A SEQUENCED LIST OF LUNAR IMPACT FEATURES LARGER THAN 200 KM

Charles J. Byrne, Image Again, charles.byrne@verizon.net.

Introduction: Very few absolute ages are available for lunar features, but more features have been positioned in time sequence using such clues as stratigraphy or degradation. While additional sample collection and analysis would provide more evidence of absolute ages, that is for some time in the future. We have a great deal of remote sensing data that can contribute to the assignment of the sequence of features. For some purposes, sequence can be used as a surrogate for age.

In order to relate sequence to time, it is important to sequence nearly all of a class of features in order to emulate the continuity of time. Otherwise, the sequence may have large gaps of uncertain duration. Therefore this sequenced list includes the impact features that are greater than 200 km in rim crest diameter. A total of 71 impact features are in this list. Features which may well be caused by impact but are too degraded for their apparent diameter and apparent depth to be measured are not included.

A wide class of information is used to allow age comparisons [Byrne 2015]. Specifically, it includes images, topography, radial profiles, crater counts, Bouguer maps and a set of parameters for location, diameter and depth. Parameters are measured from Radial Elevation Profiles based on Kaguya topographic data [Byrne 2013] and revised for this paper in the light of LRO data, recent literature, and discussions. The listed features include many of those included in traditional literature [Willhelms, 1987] as well as those identified by diverse researchers from later missions, especially the Lunar Reconnaissance Orbiter (LRO) and the Gravity Recovery and Interior Laboratory (GRAIL).

Assigning Sequence Numbers to the features requires a great deal of judgment, based on a careful but not rigorous comparison of images and topographic maps derived from an excellent online interactive mapping tool supported by Arizona State University [WMS LROC ASU 2013]. The images and topographic maps of the catalog are based on screen captures from this tool.

Two objective measures of sequence have been used in assigning Sequence Numbers: stratigraphic layers [Willhelms, 1987] and densities of small primary craters (>20 km diameter) superposed on the features [Fassett et al. 2012]. Where objective measures were lacking, judgment of the relative degrees of degradation was applied to interpolate between Sequence Numbers of features with objective measures. The result is a sequence that conforms to the stratigraphy data and also provides a smooth relation between the available densities of small superposed primary craters and Sequence Numbers.

Summary of sequence criteria: The principle criteria of relative age are:

1. Stratigraphic relationships [Willhelms, 1987]
2. Qualitative estimates of degradation of the feature's crater, peak ring, rim, and ejecta field
3. Superposed crater densities when available [Fassett et al. 2012].
4. Recently revised proposals for sequencing [Spudis, et al. 2011, Fassett et al. 2012]

Sequence Numbers of pre-Nectarian impact features: Table 1 shows the list of impact features that have been deemed to be older than the Nectaris Basin, along with their Sequence Numbers [Byrne 2015].

Table 1: Sequence of PreNectarian Impact Features

Feature	Age Group	Seq. No.
Near Side Megabasin	pN.1	1
Chaplygin-Mandel'shtam	pN.1	2
South Pole-Aitken	pN1	3
Marginis	pN2	4
Flamsteed-Billy	pN2	5
Fecunditatis	pN3	6
Jeans - Priestly	pN.3	7
Balmer-Kapteyn	pN.3	8
Cruger-Sirsalis	pN.3	9
Dirichlet - Jackson	pN.3	10
Coulomb - Sarton	pN.3 (pN5)	11
Kohlschutter-Leonov	pN.3	12
Schiller-Zuchius	pN.3 (pN7)	13
Smythii	pN.4 (pN5)	14
Amundsen-Ganswindt	pN4 (pN7)	15
Nubium	pN.4 (pN3)	16
Rupes Recta	pN.4	17
Deslandres	pN.4	18
Lorentz	pN.4 (pN6)	19
Fitzgerald - Jackson	pN.4	20
Poincare	pN4	21
Wegener-Winlock	pN.4	22
Orientale Southwest	pN.4	23
Topo-22	pN.4	24
Galois	pN.4	25
Schickard	pN.4	26
Fermi	pN.4	27
Ingenii	pN4	28
Gagarin	pN.5	29
Keeler West	pN.5	30
Birkhoff	pN.5 (pN7)	31
Harkhebi	pN.5	32
Janssen	pN.6	33
Campbell	pN.7	34
Serenitatis	pN.8 (N2e)	35
Freundlich-Sharanov	pN8	36
Grimaldi	pN.9	37
Landau	pN.9	38
Von Karman M	pN.9	39
Leibnitz	pN.9	40
Apollo	pN9	41
Milne	pN.9	42
Pasteur	pN.9	43
Nectaris	N1	44

The list of features in Table 1 includes many but not all of the pre-Nectarian features listed in [Wilhelms 1987]. New remote sensing data has brought the reality of several of those features into doubt. The age group concept was introduced in

[Wilhelms 1987] to distinguish between sets of features that were clearly different in age, based on data that was available at the time. Where the age group parameter is assigned here a decimal point is used. If the assignment of **[Wilhelms 1987] was** different, it is shown in parentheses.

New crater density data: Crater densities and limits have been measured from LRO data and reported in [Fassett et al. 2012]. Figure 1 presents a graph of crater densities (for superposed craters > 20 km in diameter) for two sets of assigned Sequence Numbers, one from this study (green) and one (black) for a subset of those features with normalized Sequence Numbers from [Fassett et al. 2012]. The crater densities and limits are also from [Fassett et al. 2012].

