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GENETIC IMPLICATIONS OF CHEMICAL AND TEXTURAL PROPERTIES OF SOME FRA MAURO BRECCIAS (APPOLLO 14)

Г.-Д. Кнёль, Д. Штёффлер, Э. Бирхауз, М. Лининг (ФРГ)

ГЕНЕТИЧЕСКИЕ ВЫВОДЫ ИЗ ХИМИЧЕСКИХ И СТРУКТУРНЫХ СВОЙСТВ НЕКОТОРЫХ БРЕКЧИЙ ФРА МАУРО («АПОЛЛОН-14»)

Предлагается модель образования брекчий формации Фра Мауро: а) образование при ударе расплава в одном или нескольких пре-имбрианских кратерах и перемешивание расплава и обломочного материала, когда начальная температура плавления была по крайней мере 1700° С; б) образование различных брекчий, начиная от плотных переплавленных пород, содержащих обломочный материал, до брекчий зювитового типа; в) концентрация в результате флотации остывшего обломочного материала в виде шлирообразных тел или образование тесной смеси обломков с отдельными кусками расплава; г) первым при высокой температуре кристаллизуется расплав на участках, богатых кластическим материалом (в светлой основной массе породы), когда получается сравнительно крупнокристаллическая структура с пижонитовым пироксеном и существенно анортитовым плагиоклазом; д) последующая кристаллизация расплава в участках, бедных кластами, когда создается мозаичная структура с пироксеном, бедным кальцием; другие варианты структуры цементирующей массы являются, вероятнее всего, следствием различий валового химического состава; е) ныне материал брекчий залегает в виде насыпной формации разной мощности, медленно охлажденной от температуры по крайней мере 600° С.

Introduction. Among the terrestrial planets of our solar system the Earth and the Moon are the only major bodies from which rock samples have been obtained for laboratory analyses. In contrast to terrestrial rocks, lunar rocks enable us to study the conditions of rock-forming processes which took place in the earliest period of the history of the solar system. Because impacts of meteorites on planetary surfaces played a pre-dominant role in the early history of the solar system it is important to study impact-metamorphosed rocks in detail in order to understand the processes which formed the planetary crustal rocks. The Mare Imbrium, a large circular impact basin, gives an important clue to the history of the Moon because the Imbrium event is presumed to have excavated a large portion of the pre-Imbrian lunar crust. The Fra Mauro formation, where the Apollo 14 crew landed in 1971, is generally believed to belong to the ejecta blanket of the Imbrium crater (Swann e. a., 1977). Indeed, all rocks sampled at the Apollo 14 site turned out to be impact breccias. These breccias are rather primitive in their mineralogy, but the provenance of their clasts in not as clear as in many terrestrial impact breccias. They have a very complex texture which indicates a multistage formation process.

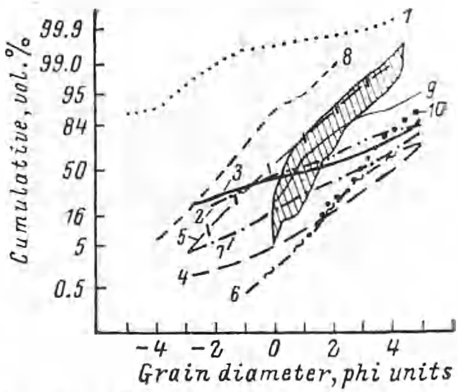
There are three main groups of breccias sampled at the Fra Mauro formation: regolith breccias with a vitric matrix, derived from local regolith by minor impact events: detrital breccias, which are composed of mineral clasts, melt inclusions, and rock fragments and which lack a crystalline or vitric matrix. They apparently consist of moderately compacted impact detritus from larger impact events. Crystalline breccias, consisting of mineral and rock fragments embedded in a more or less homogeneous crystalline matrix, constitute the third group; these breccias are derived from a mixture of impact melt and impact detritus produced by larger impact events. The aim of our microchemical and textural analyses has been the investigation of differences between these types of breccias and the development of a model of breccias formation.

