LUNAR BRECCIAS: AN ELECTRON PETROGRAPHIC STUDY


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High voltage (800-1000kv) transmission electron microscopy (TEM) analyses in conjunction with electron-diffraction, micro-probe and optical petrography, have been conducted on a series of Apollo 14 and 15 breccias with a view to elucidating the consolidation mechanisms and subsequent history of these complex fragmental rocks. The rock samples examined are 14063,47 and 14321,42 (Station C1, Cone Crater); 14301,52 (Station G1, Triplet Crater); 15418,29 and 15455,13 (Station 7, Spur Crater); and 15498,29 (Station 4, Dune Crater); together with fines - 14161,38 - from a rake sample near the lunar module. On the basis of optical petrography and chemistry, several groups of investigators (see Proc. Lunar Sci. Conferences) have proposed different classification systems for the Apollo 11, 12 and 14 lunar breccias, but correlation between the systems is presently inadequate and hinders the utilization of the results from the different groups. We have shown earlier (1,2) that several of the major factors involved - in particular, the proportion of voids and glass and the intensity of shock effects - can be resolved unequivocally only by TEM. Hence, the present study is also directed to utilizing that approach to help develop an optimum classification of the various breccia types.

Microbreccias with little or no optical evidence of recrystallization in matrix or clasts: This group is represented by 14063,47; 14301,52; 14321,42 and 15498,29. These are characterized by decreasing porosity in the matrix, in the order listed above. The sequence appears also to be in order of increasing shock deformation. The internal deformation in the clast minerals increases with decreasing porosity but is not uniform in all of the rocks due to the heterogeneity of the breccias and the incorporation of many preexisting breccia fragments in the rocks. In 14063 and 14301, many of the mineral fragments show no optical evidence of deformation, whereas in 15498 all of the clasts show strong deformation (bending, lamellae, granulation and fracturing). In 14321, some mineral clasts which show no optical evidence of deformation, nevertheless are deformed and some show evidence of annealing and marginal reaction. Although much of the dark matrix in these rocks is optically isotropic, TEM has shown (see Ref.1) that this often is a consequence of fine grain size, rather than truly amorphous character. The range of deformation in this suite of samples is illustrated by Figure 1, which shows deformation twins and dislocation walls in an augite crystal from 14063 (stereomicroscopy has shown that separate deformation events, interspersed with one heating cycle, occurred to produce the observed structure) and Fig.2, which shows a glassy "deformation lamella" in a plagioclase grain in the matrix of 15498. The latter structure is believed to have been caused by a major shock event; similar lamellae have been found in feldspars in samples from the Ries and other terrestrial craters. Of these rocks, all appear to be breccias consolidated from the regolith, except 15498, for which there is evidence that it is mainly Imbrian ejecta blanket, i.e. the Fra Mauro
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Microbreccias with optical recrystallization: In 15455,13 (a "black and white" rock) there is a marked textural contrast between the white, heavily fractured and porous glass-bonded (Fig.3a) anorthosite clast (with a granulated marginal zone) and the dark, fine-grained olivine bearing microbreccia which shows recrystallized grains of the order of 10μm grain size. The rim of the anorthosite clast in contact with the dark microbreccia is of lower porosity, due to a higher glass content (Fig.3b). The matrix of the microbreccia contains evidence of deformation (Fig.3c), as well as recovery and recrystallization. Sample 15418,47 shows more extensive recrystallization of both the (dominantly feldspathic) clasts and the light colored matrix, which has a hornfelsic texture with grain size of the order of 100μm. The plagioclase clasts contain numerous planar features and zones of cavities suggesting extensive shock damage before the recrystallization that produced its present texture. The clasts and the small grains in the matrix, though exhibiting aggregate extinction, are actually polycrystalline or have subgrain structure on a scale close to the limit of optical resolution. Electron micrographs showing recrystallization in this rock have been shown previously (2).

Glass bonded aggregates: This group is represented by 14161,38,4; a third fragment from this rake sample (14161,38,3) consists of angular fragments of minerals and breccia bonded by an intersertal matrix of plagioclase laths and microvesicular glass; these crystallites may have formed by partial crystallization or devitrification. Again, this can be considered to be a regolith breccia.

The substructures in breccias indicate that lithification at various levels of shock (pressure welding), is a major consolidation mechanism for many of the lunar breccias. Aside from much evidence of crystal deformation-dislocation arrays, deformation twins, and fractures—diaplectic (shock-produced) glass is also present. In addition, such breccias invariably showed evidence of recrystallization and recovery, particularly in the clasts. The heating responsible for the latter phenomena is also likely to have been associated with the (multiple) shock events. While some of the breccias examined showed much evidence for extensive annealing (thermal metamorphism), the presence of extensive deformation substructures in these same breccias suggests that some of the thermal metamorphism may also have been due to extensive shock heating. Glass-lithified breccias were poorly represented in the suite of Apollo 14 and 15 breccias available to us and were only found in a rake sample. These could have formed by a glass splash or by incorporation of portions of the regolith in a magma.

Fig. 1. Twins and dislocation arrays in 0.1 mm augite crystal in 14063,47.

Fig. 2. Glass "deformation lamellae" (G) in 0.5 mm deformed plagioclase crystal in 15498,29.

Fig. 3. Substructures in 15455.13 ("black and white" rock). (a) shows the substructure in the glassy, fragmented white anorthosite clast, (b) shows the higher glass content in this clast adjacent to the dark microbreccia, and (c) shows a heavily deformed region of the microbreccia. (Other regions of the latter had many recovered and recrystallized grains.)