in Figs. 1 and 2. This classification is preferred over all others (e.g., the IUGS-classification of terrestrial rocks (Streckeisen, 1974) or the purely normative classification of lunar igneous rocks by Engelhardt and Stengelin (1978)) because it allows transitional rock classes between anorthosite and norite (gabbro) or anorthosite and troctolite. Moreover, Engelhardt and Stengelin (1978) make no distinction between igneous rocks and breccias with crystalline matrix.

Additional characterization of igneous rocks may be made on the basis of the crystallization texture

Table 2. Subclassification of breccias by use of a modifier to the root names of Table 1.

breccia class	clast-content	matrix texture	mesostasis-content of matrix	matrix grain-size
fragmental breccias	with melt-particles(1) without melt-particles (cogenetic)(1)	—	—	—
(crystalline) melt breccias or impact melt breccias	clast-poor clast-bearing clast-rich	finely granular ophitic subophitic porphyritic poikilitic dendritic fibrous sheaf-like spherulitic	mesostasis-bearing mesostasis-rich	very fine fine medium coarse
(impact) glasses or glassy melt breccias	clast-poor clast-bearing	vitric partially devitrified	—	—
granulitic breccias	clast-poor clast-bearing	granoblastic poikiloblastic	—	very fine fine medium coarse

very fine grained: <0.03 mm
fine grained: 0.03 mm–0.3 mm
medium grained: 0.3 mm–3.0 mm
coarse grained: >3.0 mm

clast-poor: <10 vol.% clasts
clast-bearing: 10–25 vol.% clasts
clast-rich: >25 vol.% clasts

mesostasis-bearing: <10 vol.% mesostasis
mesostasis-rich: >10 vol.% mesostasis

Table 3. Subclassification of polymict breccias by use of a modifier to the root names of Table 1.

breccia class	composition of matrix	composition of clasts
fragmental breccias	—	
crystalline melt breccias (impact melt breccias) (impact) glasses (glassy melt breccias) granulitic breccias	conventional nomenclature according to modal and/or normative composition, e.g. noritic anorthositic dunitic (see Table 1, Figs. 1 and 2)	volume proportion of clast lithologies (using highland rock classification)

Table 4. Classification of highland rocks according to their degree of solid state shock metamorphism.

Pressure data according to Stöffler, 1971; Kieffer, 1971, 1975; Kieffer *et al.*, 1976; Schaal *et al.*, 1979; Schaal and Hörz, 1977; 1 GPa = 10 kbar

Rock type	degree of shock	estimated peak pressure (GPa)	textural characteristics
Non-porous rocks (igneous and metamorphic rocks, monomict breccias, dimict breccias, crystalline melt breccias, impact glass, granulitic breccias)	unshocked	5	primary rock texture and intragranular texture of mineral grains unchanged
	weakly shocked	5–30	intragranular fracturing and mosaicism in all mineral constituents; planar deformation structures in feldspar, pyroxene and olivine; primary rock texture unchanged
	strongly shocked	30–45	mosaicism and planar deformation structures in mafic minerals; solid state isotropization of plagioclase (maskelynite, diaplectic or thetomorphic glass); primary rock texture unchanged
Porous rocks (regolith breccias, fragmental breccias)	unshocked (friable)	0– 3	highly porous aggregation of breccia constituents
	shocked (coherent)	>3, mostly >10	moderate, small or lacking porosity in the matrix; mosaicism and fracturing of minerals; intergranular melt

Note: Rocks with glass-coating are to be designated ''glass-coated'' and the grain size. Four grain size classes are proposed for designating the average grain size of an igenous rock:

$<$0.03 mm (very fine grained)
0.03–0.3 mm (fine grained)
0.3 –3 mm (medium grained)
$>$3 mm (coarse grained)

A classification is not presented for subgroups of volcanic rocks which are predominantly basalts, because this paper is mainly concerned with the problem of classifying breccias. However, a unified subclassification of basalts should be considered in the future.

Monomict breccias and metamorphic (recrystallized) rocks

They are typically subdivided on the basis of modal mineralogy and mode of origin of the rock prior to brecciation (see Table 1 and Figs. 1 and 2).

Dimict breccias

A more specific characterization of the two lithological components is to be made according to the pertinent properties of each lithology (Tables 1, 2, 3, and 4).