Methods of Investigation and Date Reduction. Particle size analysis of the clasts was performed by a computerized Zeiss TGZ 3, by which the size of each particle is determined in thin section micrographs by an equal area method in the size range from 1.2 to 27.7 mm. The broad size range of the breccia particles required measurements at two different magnifications. The data of these two magnifications were combined by the TGZ-SUMM computer programm (Knöll, 1978). The results were again combined with the data of Wilshire and Jackson (1972) who determined the frequency of clasts greater than 1 mm of the breccias. The textural analysis of the matrix of the crystalline breccias has been performed by computer controlled line scannig with a «Zeiss Linearanalysator». Measurements and data reduction were made using the LA-phi program (Knöll, 1978) for a desk computer.

Electron microprobe analyses of clastic and matrix minerals and of the bulk matrix were carried out on ARL microprobes using various data reduction methods (Bence, Albee, 1968; Goldstein, Comella, 1969; Lidge, Gasparrini, 1969). The studies were carried out on polished thin sections or probe mounts of regolith breccia 14055, detrital breccia 14063, a dark crystalline breccia clast of rock 14306, and crystalline breccias 14006, 14066, 14311, 14320, and 14321 (microbreccia 3 according to Grieve e. a., 1975).

Fig. 1. Cumulative volume frequency curves of the lunar breccias (hatched area) compared with lunar soils and pyroclastic deposits.

Numbers refer to Apollo 14 samples. The grain size distribution of 14063 is extended to 12.5 phi (063 tot), whereas the grain size of the other breccias is restricted to grains greater than 4.75 phi. *1* — 0.63 tot; *2* — 141; *3* — 149; *4* — 259; *5* — base surge plane beds; *6* — base surge dunes; *7* — rhyolitic ash flow; *8* — basaltic fall out; *9* — suevit; *10* — glass bomb, Ries.



Textural Properties of the Breccias. Fig. 1 shows the grain size distribution (cumulative volume frequency curves) of the clastic fraction of lunar breccias compared with lunar soils (McKay e. a., 1972, terrestrial impact deposits from the Ries impact crater, FRG) and pyroclastic deposits (Sheridan, 1971). It is apparent that the clasts in the lunar breccias lie between the coarser grained suevite and the finer grained mature lunar soil 14259. The suevite results from a single impact whereas the lunar soil 14259 has a grain size distribution which was equilibrated by multiple impacts and which will not change by further impacts. This indicates, that the clast in the breccias have undergone several impacts, compared to the suevite, but have not reached the state of a mature lunar soil (Stöffler e. a., 1976). The comparison of the clasts with the immature 14141 and 14149 evidently indicates that it is impossible to produce the size distribution of a breccia by the annealing of lunar regolith as Warner (1972) proposed. The immature lunar soils have a much larger content of coarse grains which cannot be destroyed by annealing.

The grain size statistics of the breccias are different from those of any pyroclastic deposit. This indicates that the processes (shock comminution, melting, ballistic transportation) which form impactoclastic deposits are different from those forming pyroclastic sediments.

The textural analysis of the matrix of the crystalline breccias showed that there are up to three types of matrix within a breccia. The modal composition (fig. 2) of the matrices confirmed this fact. The matrix types differ mostly in the content of interstitial mesostasis. It amounts to 5—10% of the light matrix. The dark matrix has a higher pyroxene and olivine content. The grain size of the minerals in the light matrix is generally larger than those in the dark matrix. Additionally, the size of the matrix minerals has a bimodal distribution, which indicates an admixture of clasts to the matrix (fig. 3). Both matrix types differ also in the specific surface area and contact area of their mineral constituents. Whereas in the light matrix the contact area of mesostasis and plagioclase and of mesostasis and

