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Lunar Highland Stratigraphy and Radiometric Dating

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Lunar highland stratigraphy and radiometric dating

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Radiometric age data for lunar highland rocks do not in any simple way reflect the time of excavation of the major circular basins from which they are believed to originate. Instead, many rocks are of a more local origin and, in addition, radiometric clocks are not necessarily reset at the occasion of the basin forming impact. The concept of thick hot ejecta blankets far away from the basin cannot be maintained. Arguments supporting this (small) 'crater dominated chronology' are summarized.

Introduction

One essential for the reconstruction of the Moon's evolution is the knowledge of the succession of the various endogenic and exogenic processes in time. One way to obtain such information is to estimate relative ages of lunar features by conventional stratigraphy, but this cannot resolve time-dependent fluctuations in the intensity of lunar processes.

The study of meteoroid impact crater densities on the various lunar surface areas can yield age differences of lunar events, but problems remain such as the proper recognition of primary craters and their distinction from secondaries or the detection of subsequent erasure of pre-existing craters.

'Absolute' time for lunar rocks and hopefully for the events which caused their formation and deposition can only be measured radiometrically. Radiometric ages can serve for calibration of the relative time sequence of lunar events as obtained by the other methods and, more importantly, to make possible comparisons with geological time on Earth and eventually on other planets. The aim of this paper is a discussion of the relevance of highland rock ages to lunar highland- and basin stratigraphy.

Highland stratigraphy

The importance and significance of the large circular multi-ring mare basins for the genesis and modification of the highland crust was already recognized by Gilbert in 1893 who interpreted the radial features emerging from Mare Imbrium as being the result of a giant meteoroid impact on the lunar surface by which vast amounts of crustal material were excavated and laterally transported over large radial distances. The entity of this material deposited in the form of ejecta blankets is now called Fra Mauro Formation.

Similar, but much more detailed and sophisticated arguments by many authors led to the establishment of a stratigraphic system as basis for mapping the lunar nearside surface (Wilhelms & McCauley 1971) – which currently is extended to the farside – and polar regions.

For the lunar highland regions visited so far the relations between selenological formations

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and the presumably related basins are as follows: Fra Mauro Formation(A14)–Imbrium Basin; Apennine Mountains (A15)–Imbrium Basin; Descartes Mountains, Cayley Formation (A16)–Nectaris?, Imbrium?, Orientale Basin??, Massifs and Sculptured Hills (A17)–Serenitatis; Apollonius Mountains (L20)–Fecunditatis Basin?, Crisium Basin?

Judged simply from proximity of Apollo stations to basins it is without doubt that almost all material from the highland near the Apollo 15 site has been somehow involved in the Imbrium event, whereas the Apollo 17 materials derive almost exclusively from the Serenitatis Basin. For the other stations a more composite derivation is likely (McGetchin *et al.* 1973) and evidence is growing that the contribution of local material reworked by secondary projectiles from the basins at a landing site is large (Dence *et al.* 1974; Stöffler *et al.* 1974).

Lunar highland material although being igneous or metamorphic in origin has been deposited in the form of layered pyroclastic sediments. No highland bedrocks have been observed.

Highland breccias

Highland rocks are mechanically deformed or shocked rocks which in the case of polymict breccias comprise rock types of different provenance, petrological type and ages. They suffered from varying degrees of shock metamorphism or thermal metamorphism which apparently led very often to annihilation of primary textures or annealing of shock textures. All metamorphic grades are observed. For many breccias it is found that steep thermal gradients over distances of sometimes only millimetres have prevailed at some time in their history. In many cases in situ produced rock glass coexists with apparently unaffected rock. The intense bombardment of the lunar highland crust by meteoroids and planetesimals has physically destroyed the rocks from the early primitive crust and only few candidates are known which are presumably direct descendants therefrom (Taylor & Bence 1975).

Radiometric dating

At present about 150 age determinations have been carried out by various dating techniques on a total of about 100 different highland rocks. There exists also an appreciable number of individual rocks for which ages have been determined by more than one method (mostly ^{39}Ar-^{40}Ar and Rb-Sr-technique). Generally, the concordance between these ages is very good (Stettler *et al.* 1973; Tera *et al.* 1974; Turner 1975; Horn *et al.* 1975). The occurrence of trapped excess Argon as in olivines from troctolite 76535 (Huneke & Wasserburg 1975) must therefore be regarded as exceptional.