Polymict breccias

The breccia *matrix* should be characterized according to the following properties (Tables 2 and 3):
1) mineralogical or normative composition (Table 3)
2) texture (Table 2)
3) grain size (Table 2)
4) mesostasis content (Table 2)

The *clasts* should be designated according to:
1) the compositional and textural type (Tables 1–4)
2) the volumetric proportion (Table 3)

For the *whole breccia* the clast-content should be given according to the scheme in Table 2.

All highland rocks may be subclassified according to the degree of *shock metamorphism* caused by the latest shock event which predominantly resulted in solid state deformation or transformation (intergranular fracturing, mosaicism, planar deformation structures in the mineral constituents, and solid state isotropization or incipient selective melting of feldspar; Table 4).

3. NOMENCLATURE PRINCIPLES

The basic principle of the nomenclature proposed for the textural classes of lunar highland rocks (Table 1) is to assign short *root names* to the individual rock classes. For a complete and exact naming of a particular sample this root name should be combined with one or more *modifiers* which describe second-order properties of the sample. It is most convenient if the modifiers are adjectives or prepositions (Table 2, 3, and 4; Figs. 1 and 2). We attempted to use only non-genetic, textural terms for the root names and modifiers and to avoid root names which consist of more than two words. However, as the history of lunar rock terminology shows, it is extremely difficult to fulfill these two requirements and to keep a completely uniform scheme of terms without ending in an odd or meaningless nomenclature. Consequently, the proposed names in Table 1 represent a compromise between purely non-genetic and well known, commonly used genetic terms. In some of the latter cases, alternative, non-genetic terms have been suggested.

In the group of *Igneous Rocks,* the naming is based on the proposal of Prinz and Keil (1977). The names of the plutonic rock classes are given in Table 1 and in Figs. 1 and 2. Textural terms commonly used in terrestrial igneous petrology may be applied for the characterization of the crystallization texture of igneous highland rocks (e.g., granular, ophitic, subophitic, intersertal, porphyritic etc.). In addition, igneous rocks may be termed very fine grained, fine grained, medium grained, or coarse grained (see section 2.2 for the proposed grain size ranges).

In the group of *Metamorphic Rocks,* the term granulitic is proposed in conjunction with a compositional name of the kind suggested for plutonic rocks, e.g., *granulitic norite*. Granulitic is meant in a more restricted, textural sense compared to the usage in terrestrial petrography. For lunar highland samples it indicates a granoblastic or poikiloblastic recrystallization texture.

In the group of *Breccias,* the term "breccia", which is part of the root name in most rock classes (Table 1), can be combined with the term "impact" if this appears necessary in a particular case. In the case of monomict breccias, it is suggested to use the compositional plutonic rock names as given in Table 1 in the composite root name, e.g., *cataclastic anorthosite*. For dimict and polymict breccias, the compositional characterization of the breccia components, e.g., the matrix, is made by a modifier, e.g., *anorthositic granulitic breccia* (Table 3). In the breccia class "crystalline melt breccia" ("impact melt breccia"), which comprises a large variety of matrix textures and compositions, the general adjective "crystalline" can be replaced by a term for the matrix texture in any particular case (Table 2), e.g., *poikilitic melt breccia*. The term "impact" could be deleted in such a case. This holds also for the breccia class "impact glass". If a lunar glass body is clast-free, the term "glass" is most appropriate if an impact origin is not certain. For the breccia class "granulitic breccia", there are two options for naming a particular sample, e.g., "granoblastic (or poikiloblastic) granulitic breccia" or just "granoblastic (or poikiloblastic) breccia", in combination with a compositional term, e.g., *noritic granoblastic* breccia (Table 3).

All other terms proposed in Tables 1, 2, 3, and 4 are self-explanatory. A list of previously used rock names or designations, excluding igneous rocks, is given in Table 5 for each newly proposed rock class. The old names are either synonymous with the new name or they designate only a subclass of the rock class in question. Synonyms are italicized in Table 5.

