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# Lunar Cratering

G. Neukum

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# Lunar cratering

By G. Neukum
*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*

The form of the lunar impact crater size-frequency distribution is discussed. Latest results on the lunar cratering chronology in the first 1.5 Ga after its formation are reviewed. It is shown that most cratering arguments speak against an extraordinary high flux increase ('cataclysm') at *ca.* 4 Ga ago. From age determination by crater frequency measurements, it is concluded that the dominant process of the formation of light (Cayley) plains is not deposition of basin ejecta but an endogenic one.

## 1. Introduction

The cratering history of the Moon in its early past would still be a guess without the Apollo missions to the Moon and the recovery of lunar rocks and superb photography of the lunar surface. Only the correlation of crater frequencies of the Apollo landing sites with the radiometric ages of the respective lunar rocks made a quantitative analysis possible. The work of Shoemaker (1970*a*), Baldwin (1971), Hartmann (1970, 1972); Bloch *et al.* (1971); Soderblom & Boyce (1972), Neukum *et al.* (1972) showed that the cratering rate decreased over several orders of magnitude during the first 1–1.5 Ga after the Moon's formation. Details of this decrease have recently been evaluated by Neukum *et al.* (1975*b*). Baldwin (1974) and Hartmann (1975) critically discussed the possibility of rapid fluctuations in cratering rate at 4 Ga ago ('cataclysm') which was suggested by the great number of highland rock ages scattering around this date (cf. Tera *et al.* 1974).

We want here to summarize the latest ideas on the lunar cratering chronology and point out some unresolved problems.

## 2. The lunar primary impact crater-size distribution

A basis for the interpretation of lunar crater frequency measurements is the knowledge of the primary production crater size-frequency distribution. A new study of production crater populations has been performed by Neukum *et al.* (1975*a*). The resulting crater size-frequency distribution curve is shown in figure 1 in comparison with distributions earlier reported in the literature (Shoemaker *et al.* 1970*b*; Baldwin 1971; Hartmann & Wood 1971). The new calibration distribution allows the comparison of crater frequencies in the size range 300 m $< D <$ 20 km and shows that the former laws $N \propto D^{\alpha}$ ($N$ = cumulative crater frequency, $D$ = crater diameter) with constant $\alpha$ do not completely represent the lunar primary impact crater production distribution. On the contrary $\alpha$ is a function of $D$. (For analytical representation of the distribution and numerical calculation purposes cf. Neukum *et al.* 1975*a*.) In figure 1, the calibration distribution is normalized to the Mare Serenitatis crater frequency ($N = 3.8 \times 10^{-3}\ \text{km}^{-2}$ for $D$ = 1 km).

The comparison of crater frequencies in different areas gives a means of dating individual lunar provinces. The application of the calibration distribution allows the comparison of crater frequencies obtained for differently sized craters. This is important because the size of craters to be measured in a certain area depends on the size of the area, its age and its erosional state. It is, for example, impossible to measure production frequencies for craters with $D < 0.8$ km in areas with formation ages $\gtrsim 4$ Ga. The measurement of large craters may in some cases be impossible because of the smallness of the area. An example for this case is the Apollo 17 landing site: Craters with diameters $> 1.3$ km do not exist in this small valley.