If an age – obtained by either method – is regarded as being reliable and meaningful by all available criteria it means that the time is measured at which the respective isotopic system became closed. For the water-free lunar rocks this apparently is the time when the rock or mineral has cooled below a critical temperature range. Cooling times are in general very short compared to the ages of the rocks; this implies that that event is dated which caused the rocks' formation or last significant thermal overprinting.

A complication arises from the fact that it is not very well understood what temperatures *and* times are required for totally degassing or re-equilibrating a rock or mineral. This is important insofar as at conditions of shock metamorphism very high temperatures prevail only for seconds, minutes or hours, since the heat is rapidly dissipated to the admixed cold material.

In this respect, lunar metamorphic conditions (at least at or near the surface) are rather different from the circumstances of terrestrial metamorphism. In fact, there exist many lunar rocks for which petrological evidence indicates high temperatures, but nevertheless, the age record from the time before is not completely annihilated (e.g. breccias 79155 and 77017, Kirsten & Horn (1975); and figure 1; 14321, Mark *et al.* (1975); 65015, Jessberger *et al.* (1974); 72435, Papanastassiou & Wasserburg (1975); 77115, Stettler *et al.* (1975); 73215, Jessberger *et al.* (1976). Similar observations were made at terrestrial impact craters (Köfels/Austria, Lippolt (1969, private communication); Brent/Ontario, Hartung *et al.* (1971)).

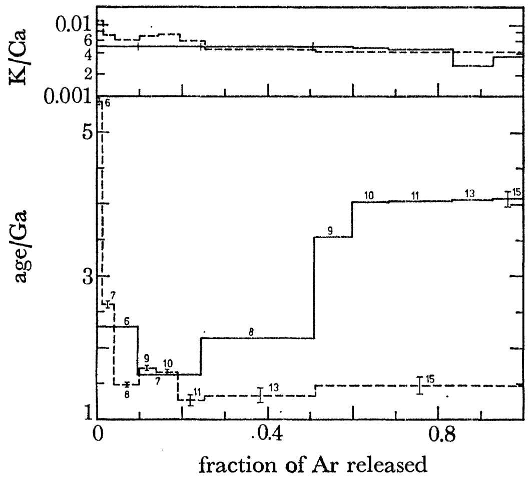

FIGURE 1

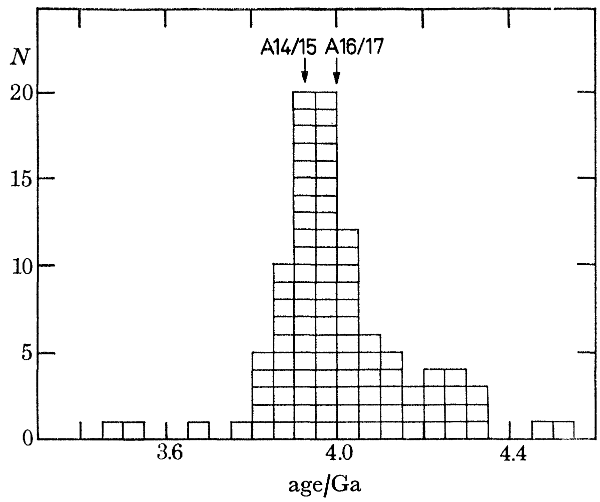

FIGURE 2

FIGURE 1. ^{39}Ar-^{40}Ar release patterns and apparent K/Ca ratios for anorthositic breccia 77017,32 A (—), and for a black glass vein penetrating the breccia (77017,32 B) (– – –). Although the glass indicates high temperature of formation, the host material was only partially affected. (Cf. Kirsten & Horn 1975.)

FIGURE 2. Histogram of radiometric lunar highland rock ages.

INTERPRETATION OF HIGHLAND ROCK AGES

In figure 2 a histogram of the available highland rock and mineral ages is given. In this diagram no distinction is made between ages obtained for coarse fine fragments and large rocks as it recently became quite clear that high ages (> 4.1 Ga) are not only found for coarse fines (Schaeffer & Husain 1973; Kirsten & Horn 1975), but also for a significant number of large rocks (Schaeffer & Husain 1974; Turner & Cadogan 1975; Papanastassiou & Wasserburg 1975; Stettler *et al.* 1975; Jessberger *et al.* 1976). There exists, however, a lack of Rb-Sr ages for the time between 4.0 and 4.5 Ga (Papanastassiou & Wasserburg 1975). In part this is due to the fact that coarse fines fragments are not very suitable for Rb-Sr mineral isochrone dating because of small sample weights. Also, many Rb-Sr ages in the 4.0 Ga range do not exclude ages above 4.1 Ga if the stated errors are taken into account. A further bias can result from the fact that the high ages are frequently found for plagioclase rich rocks, and these are difficult to date by the Rb-Sr method, since they have low Rb/Sr ratios. If the lack of high Rb-Sr ages should persist in the future, it would become increasingly difficult to understand why concordance between the two methods should be restricted to ages *below* 4.0 Ga.