4. DESCRIPTION AND DETERMINATION OF HIGHLAND ROCK CLASSES

A key chart for the classification of a lunar highland rock sample is presented in Fig. 3 which is adapted from Fig. 15 of Stöffler *et al.* (1979 a). The various rock classes listed in Table 1 and Fig. 3 have the general petrographic characteristics outlined in the following sections. These sections are adapted in part from Stöffler

Table 5. List of previous names and designations for non-igneous lunar highland rocks (breccias and metamorphic rocks). Previous names which are fully synonymous with the proposed new name are italicized, the other ones designate only a subclass of the new rock class in question.

A. METAMORPHIC ROCKS

Proposed name: *granulitic rock*[1)]

[1)] plutonic rock names

Previous names or designations	Reference
hornfelsed noritic microbreccia	Chao *et al.*, 1972
granulitic norite breccia	Taylor *et al.*, 1972
granulitic or poikilitic crystalline rock	Simonds *et al.*, 1974
clast-free granulitic impactite	Warner *et al.*, 1977
meta-"rock"	Stöffler *et al.*, 1979a

B. BRECCIAS

1. Monomict breccias

Proposed name: *cataclastic rock*[1)]

[1)] plutonic rock names

Previous names or designations	Reference
brecciated anorthositic rock	Chao, 1973
cataclastic anorthosite	LSPET, 1973a
	Warner *et al.*, 1976
brecciated gabbroic rocks	LSPET, 1973b
Apollo 16 B_1-group (in part)	Wilshire *et al.*, 1973
Apollo 16 C_1-group (in part)	Wilshire *et al.*, 1973
class 4-rock (cataclastic breccia)	Stöffler *et al.*, 1974
cataclasite	James, 1977
cataclastic rock	Phinney *et al.*, 1977
	Stöffler *et al.*, 1979a

Proposed name: *recrystallized cataclastic rock*[1)]

[1)] plutonic rock names

Previous names or designations	Reference
brecciated and recrystallized anorthositic rocks	Chao, 1973
cataclastic breccia with recrystallization	Stöffler *et al.*, 1974
recrystallized anorthosite	Vaniman *et al.*, 1976
metacataclastic rock	Stöffler *et al.*, 1979a

2. Dimict breccias

Proposed name: *dimict breccia*

Previous names or designations	Reference
partially molten breccia	LSPET, 1973a
Apollo 16 B_2-group (in part)	Wilshire *et al.*, 1973
black and white rock	Warner *et al.*, 1973
	James, 1977
	McGee *et al.*, 1979

Table 5. *(Continued)*

Previous names or designations	Reference
white portion: cataclastic rock	Phinney *et al.*, 1977
black portion: basaltic matrix breccia	Phinney *et al.*, 1977
dike breccia	Stöffler *et al.*, 1979a

3. Polymict breccias

Proposed name: *regolith breccia (or soil breccia)*

Previous names or designations	Reference
regolith microbreccia	Chao *et al.*, 1971
	Chao, 1973
(glass-rich) *regolith breccia*	Engelhardt *et al.*, 1972
regolith breccia	Quaide and Wrigley, 1972
	James, 1977
	Stöffler *et al.*, 1979a
grade 1 metamorphic breccia	Warner, 1972
Apollo 14 F_1-group	Wilshire and Jackson, 1972
dark matrix breccia (DMB)	LSPET, 1973b
	Delano *et al.*, 1973
	Vaniman *et al.*, 1976
	McGee *et al.*, 1979
glassy breccia	Warner *et al.*, 1973
class 3 - rock (regolith breccia)	Stöffler *et al.*, 1974
vitric matrix breccia	Phinney *et al.*, 1977
soil breccia	Warner *et al.*, 1978

Proposed name: *fragmental breccia*

Previous names or designations	Reference
feldspathic breccia	Chao *et al.*, 1972
glass-poor breccia with fragmental matrix	Engelhardt *et al.*, 1972
grade 3 metamorphic breccia	Warner, 1972
Apollo 14 F_3-group	Wilshire and Jackson, 1972
Apollo 16 B_2-group (in part)	Wilshire *et al.*, 1973
Apollo 16 B_3-group (in part)	Wilshire *et al.*, 1973
polymict breccia	LSPET, 1973a
light matrix breccia	Warner *et al.*, 1973
	Phinney *et al.*, 1977
	McGee *et al.*, 1979
fragmental breccia	Simonds *et al.*, 1974
	McGee *et al.*, 1979
glass-poor feldspathic breccia	James, 1977
clastic breccia	Stöffler *et al.*, 1979a