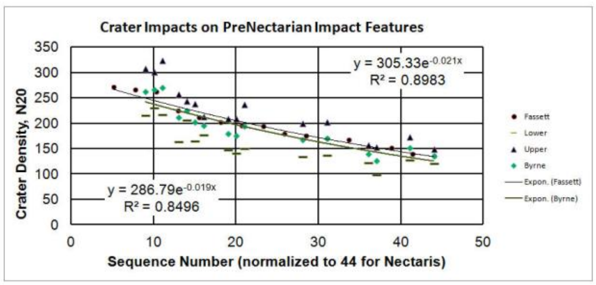

Figure 1: This graph compares the Sequence Numbers of [Fassett et al. 2011] with those of Table 1 for preNectarian features. Crater Density of superposed craters larger than 20 km are plotted for each sequence. Since there are fewer features in the Fassett sequence, those Sequence Numbers are normalized so that Nectaris is assigned Sequence Number 44 in each case. Error bars on crater density are from [Fassett et al. 2011].

As can be seen from Figure 1, the trend lines of sequences are very similar. Crater densities for two features, the South Pole-Aitken Basin and Serenitatis Basin were outliers (in both sequences), therefore these data points are not on the graph or included in the computation of the trend lines. The Sequence Numbers of [Fassett et al. 2012] were assigned rigorously to agree with the crater densities, with the result that the standard deviation from the trend line was only 7 while the average crater density standard deviation, considering the number of craters, would be 14. In this study, the large Sequence Numbers were set to honor large changes in crater counts only, with the result that the standard deviation from the trend line for this study was 16, which allows for deviations to be allocated to either crater density or, to a lesser extent, Sequence Numbers. The sequence presented here balances uncertainty in the crater densities with observed degradation factors.

Sequence Numbers for younger periods: Sequence Numbers have been assigned to features in the Nectarian, Early Imbrian, and Later Imbrian periods but they are not listed here because of space limitations. There are no craters in the Eratosthenian or Copernican periods greater than 200 km in diameter. Figure 2 graphs crater densities (as available) against Sequence Numbers of all the features assigned Sequence Numbers in this study.

In Figure 2, the trend line is complex, following the trend of Figure 1 for the preNectarian features, flattening for the Nectarian features and then dropping rapidly but smoothly. Remarkably, considering the complexity and range of the data, the trend line is simply a third order polynomial of the Sequence Number. This orderly behavior supports both the quality of the crater density data and the value of adding the large craters in the range of 200 km to 300 km and their Sequence Numbers to the database.

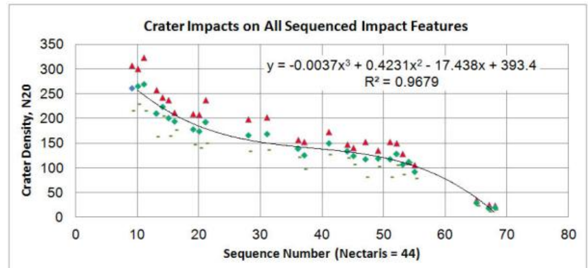

Figure 2: This shows the superposed crater density for the entire range of the impact features assigned Sequence Numbers here. Points are graphed only if crater densities are available from [Fassett et al.]. The red triangles are upper limits and the black dashes are lower limits from [Fassett et al. 2012].

The proposed sequence of the features in this catalog has implications about the history of lunar impacts, using the Sequence Number as a surrogate for time. It is understood that Sequence Number is not a linear function of time because the production rate of impactors is itself a function of time.

Additional crater density measurements: The crater density measurements of [Fassett et al. 2012] are very valuable. Additional measurements of craters in the 200 km to 300 km range would be very desirable.

References: **Byrne, C.J.,** The Moon's Near Side Megabasin and Far Side Bulge, Springer, 2013, DOI 101007/978-1-4614-6949-02013. **Byrne, C.J.,** The Moon's largest craters and basins: Images and topographic maps from LRO, GRAIL, and Kaguya, manuscript due to Springer, 2015. **Fassett, C.I.,** et al., Lunar Impact Basins: Stratigraphy, sequence and ages from superposed impact crater populations measured from Lunar Orbiter Laser Altimeter (LOLA) data, JGR, Vol. 117, 2012. **Mazarico, E.M.,** Personal communication, GRAIL 1 degree Bouguer data, 2014. **Neumann, G.A., Draft manuscript GRAIL Bouguer maps, 2013. Spudis, P.D., Wilhelms, D. E., and Robinsone, M. S.**, Sculptured Hills: Implications for the relative age of Serenitatis Basin chronologies and the cratering history of the Moon, LPSC 2011, Abstract 1365. **Wieczorek, M.A. et al.,** "The crust of the Moon as seen by GRAIL", Science, DOI: 10.1126, December 5, 2012. **Wilhelms, D.E.,** The geologic history of the Moon, USGS Professional Paper, 1348, U. S. Gov. Printing Office, 1987. **WMS LROC ASU,** Arizona State University, Web Mapping System of the Moon using lunar imagery from the Lunar Reconaissance Orbiter (LROC), http://wms.lroc.asu.edu/lroc, 2013.