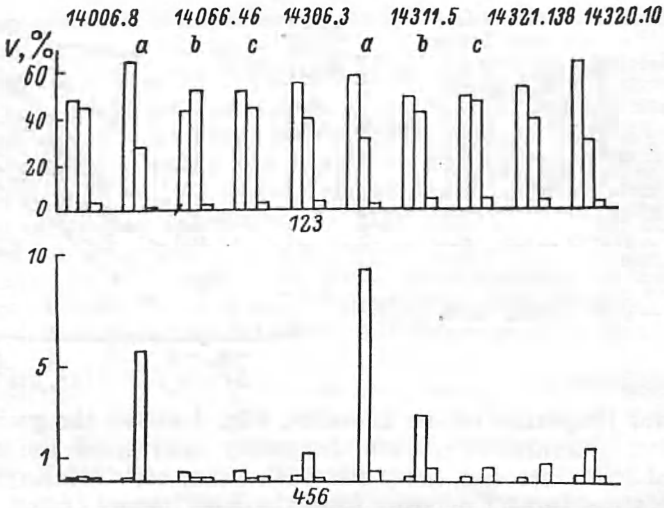


Fig. 2. Modal composition of the matrix of crystalline breccias.

a — light matrix; *b* — regular dark matrix; *c* — dark matrix with prismatic pyroxenes (14311) or lath-like ilmenites (14066); *1* — plagioclase; *2* — pyroxene+olivine; *3* — ilmenite; *4* — metal (Fe—Ni)+sulfide; *5* — mesostasis; *6* — zircon+spinel.

pyroxene+olivine dominates, in the dark matrix plagioclase — pyroxene+olivine contacts are prevailing.

Chemical Properties of the Breccias. One major question is the nature of those rocks of the pre-Imbrian lunar crust, which by fragmentation have contributed to the mineral and rock clast population of the Fra Mauro breccias. We have made an attempt to solve this problem by a statistical analysis of the chemical composition of the clasts embedded in lunar breccias. For this purpose 6072 chemical analyses of plagioclase, pyroxene and olivine of different rock types were taken from the literature (Stöffler, Knöll, 1977). These analyses were then classed into the following rock groups which are the potential sources of the mineral clasts of the lunar breccias: mare-basalts (MB), KREEP- and high-alumina-basalts (HAB), anorthositic-noritic-troctolitic rocks (ANT).

The dunitic and peridotitic rocks are another possible source rock group of the breccias, but there are not enough analyses in the literature to warrant a separate statistical group. Because the concentrations of the major and minor elements in minerals depend in their chemical environment during crystallisation, these differences were used to distinguish the provenance of the minerals. Multiple correlation analyses showed that the following correlations of elements are the best for the provenance analyses of the mineral clasts in the breccias:

plagioclases: FeO—anorthite-content,
olivines: CaO—forsterite-content,

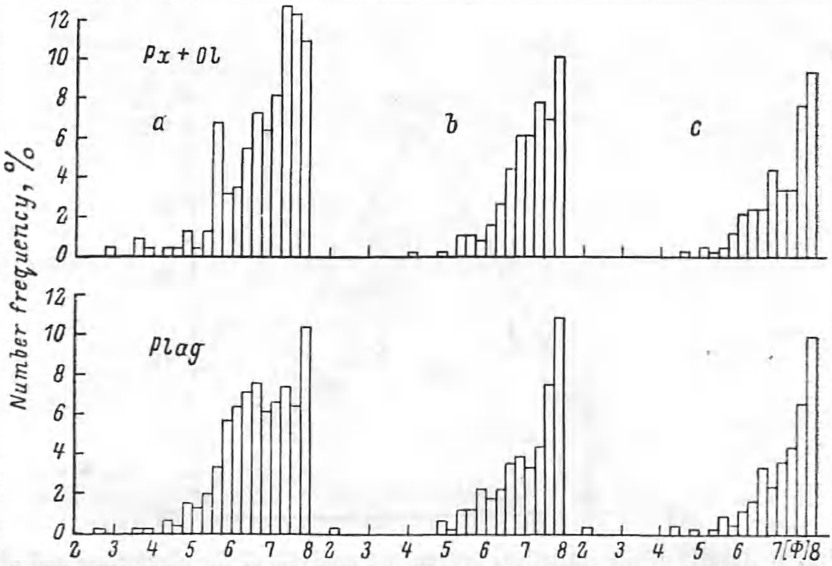


Fig. 3. Grain size distribution of matrix minerals of breccia 14311 determined by line scanning.