Table 5. *(Continued)*

Proposed name: *(crystalline) melt breccia or impact melt breccia*

Previous names or designations	Reference
annealed Fra Mauro breccia	Chao *et al.*, 1972
glass-poor fragmental rocks with crystalline matrix	Engelhardt *et al.*, 1972
annealed breccia	Quaide and Wrigley, 1972
Apollo 14 grades 4–8 metamorphic breccias	Warner, 1972
Apollo 14 group F_4	Wilshire and Jackson, 1972
pyroxene poikiloblastic breccia (POIK)	Delano *et al.*, 1973
light matrix breccia (LMB)	Delano *et al.*, 1973
feldspathic intersertal igneous rocks (FIIR)	Delano *et al.*, 1973
Apollo 16 high grade metamorphic rocks	LSPET, 1973a
type 1 and 2 of light gray breccia	LSPET, 1973b; James, 1977
blue gray breccia	LSPET, 1973b; James, 1977
green gray breccia	LSPET, 1973b; James, 1977
metamorphosed breccia	Warner *et al.*, 1973
melted matrix breccia	Warner *et al.*, 1973
mesostasis-rich rocks (breccias)	Warner *et al.*, 1973, 1976
basalts (in part)	Warner *et al.*, 1973
poikilitic rock	Warner *et al.*, 1973, 1976
Apollo 16 groups C_2, B_4, B_5	Wilshire *et al.*, 1973
crystalline breccias with poikilitic, micropoikilitic, subophitic, granular and clast-rich ophitic matrix	Simonds *et al.*, 1974
class 6 rock (melt rock)	Stöffler *et al.*, 1974
recrystallized/remelted noritic breccia	Vaniman *et al.*, 1976
pyroxene poikilitic rock	Vaniman *et al.*, 1976
subophitic-granular-micropoikilitic breccias	Warner *et al.*, 1976
thermally metamorphosed breccia	James, 1977
crystalline matrix breccia	Phinney *et al.*, 1977 Stöffler *et al.*, 1979a
basaltic matrix breccia	Phinney *et al.*, 1977
poikilitic matrix breccia	Phinney *et al.*, 1977
high grade breccia	Phinney *et al.*, 1977
low grade breccia	Phinney *et al.*, 1977
poikilitic breccia	Phinney *et al.*, 1977
impact melt rock	McGee *et al.*, 1979

Proposed name: *(impact) glass or glassy melt breccia*

Previous names or designations	Reference
Apollo 17 glass-bonded agglutinate	LSPET, 1973b
glass and devitrified glass	Warner *et al.*, 1973
Apollo 16 group G	Wilshire *et al.*, 1973
class 1 and 2 rock (glassy agglutinate and glass)	Stöffler *et al.*, 1974
agglutinate	Vaniman *et al.*, 1976
light matrix breccia (?)	Vaniman *et al.*, 1976
glassy breccia	Warner *et al.*, 1976
glassy matrix breccia	Phinney *et al.*, 1977
vitric matrix breccia	Stöffler *et al.*, 1979a

Table 5. *(Continued)*

Proposed name: *granulitic breccia*

Previous names and designations	Reference
Apollo 16 group C_2 (in part)	Wilshire *et al.*, 1973
class 5 rock (polymict metamorphic breccia)	Stöffler *et al.*, 1974
recrystallized noritic breccia (?)	Vaniman *et al.*, 1976
light matrix breccia (in part)	Vaniman *et al.*, 1976
granulitic impactite	Warner *et al.*, 1977
recrystallized ANT-rocks	Warner *et al.*, 1978

et al. (1979 a). Other parts are supplemented and updated with respect to the nomenclature proposed here. Typical microphotographs may be found in Stöffler *et al.* (1979 a).