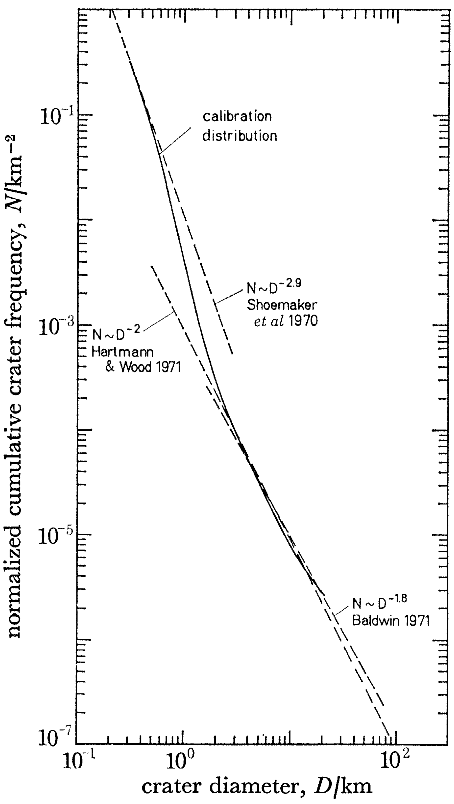



FIGURE 1. Primary lunar impact crater size-distribution (calibration distribution) normalized to the Mare Serenitatis light interior crater frequency ($N = 3.8 \times 10^{-3}$ km$^{-2}$ for $D = 1$ km).

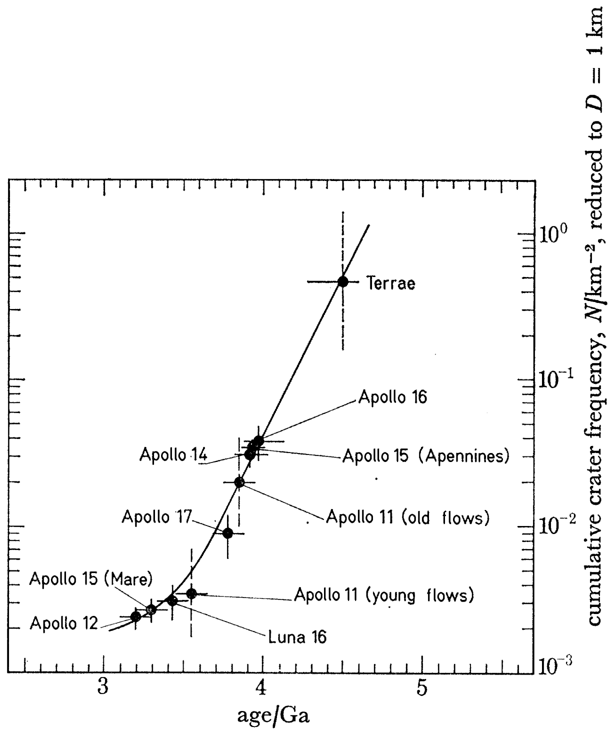



FIGURE 2. Relation between cumulative crater frequencies at the various Apollo and the Luna 16 landing sites and the radiometric ages of the respective rocks.

The calibration distribution is best defined in the diameter range $0.8 < D < 5$ km which is most important for age dating by crater frequency measurements. This is the size of craters present in most areas of interest. The high frequency of those craters usually leads to good statistics. The measurements can in most cases be interpreted safely because erosion processes can usually be neglected for this crater size and secondary cratering effects mostly are small.

Any lunar primary production crater population must show a distribution in accordance with the derived calibration curve. Otherwise, the populations have been modified by endogenic (e.g. lava flows) or exogenic (e.g. blanketing) processes.

## 3. Correlation between crater frequencies and ages

As already stated, the Apollo missions were most valuable for quantitative age determination by the method of crater frequency measurements. The correlation of the radiometric ages of the lunar rocks with the crater frequencies at the respective landing sites results in an empirical dependence of crater frequency on surface formation age. Most recent results for this dependency taken from Neukum *et al.* (1975*b*) and Neukum & König (1975) are displayed in figure 2. All measurements are reduced to $D = 1$ km through application of the calibration distribution. The crater frequency to age dependency is sufficiently well defined in the range 3.2 Ga $\leqslant t_A \leqslant$ 4 Ga thus allowing age determination by crater frequency measurements with an uncertainty of $\pm$50 Ma. The uncertainty for 4 Ga $< t_A <$ 4.5 Ga is great because of the great error limits in both crater frequency measurements and age determination (cf. Neukum & König 1975). This complex is discussed in further detail in §4 of this paper.

The cratering rate is approximately given by $\partial N/\partial t \propto N$. We see from figure 2 that the cratering rate decreased by more than one order of magnitude between 4 and 3 Ga ago.