Further explanation see fig. 2.

pyroxenes: $CaO-TiO_2$ and enstatite—ferrosilite—wollastonite-content.

The statistical analyses of the clast provenances were performed using the computer program PIOS (Knöll, 1978) based on techniques described by Stöffler and Knöll (1977). These calculations showed that there are variations in the clast provenance which vary from breccia to breccia as well as from mineral to mineral. This latter variation is not surprising considering that the minerals included in the calculations occur in different proportions in their source rocks. However, there remain open questions in the interpretation of the data (Stöffler, Knöll, 1977). The olivines are predominantly derived from ANT-rocks — and from an unknown component X (fig. 4), which most probably represent the dunitic component (very low CaO-content; compare Steel, Smith, 1975). The plagioclase clasts have a greater variation of source rocks. Some breccias have a rather low HAB-content combined with a surprisingly high MB-content, whereas other breccias are enriched in the ANT-component with a higher HAB-content (fig. 4). The pyroxene clasts (fig. 5) are derived from three main rock types with rather similar HAB-content. They are very variable in their ANT- and MB-content. The proportions of these three types of source rocks vary also to some degree if different element correlations are used for the provenance

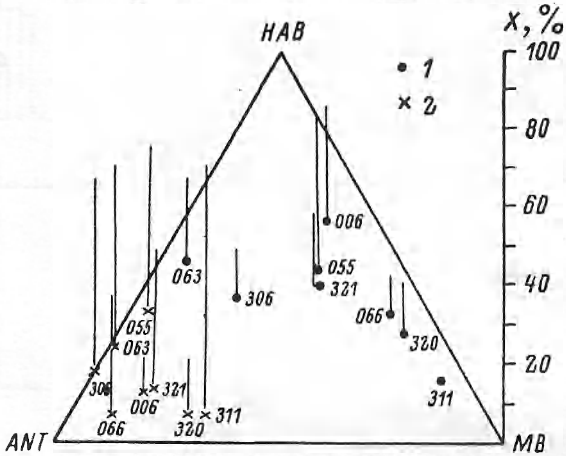


Fig. 4. Results of the statistical provenance analysis of the plagioclase and olivine clasts in lunar breccias.

Bars indicate the content of unknown component X; numbers refer to Apollo 14 samples; ANT, HAB, MB — see text; *1* — plagioclase; *2* — olivine.

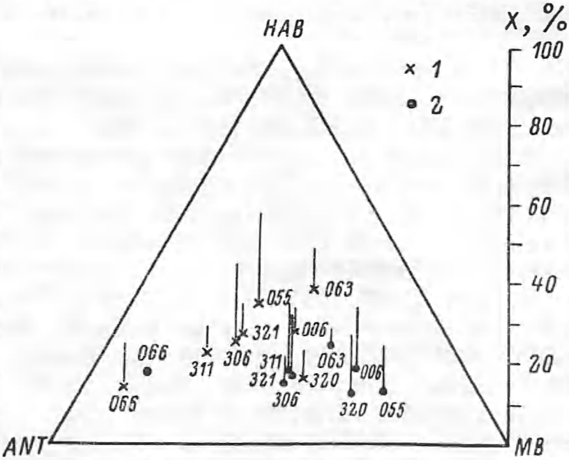


Fig. 5. Results of the statistical provenance analysis of the pyroxene clasts in lunar breccias.

1 — $CaO—TiO_2$; *2* — Fs—En—Wo.