4.1 Igneous (magmatic) rocks

Rocks of this class display either igneous crystallization or cumulate textures. *Basalts* have various crystallization textures ranging from ophitic, subophitic, intersertal, to porphyritic. Plagioclase is predominant over clinopyroxene, olivine, and ilmenite. Most basalts are fine-grained (<0.3 mm). *Plutonic rocks* display a wide compositional range (Table 1 and Fig. 1) and mostly have granular mosaic textures of plagioclase with interstitial anhedral or intragranular subhedral to euhedral pyroxene and/or olivine. Another plutonic type displays cumulate texture. Igneous rocks commonly have grain sizes of 1–5 mm, i.e. are medium to coarse grained. Except for some dunitic rocks, plagioclase (anorthite) predominates (see reviews of Prinz and Keil, 1977; Meyer, 1977; Warren and Wasson, 1977, 1978; Norman and Ryder, 1979).

4.2 Metamorphic (recrystallized) rocks

The texture of these "granulitic rocks" is typically granoblastic to poikiloblastic (Warner *et al.*, 1977; Bickel and Warner, 1978) and is formed obviously by solid state recrystallization induced by thermal metamorphism of variable source rock types. Usually granulitic rocks are plagioclase-rich (anorthositic, anorthositic-gabbroic, anorthositic-noritic). They display a wide range of grain sizes, very fine-grained to medium-grained (<3 mm). Some seem to be transitional to plutonic rocks. Compared to granulitic breccias, samples of this class are rather rare in the Apollo and Luna rock collections (Bickel and Warner, 1978).

4.3 Breccias

Depending on the number of different lithologic components the breccias are either *monomict, dimict,* or *polymict*. Genetically, these breccias were formed in impact craters by different processes which have been discussed in detail by James (1977), Simonds *et al.* (1977), Phinney *et al.* (1977), McGee *et al.* (1979), and Stöffler *et al.* (1979 a).

4.3.1 Cataclastic rocks

The texture of these rocks is characterized by an intragranular cataclasis and intergranular brecciation of either igneous rocks, granulitic rocks, crystalline melt breccias or granulitic breccias. Small mineral fragments are typically displaced along former grain boundaries of the precursor rock, while large relic grains remain in situ. Such monomict breccias are best developed in coarse-grained source rocks with homogeneous texture (igneous and metamorphic).