## 4. Formation of large basins and light plains

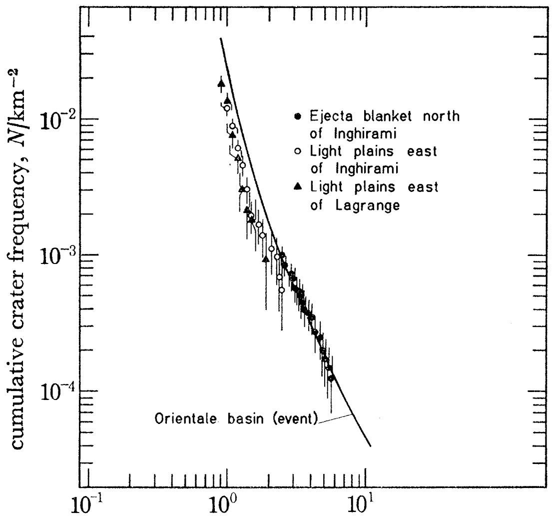
The great number of lunar highland rock ages around 4 Ga has been interpreted to be due to an extraordinary high impact rate ('cataclysm') at that time (cf. Tera & Wasserburg 1974). Tremendous metamorphic effects seemed to have reset the radiometric clock. The formation of lunar light plains (termed Cayley Plains on the front side) seemed to fit in this concept. Eggleton & Schaber (1972) deduced that these plains were formed by deposition of highly fluidized ejecta during basin excavation. Naturally, much of the material found on the lunar surface, especially in the light plains, should stem from this ejecta deposition and should show the time of basin formation due to resetting of the radiometric clocks. Soderblom's & Boyce's (1972) work on the ages (derived from cratering investigations) of Cayley Plains seemed to support these assumptions. Recently, however, the idea of a lunar 'cataclysm' has been criticized by Baldwin (1974) and Hartmann (1975). We support their argumentation (Neukum *et al.* 1975*b*) and want to add here some additional results on the formation of light plains and their genetic relation to large basins.

We have investigated the light plains in the vicinity of Orientale basin, Imbrium basin and Serenitatis basin in detail. Figure 3 displays crater frequency measurements in light plains in the vicinity of the Orientale basin. The Orientale basin 'event' curve is derived from measurements by Neukum *et al.* (1975*a*) in Orientale inter-ring areas and on the ejecta blanket and is identical with the calibration distribution. The measurement here on the ejecta blanket north of Inghirami in figure 3 agrees with it. However, all light plains in the vicinity, supposed to be genetically related to the formation of Orientale basin, are clearly younger than it, as shown by their lower crater frequencies.

We get analogous results for the light plains in the vicinity of the Imbrium basin (figure 4). The Imbrium basin 'event' curve is taken from Neukum *et al.* (1975*a*). The investigated light plains are not older than Imbrium basin but in some cases clearly younger. An extreme example is the light plains unit in crater Albategnius. This plain is far younger than the Orientale basin.

The Fra Mauro Formation interpreted as basin ejecta (cf. Eggleton & Schaber 1972) shows a frequency slightly lower than the Imbrium basin frequency but is compatible with it within the error limits of measurement.

Figure 5 shows frequency measurements in the Taurus–Littrow area of the Serenitatis basin. The Imbrium basin and Orientale basin 'event' frequencies are given for comparison. The frequencies measured on several light plains lie clearly below the Orientale event frequency. The all-crater measurements on the Serenitatis ring in this area display a peculiar behaviour:



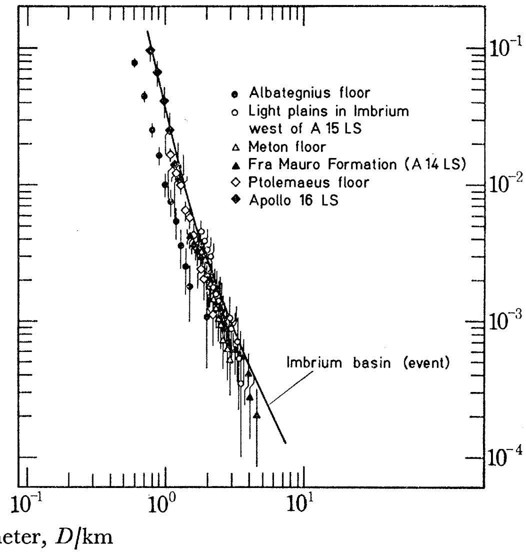




FIGURE 3. Cumulative crater frequencies at various light plains in the vicinity of Mare Orientale compared with the crater frequency determining the Orientale excavation event.

FIGURE 4. Cumulative crater frequencies at various light plains surrounding Mare Imbrium and on the Fra Mauro Formation in comparison with the Imbrium excavation event frequency.

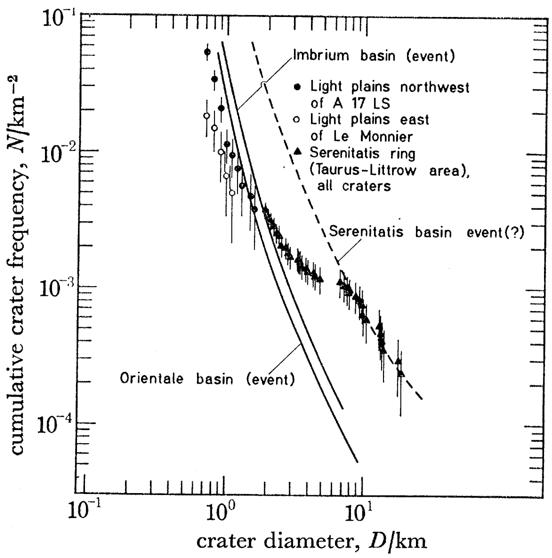



FIGURE 5. Cumulative crater frequencies for light plains in the Taurus–Littrow area compared with the Orientale and Imbrium event frequencies and with the all-crater frequency on the Serenitatis ring at this site.

The measured distribution deviates from the calibration distribution (dashed curve) at $D \approx$ 10 km, flattens between 10 and 3 km crater diameter and steepens again at $D < 3$ km seeming to approach the Imbrium basin 'event' frequency asymptotically. This result can be interpreted in the following way: lineations on the Serenitatis ring pointing towards the centre of Imbrium basin show that Imbrium ejecta have affected this region. They seem to have destroyed craters with $D < 10$ km. Larger craters survived. Today we seem to observe the sum of the pre-Imbrium crater population and the post-Imbrium cratering. If this interpretation is correct, then we should be able to determine the cratering rate at the time of the formation of the Serenitatis basin from the craters with $D > 10$ km, if radiometric age measurements of rocks are available dating the Serenitatis event.

Schaeffer (1975) has measured ages around 4.3 Ga for a certain number of Apollo 17 highland rocks. If these are the candidates we are looking for, the correlation of these ages with the crater frequency measured provides us with a point fitting well in the relation given in figure 2. It would fall only slightly above the curve. This result speaks in favour of a more continuous decrease in cratering rate in the time $4 < t_A < 4.5$ Ga and against a 'cataclysmic' upward fluctuation in cratering rate around 4 Ga ago. This result is further supported by the fact that we deal with craters with diameters roughly between 10 and 20 km. These are the sizes for which the size-distribution has been constant between *ca.* 3 and 4 Ga. One family of objects with relatively constant dynamical characteristics seems largely responsible for the production of measured craters of this size. It would, therefore, be implausible to assume that the impact rate of these objects would have changed so drastically in a very short time (order 100 Ma) around 4 Ga ago, so that the difference of about 1 order of magnitude of the observed Imbrium and Serenitatis event frequencies could have been produced.