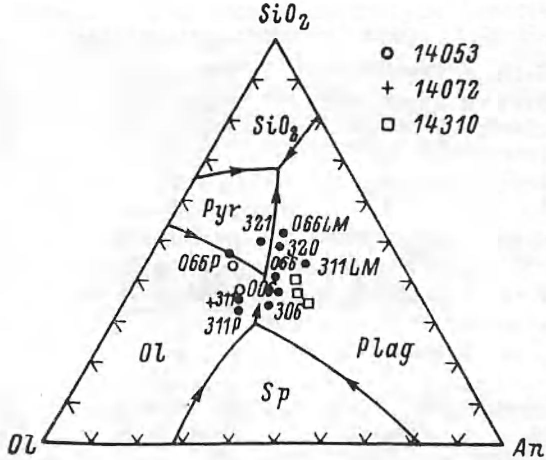


Fig. 6. Bulk chemical analyses of the matrix of Apollo 14 and of large rocks with basaltic texture in the pseudo-ternary system olivine—anorthite—silica.

Numbers refer to Apollo 14 samples; *LM* — light matrix, *P* — dark matrix with prismatic pyroxene or lath-like ilmenite, other — regular dark matrix.

analysis. From this difference estimates of the error involved in the provenance analysis can be obtained.

The bulk chemical analyses of the matrix of the crystalline breccias were made by the microprobe using the defocussed beam method. These analyses were recalculated to the pseudo-ternary system olivine—anorthite—silica (described by Walker e. a., 1972). This system is shown in fig. 6. This figure includes analyses of Fra Mauro melt rocks with basaltic texture for comparison with the matrices of the breccias. It can be seen clearly in fig. 6 that the light matrices represent a plagioclase-enriched KREEP-basalt melt, whereas the dark matrix of 14311 resembles an olivine enriched high alumina basalt melt. It can also be seen in fig. 6 that minor chemical changes of the melt can produce different rock textures resulting from different crystallisation sequences.

The composition of the matrix minerals is very variable which indicates that fragments contribute to the mineral population down to grain sizes of 1 u. Scanning electron microscopy confirms this assumption as well as the grain size statistics of the matrix (fig. 3). Pigeonitic pyroxenes and anorthite-rich plagioclase are enriched in the light matrices and low-Ca-pyroxenes in the dark matrices.

Conclusions. The date of the breccias of the Fra Mauro formation presented in this paper indicate a multistage formation. The fact that the mineral fragments embedded in the breccias are derived from several rock types makes it very likely that they are the product of several impacts. This is confirmed by the grain size statistics of the clasts, which indicates that the clastic fraction of the

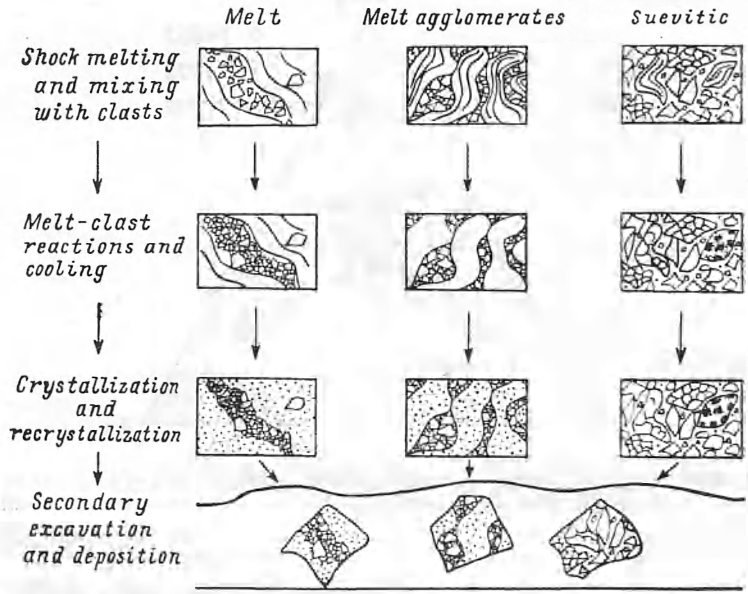


Fig. 7. Model of breccia formation of crystalline and detrital breccias.