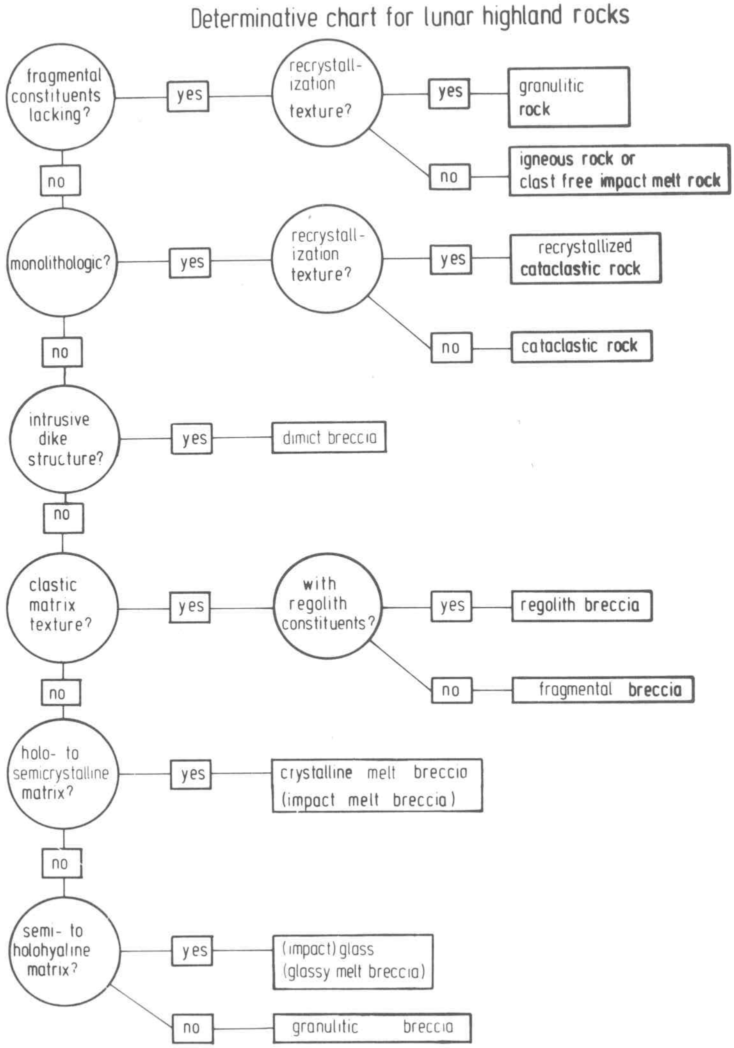

Fig. 3. Determinative chart for the classes of lunar highland rocks adapted from Fig. 15 of Stöffler *et al*. (1979 a). Further subclassification is to be made according to Tables 1, 2, 3 and 4. The term "recrystallization texture" is preferred here over "metamorphic texture" in order to facilitate the recognition of the metamorphic texture.

4.3.2 Recrystallized cataclastic rocks

In some monomict breccias, the fine-grained intergranular highly brecciated regions are affected by a subsequent thermally-induced recrystallization. Thereby a granoblastic texture is formed in those regions and the cataclastic texture appears as a relic in a partially recrystallized breccia. All other characteristics are identical to those of the cataclastic rocks described above. The genetic interpretation of cataclastic rocks and their relation to parent impact formations have been discussed recently in detail (Stöffler *et al*., 1979 a).

4.3.3 Dimict breccias

Samples of this class are composed of two different types of lithologies with distinctly different textures. One textural unit appears intrusive with respect to the other unit, resulting in a vein- or dike-like structure. The intrusive component commonly contains clasts and has a very fine-grained aphanitic matrix texture; it can be classified per se as a crystalline melt breccia. The clastic inclusions are mostly derived from the adjacent lithology, which belongs to the class of cataclastic rocks in most cases. Texturally these rocks are comparable to terrestrial "pseudotachylites" (Wilshire, 1971; James, 1977; McGee *et al.*, 1979; Stöffler *et al.*, 1979 a).

4.3.4 Regolith (soil) breccias

Samples of this type consist of the fine-grained particulate constituents of the regolith: rock, mineral, and glass fragments; glass spherules; glassy agglutinates; and minor meteoritic fragments. These were agglomerated to a more or less coherent rock by shock lithification or sintering of hot glass (Kieffer, 1975; Simonds, 1973; Simonds *et al.*, 1977). Thereby glass is formed along grain boundaries in the matrix; this glass causes the coherence of the clastic particles. The grain size of the largest clasts in the regolith breccias rarely exceeds 1 centimeter. Most significant for the recognition of regolith breccias is the presence of intact or broken glass spherules, glassy agglutinates, and finely dispersed matrix glass. All other types of highland breccias are free of these constituents. The compositional and textural variation of lithic clasts is larger than in all other breccia types due to the intense impact gardening of the regolith material.

4.3.5 Fragmental breccias

Fragmental breccias are composed of clastic rock debris derived from different lithologies of variable composition, texture, and degree of shock. The grain size of the clasts ranges from several centimeters down to the micron scale. Because of the clastic matrix, these breccias are weakly coherent and porous. According to Table 2, two subclasses may be distinguished. One type contains vitric or devitrified melt particles which have the same chemical composition and appear to be cogenetic, i.e. that the melt was formed in the same cratering event from which the admixed clastic rock material was derived in analogy to the terrestrial suevite breccia. Examples of this type most probably are the Apollo 14 so-called "white rocks" 14063 and 14082 (James, 1977; Stöffler *et al.*, 1979 a). The other type is free of such cogenetic melt particles and may be equivalent to the clastic breccia layers of the bulk ejecta blanket or fallback formations of large terrestrial craters (compare Stöffler *et al.*, 1979a). Possible examples are the "white breccia boulders" (67455, 67475) of North Ray crater (Apollo 16). The compositional and textural variations in the lithic clast population of fragmental breccias is very large, similiar to that of regolith breccias, i.e. distinctly larger than in all other types of polymict breccias.