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The high ages (> 4.05 Ga) displayed in figure 2 are exclusively obtained on A16 and 17 rocks (and one L20 sample), whereas the A14 ages are *all* below 4.05 Ga (of course there are also younger A16/17 rocks). The arrows in the histogram indicate the most frequent age values for the respective landing sites. It seems inadequate to us to calculate mean age values because it is more likely that the *quantity of similar* ages found for rocks from a given landing site (with a presumed common history) holds the key for the age of the subsurface, and not the diversity of ages. Mean ages would be 3.95 Ga (A14); 4.06 Ga (A16), and 4.19 Ga (A17); but an *a priori* acceptance of a diversity of ages at one landing site would rule out a common origin of rocks from one site as it is likely if a relation between basin formation and corresponding highland formation does exist at all.

The peaks of ages for Apollo 14/15 and Apollo 16/17 rocks are about 75 Ma apart, just at the border line of statistical significance. If, however, the ages of the respective formations and basins are hardly or not at all resolvable, we have two possibilities: (1) the presumed large impact events occurred at about the same time; (2) the ages do not straightforwardly reflect the time of basin forming impact events and the deposition of associated hot ejecta blankets. Rather, they reflect overall influx rates for small and medium sized meteoroids by which the highland surface has been cratered up to saturation.

In a recent paper, Turner (1975) has presented a well balanced summary of arguments for and against the 'basin dominated chronologies' or 'crater dominated chronologies'. Here, we want to summarize our arguments in favour of a crater dominated chronology (some of them were already given in Kirsten & Horn (1975)).

(*a*) The observed distribution of highland rock ages matches distributions which were calculated under the assumption that equilibration or outgassing of surface or near surface rocks depends on and is determined by the cratering rate (Hartung 1974; Turner & Cadogan 1975; Wetherill 1975). It is true that observed ages below 3.85 Ga are somewhat underrepresented, but this might well be due to a systematical sampling bias. Rocks with the indications of 'recent' shock effects tend to be considered as 'not suitable for dating purposes'.

(*b*) The coexistence of isotopically unequilibrated rocks or rocks with different ages within one and the same breccia (cited above) is incompatible with the assumption of thick hot ejecta blankets at the edge of the basins (A15/17) and even further away (A14/16). Locally hot, but rapidly cooling impactites can occur within medium sized or small craters or within their ejecta blankets.

(*c*) There is no systematical correspondence between certain petrological rock types and certain ages. For instance, anorthosites cover the age range from 3.5 to 4.2 Ga (e.g. 60025; 15415; 67075; 60015; Schaeffer & Husain 1974).

(*d*) Individual highland rocks have been assigned to the various circular basins on the basis of compositional peculiarities of the impacting bodies, that is, basin fingerprints in the form of an admixed meteoritic component (Morgan *et al.* 1974). There exists no correlation between this classification and the ages of the rocks. Ages of the rocks supposedly derived from one and the same basin scatter widely. Let us make some generalizations in order to interpret this observation. In figures 3*a*, *b* we have summarized how various measurable properties of lunar rocks respond to elevated temperatures.

Large scale morphology can survive high temperatures even beyond the melting temperatures of constituent rocks; the same is true for the refractory meteoritic component and Rb-Sr- and U-Pb whole rock isochrones. Contrary, Rb-Sr mineral isochrone ages and ^{39}Ar-^{40}Ar ages are affected at lower temperatures. Therefore, although a given meteoritic component might have been added to a breccia at the time of impact, the age may have been subsequently reset by heating or even melting without changing the meteoritic component fingerprint (rock age < basin age). On the other hand, the meteoritic components could have been admixed to a breccia without the implication that the age became affected in this process, which presumably was the excavation event (rock age > basin age) or possibly a smaller cratering event.