The analyses of KREEP-basalt 14310 are taken from Kushiro e. a. (1972), LSPET (1971), and Longhi e. a. (1972). The analyses of high alumina basalts 14053 and 14072 are taken from Walker e. e. (1972), Lenghi e. a. (1972), Bence and Papike (1972).

breccias are formed by many impacts, but have not reached the state of a mature soil. From lunar orbital data it is well known that KREEP material is enriched in the Fra Mauro formation and in adjacent old pre-Imbrian terrane. Because there is an appreciable amount of KREEP within the breccias of the Fra Mauro formation, it can be concluded that this material is local and was mixed with the Imbrian and pre-Imbrian ejecta. The existence of mare basalt derived minerals indicates a pre-Imbrian magmatic activity of the mare basalt type. This confirms the suggestion of Ryder and Taylor (1976) who postulate the existence of pre-Imbrian volcanism of the mare-basalt type. The data discussed above and a comparison of the lunar breccias with terrestrial impact formations lead to the following model of breccia formation.

a) Generation of impact melts in one or more local pre-Imbrian craters and mixing of melt with more or less shocked clasts during the excavation phase with starting temperatures of at least 1700 °C. This leads to a series of breccia types which varies from coherent impact melt rocks to suevitic detrital breccias (fig. 7). The cold clastic material is enriched in schlieren-like bodies by flotation effects and forms the parent of the light matrix of a first breccia type. In another breccia type there appears to be an intimate mixture of impact detritus with individual pockets of melt, which is the parent of the light and dark matrix of a second breccia type. Breccias 14006 and 14311 are close to the first type; 14066, 14306 (dark breccia host), 14320 and 14321 (microbreccia 3) are transitional to the second type; 14063 and possibly 14306 represent the third, suevitic type.

b) First crystallisation of the melt in the clast-rich areas (light matrix) at high temperatures with clasts acting as nucleaaction centers. This forms a relatively coarse grained texture with pigeonitic pyroxenes and anorthite-rich plagioclases.

c) Subsequent crystallisation of melt in the clast-poor areas (dark matrix) at lower temperatures (supercooled liquid) with formation of a large number of nuclei. This forms a mosaic-like texture with low-Ca-pyroxenes. The further varaiations of the chemical composition of the dark matrix are the result of different degrees of clasts melting. The breccia material now resides in a more or less thick impact formation with slow cooling from temperatures of at least 600° C, as indicated by the preservation of highly silicous glass (Stöffler e. a., 1978).

d) Fragmentation, ejection, and incorporation of this impact formation into the Fra Mauro formation by secondary projectiles of the Imbrium impact according to the model Oberbeck (1975).

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МИНЕРАЛЫ ЛУННОГО ГРУНТА, ДОСТАВЛЕННЫЕ АВТОМАТИЧЕСКОЙ СТАНЦИЕЙ «ЛУНА-24»

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MINERALS OF LUNAR SOIL BROUGHT BY «LUNAR-24» AUTOMATIC STATION

The fine fraction (0.20—0.37 mm) of two Luna 24 soil samples from the depth of 92 and 184 cm has been studied. Microgabbro fragments prevail amongst the regolith rocks. The widespread rock-forming pyroxenes, plagioclases, olivines were investigated as well as the following less common minerals: SiO_2 minerals, potassium feldspar, ilmenite, chromite, ulvöspinel, chrommagnetite and magnetite, troilite, pyrrhotite, cubanite (?), schreibersite, kamacite, oldhamite. In vacuoles of glasses are revealed sylvine and halite. Observations on magnetite, pyrrhotite, sylvite and halite are new in the lunar mineralogy. The investigated material gives evidence of having been formed in endogenous magmatic and impact processes.

Проведено исследование мелкой фракции (0.20—0.37 мм) двух проб лунного грунта АЛС-24, взятых с глубины 92 и 184 см. Изучались широко распространенные породообразующие минералы пироксены, плагиоклазы, оливины, а также более редкие — минералы кремнезема, калишпат, амфибол, ильменит, хромит, ульвёшпинель, хроммагнетит и магнетит, троилит, пирротин, кубанит (?) шрейберзит, камасит и ольдгамит. В микровакуолях стекол обнаружены сильвин и галит. Данные по магнетиту, пирротину сильвину и галиту являются новыми для лунной минералогии