The crater frequencies measured on the light plains and the fact that some did not form contemporaneous with either basin on the Moon but are younger than the youngest basin Orientale lead us to conclude that part of the light plains was formed by endogenic processes and not by exogenic ejecta deposition, a view also favoured before the Apollo 16 landing. We want to emphasize that the rocks sampled on a very small light plains area close to real mountainous highland regions should not be taken to be necessarily representative for the light plains and their formation in general.

## 5. Conclusions

The recent work of Baldwin (1974) and Hartmann (1975) and our own former results (Neukum *et al.* 1975*b*) and data presented here favour by far a relatively smooth continuous decay in cratering rate in the time $3 < t_A < 4.5$ Ga ago. A 'cataclysmic' event of an extraordinary high impact rate at $\approx 4$ Ga ago cannot be supported by these cratering investigations.

The question of the formation of light plains is not yet answered completely. An endogenic origin believed in before the Apollo 16 landing is the only conceivable process for some light plains being younger than the Orientale event. Other light plains like that at the Apollo 16 landing site may have really been formed by ejecta deposition. Probably, both processes acted. Judging from our measurements, we are inclined to believe that the dominant process seems the endogenic formation. Considering the crater frequency data which lie in most cases below the data for the respective basin excavation, it seems that the large basin-forming events triggered a series of endogenic activities in their vicinity which declined in the first 100–200 Ma after the events. The formation of the Imbrium basin seems to have played an extraordinary role because most of the light plains on the lunar front side have formed in the ≈ 200 Ma after this event.

An argument against this interpretation presented here could be that we do not see any igneous highland rocks but highly metamorphosed breccias. This argument, however, is meaningless because the overall high impact rate in the time > 3.8–4 Ga ago must have destroyed, metamorphosed and turned to breccias practically all igneous rocks in the upper several 100 m of the Moon.

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## References (Neukum)

Baldwin, R. B. 1971 *Icarus* **14**, 36–52.
Baldwin, R. B. 1974 *Icarus* **23**, 157–166.
Bloch, M. R., Fechtig, H., Gentner, W., Neukum, G. & Schneider, E. 1971 *Proc. Lunar Sci. Conf.* 2nd, **3**, 2639–2652.
Eggleton, R. E. & Schaber, G. G. 1972 *NASA SP*-315, 29–7.
Hartmann, W. K. 1970 *Icarus* **13**, 299–301.
Hartmann, W. K. 1972 *Astrophys. Space Sci.* **17**, 48–64.
Hartmann, W. K. 1975 *Icarus* **24**, 181–187.
Hartmann, W. K. & Wood, C. A. 1971 *The Moon* **3**, 3–78.
Neukum, G. & König, B. 1975 To be published in *The Moon.*
Neukum, G., König, B. & Arkani-Hamed, 1975*a* *The Moon* **12**, 201–229.
Neukum, G., König, B., Fechtig H. & Storzer, D. 1975*b* In *Proc. Lunar Sci. Conf.* 6*th.*
Neukum, G., Schneider, E., Mehl, A., Storzer, D., Wagner, G. A., Fechtig, H. & Bloch, M. R. 1972 *Proc. Lunar Sci. Conf.* 3rd, **3**, 2793–2810.
Schaeffer, O. A. 1977 *Phil. Trans. R. Soc. Lond.* A **285**, 137–143 (this volume).
Shoemaker, E. M. 1970*a* *Publicaciones Instititubo Investigaciones Geologicas* **24**, Universidad Barcelona.
Shoemaker, E. M., Batson, R. M., Bean, A. L., Conrad, C. Jr, Dahlem, D. H., Goddard, E. N., Hart, M. H., Larson, K. B., Schaber, G. G., Schleicher, D. L., Sutton, R. L., Swann, G. A. & Waters, A. C. 1970*b* *NASA SP*-235, 113–156.
Soderblom, L. A. & Boyce, J. M. 1972 Apollo 16 Preliminary Science Report, 29–3.
Tera, F., Papanastassiou, D. A. & Wasserburg, G. J. 1974 *Earth Planet. Sci. Lett.* **22**, 1–21.