4.3.6 Crystalline melt breccias (impact melt breccias)

Breccias of this class are the most frequent in the lunar highland rock collection. The most common type is composed of rock and mineral clasts embedded in an *igneous-textured* crystalline *matrix*. The clasts are homogeneously distributed or are concentrated in schlieren-like bodies. In the latter case, the overall rock texture is rather heterogeneous. In some rocks the texture of the crystalline matrix itself may be heterogeneous on the macro- and micro-scale. Typical matrix textures are very fine-grained and range from granular, ophitic, subophitic, poikilitic, to porphyritic. These rocks may contain small amounts of mesostasis. From the chemical and petrographic characteristics of the matrix and of the clast population, it was concluded that these breccias result from the crystallization of a fragment-laden, coherent impact melt (e.g., Simonds *et al.*, 1976; Onorato *et al.*, 1976) or from clast-rich melt agglomerates similar to the very melt-rich suevitic breccias observed at terrestrial impact craters (Stöffler *et al.*, 1978). The most abundant minerals of the igneous-textured matrix types are plagioclase, pyroxene and/or olivine, and minor ilmenite. In the mineral clast population, plagioclase generally dominates over pyroxene and olivine. Accessory minerals generally are ilmenite, spinel, Ni-iron metal, various sulfides, zircon, baddeleyite, and phosphate minerals. Rock fragments in these breccias include variable types of igneous and metamorphic rocks, cataclastic rocks, and polymict breccias with crystalline matrix. Breccias with coarser grained matrix (e.g., pokilitic, intersertal) tend to be poorer in clasts than those with very fine-grained matrix.

A second type of melt breccia is characterized by a *matrix with devitrification texture* and appears to be transitional to the "glassy breccias" ("impact glasses"). The textures range from spherulitic to dendritic, fibrous, and sheaf-like and are very fine-grained or even cryptocrystalline. The most common crystallization products are plagioclase, pyroxene, olivine, and ilmenite. The rock and mineral clasts are similar to those observed in igneous textured melt breccias, but are generally smaller in grain size and less abundant. Breccias of this type are considered to result from a subsolidus crystallization of quenched fragment-laden impact melt.

Vesicles are abundant in some samples of both types of crystalline melt breccia, in others they are lacking. The occurrence and selenological provenance of melt breccias is discussed by James (1977), Phinney *et al.* (1977), Simonds *et al.* (1977), and Stöffler *et al.*, (1979 a).

4.3.7 Impact glass; glassy melt breccias

Samples of this type are typified by a vitric matrix in which fragmental minerals and rocks are embedded. Some glasses are free of clasts. The matrix may be partially devitrified. Schlieren and vesicles are common. Some vesiculated glasses have extremely irregular shapes (agglutinates) and are related to glass-rich regolith breccias. Impact glasses form relatively small particles (0.005–30 mm) of various shapes (spheres or other bodies of revolution, slaggy shapes, and fragments) and are the most characteristic constituents of the regolith. Glasses also occur as clasts in certain types of fragmental breccias or as coatings on larger rocks. Many glasses contain small Ni-bearing iron-spherules and troilite. In general, glasses originate from quenched, ballistically transported fragment-laden impact melts. Some glasses may be of volcanic origin.

4.3.8 Granulitic breccias

In contrast to clast-free granulitic rocks described in section 4.2, these rocks contain mineral and rock clasts or relics of clasts which obviously survived the recrystallization of the breccia matrix. This matrix is granoblastic to poikiloblastic and commonly fine-grained. The clasts may also display a recrystallized texture. The modal composition of the matrix is dominated by plagioclase, forming a mosaic of grains meeting at 120° triple junctions. Small euhedral pyroxene and olivine are embedded within and in between plagioclase (granoblastic breccias). In poikiloblastic textures, plagioclase forms minute euhedral crystals disseminated in larger pyroxene and/or olivine crystals. Ilmenite is rare. Granulitic breccias are interpreted to be formed by thermally induced subsolidus recrystallization of variable breccia precursors (Warner *et al.*, 1977; Bickel and Warner, 1978). The heat may have been delivered by a global crustal metamorphism (Warner *et al.*, 1977; Stewart, 1975) or by a surrounding hot impact melt (Stöffler *et al.*, 1979 b). The latter is commonly observed in shocked clasts of crystalline rocks within terrestrial impact melts.

Acknowledgments—We thank Dr. O. B. James for very helpful comments and suggestions. Thanks are also due to Dr. A. Basu and Dr. K. Keil for their constructive criticism of the manuscript. The first author is indebted to the Deutsche Forschungsgemeinschaft (German Science Foundation) for financial support.

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