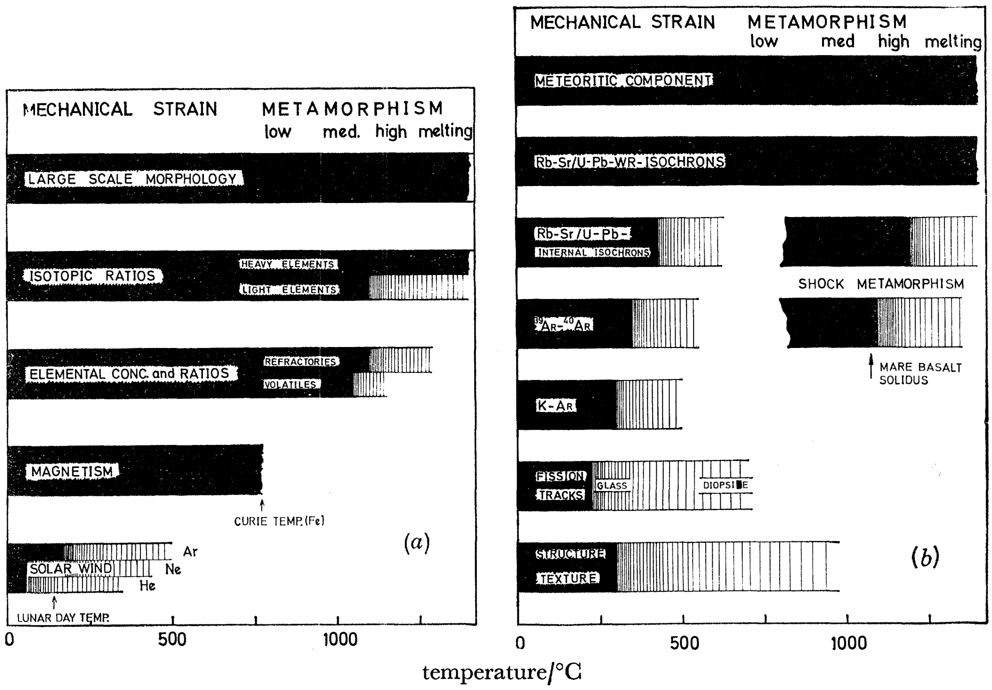

FIGURE 3 *a*, *b*. Various parameters frequently measured for lunar rocks and their response to elevated temperatures. Black areas represent thermal regimes where the respective parameter is not thermally affected. The bars labelled 'shock metamorphism' refer to very short times of thermal strain.

In view of the enumerated evidence the age of a single highland rock cannot be directly related to a basin age, even if the origin of the rock would be known. The difference for the mean ages of the various landing sites (A16/17 A14/15; figure 2) may reflect the preponderance at A16/17 of anorthositic lithologies, which are known to be more retentive than noritic or gabbroic lithologies. In addition, coarse fines and breccia clasts have been dated preferably from A16/17. Their chances to survive the multiple meteoroid impacts are higher than those of larger rocks.

Matrix from the suevite type breccias from A17 may be exceptional. These matrix substances of Apollo 17 boulders are most likely crystallized from basin derived melts. Their ages cluster around 4.00 ± 0.05 Ga. In this case the age may be ascribed to the excavation of Serenitatis basin (Kirsten *et al.* 1973; Turner & Cadogan 1975; Jessberger *et al.* 1976).

Conclusions

Lunar highland rock ages do in general reflect the high cratering rate beyond 4.3 Ga ago. Its rapid decrease afterwards enabled an increasing number of rocks to survive the bombardment. During the same period the large basin forming impacts occurred. The lower age limit

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for the large impacts is 3.78 ± 0.04 Ga. This follows from the well determined age of the subfloor basalt in the Taurus-Littrow Valley (Kirsten & Horn 1975; Turner & Cadogan 1975). This oldest mare surface postdates the youngest basin forming impact (Orientale) since no ejecta debris is found on it. The Serenitatis event very likely occurred 4.00 ± 0.05 Ga ago. The stratigraphic age sequence indicates that twelve large circular basins are younger than the Serenitatis Basin (Stuart-Alexander & Howard 1970; Hartmann & Wood 1971). The ages for these basins are then closely bracketed between 3.78 and 4.00 Ga.

As a further consequence the widely accepted assumption of thick hot ejecta blankets around Serenitatis Basin (and the other basins) has to be rejected; otherwise the common occurrence of unequilibrated old and very old clasts in the breccias cannot be understood.

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