9 History of the Moon

2,415 samples weighing a total of 382 kg (842 lbs) were returned from the Moon by the six Apollo missions. In this book we have investigated the story of only six of these samples, a mere 11.2 kg of material, an infinitesimal fraction of the total haul. These six stories are each a small piece of a larger work. This larger work is the history of the lunar surface.

Themes and Variations

When you take a look at a summary of the six samples (Table 9.1), two themes are readily apparent.

Sample	Mass [g]	Sample	Source	Radiogenic Age [billion yrs]
10022	95.6	Basalt	Mare Tranquillitatis	3.59
12033	450	Regolith	Copernicus Crater	0.80
14321	8,998	Impact Breccia	Imbrium Crater	3.87
15415	269.4	Anorthosite	Ancient Lunar Crust	4.15
67015	1194	Impact Breccia	Nectaris Crater	3.92
72535	221.4	Impact Melt	Serenitatis(??) Crater	3.89

Table 9.1: Summary of the six samples in this book.

The first apparent theme is their radiogenic age: the samples are ancient. Five of the six samples are older than 3.5 billion years old, older than >99.9% of the Earth's surface. The history of the Moon is the history of an ancient surface. Most of the significant change of the lunar surface happened a long time ago, long before the current crust of the Earth was formed. The history of the first billion years of the solar system cannot be found on the Earth; those surfaces are long gone. If you want to know what happened in the first billion years of our solar system, you have to look to the Moon.

The second theme is that the energy that created the samples came predominately from impact processes. The history of the lunar surface is mainly a story of objects raining down on the Moon and modifying its surface. Volcanism played a very minor role in the global history of the lunar surface. The mare surfaces may cover a large part of the lunar near side, but the mare are a relatively recent, thin veneer of material over an extensive, impact-modified ancient surface.

Putting these two themes together, we can surmise that the history of the early solar system is a history of impacts. It is a history that is shared by all of the surfaces in the inner solar system.

Not all of the events witnessed by the samples are ancient. From the exposure age of three of the samples, (Table 9.2), scientists were able to determine that three small, local impacts events happened relatively recently. These events are important since they demonstrate that impacts are still modifying the surface of the Moon.

Sample	Exposure Source	Exposure Age [billion yrs]
14321	Cone Crater	0.025
67015	North Ray Crater	0.047
72535	Tycho Crater	0.096

Table 9.2: Age of recent craters from samples' exposure ages.

In Situ

At the very beginning of this book, I said that one of the most important characteristics of the Apollo samples is that they have a **Context**. In the chapter that followed, we saw that establishing the context of the samples is not a simple problem.

The specific context (the collection site) of the sample is usually easy. Most of the Apollo samples were documented on the surface of the Moon. Some were documented in great detail, some by just a single photograph. There is little controversy about where the samples were collected.

The tricky part is to relate a sample to a particular geological unit. Sometimes this is pretty straightforward. There is little controversy that sample `10022` represents a piece of Mare Tranquillitatis or that `14321` is a piece of the Fra Mauro formation and was created by the Imbrium impact event. The connection of the ropy glass in `12033` with the Copernicus impact event is pretty solid, but there is certainly room for other interpretations. The connection between `67015` and the Nectaris impact is fraught with controversy. So, too, is the connection between the impact melt `72535` and the the Serenitatis impact event. We have no idea where `15415` began its life or even if the measured radiogenic age really represents when it formed.

I believe that the story of the context of our six samples is representative of the entire collection of Apollo samples. Many samples have strong connections to specific geological units with well-defined histories. Some samples may have a good connection to a unit, but the history of that unit may be problematic. And some samples have weak connections to geological units whose histories are a mess or completely unknown.

From Local to Global

The story the Apollo samples tell covers an area far larger than the area explored by the Apollo missions. Scientists can relate well-known local samples with global features. The Apollo lunar samples can give us insight into the stories of places far away from where the samples were collected.

Way back in Chapter 3, we saw that the relative age of overlapping surfaces can be determined by using stratigraphy. (Young features overlie older features.) The samples allowed us to turn those relative ages into absolute ages. The samples *calibrated* the local stratigraphy.

Throughout this book, I have talked about the importance of determining the age of certain events. Some events, like the formation of the Imbrium impact basin, have left a signature across the surface of the Moon. Knowing the age of these far-reaching events allows us to determine the ages of surfaces all over the Moon, and to see how distant surfaces are related. When scientists determined the age of the Imbrium impact event by finding the formation age of sample 14321, the age of an important time maker was then known: it has been **calibrated**.

The Lunar Geological Time Scale

In Chapter 4, we were introduced to the lunar geological time scale as way to relate the ages of features across the Moon. The sample from that chapter, 12033, was instrumental in determining the age of the Copernicus Crater. Other samples we looked at played equally key roles in establishing important time markers in other eras (Figure 9.1).

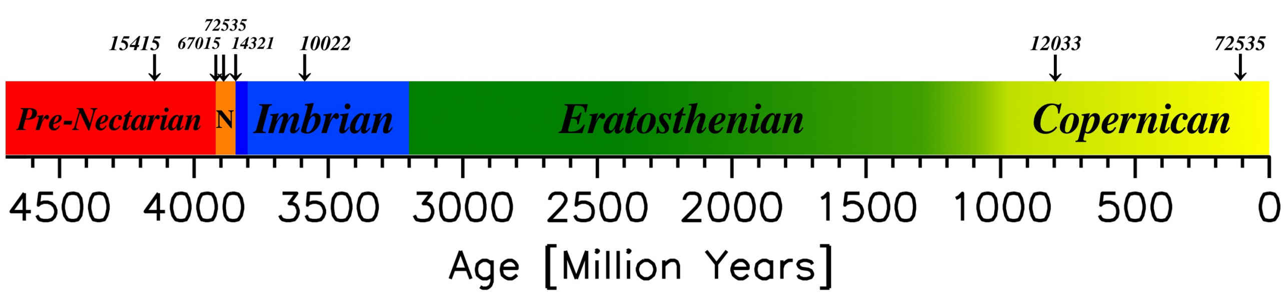

Figure 9.1: Lunar Geological Time Scale

With the lunar geological time scale calibrated, features across the surface of the Moon, including places not visited by the Apollo missions, can be placed into geological eras and constraints can be placed on their absolute ages. For example, Figure 9.2 shows the geological map of the region surrounding the Orientale impact basin, a feature on the very western edge of the lunar near side. This basin is the youngest and freshest of the large impact basins on the Moon. It is way outside of the Apollo landing zone of the Moon, so Apollo did not explore it. We do not have any samples from this region.[103] Even without samples, however, broad absolute ages can be determined for features in this region using the calibrated geological timescale. For example, in the very center of the basin sits a mare surface (red, labeled `EIm`) that scientists have assigned to the very end of the Imbrium Era or the beginning of the Eratosthenian Era. This means that this mare most likely has an age in the range of about 2.8 billion to 3.4 billion years. This is most likely a rather young mare surface.

[103] This may not be entirely true; some have argued that the Apollo 16 samples contain material ejected from the Orientale Basin.

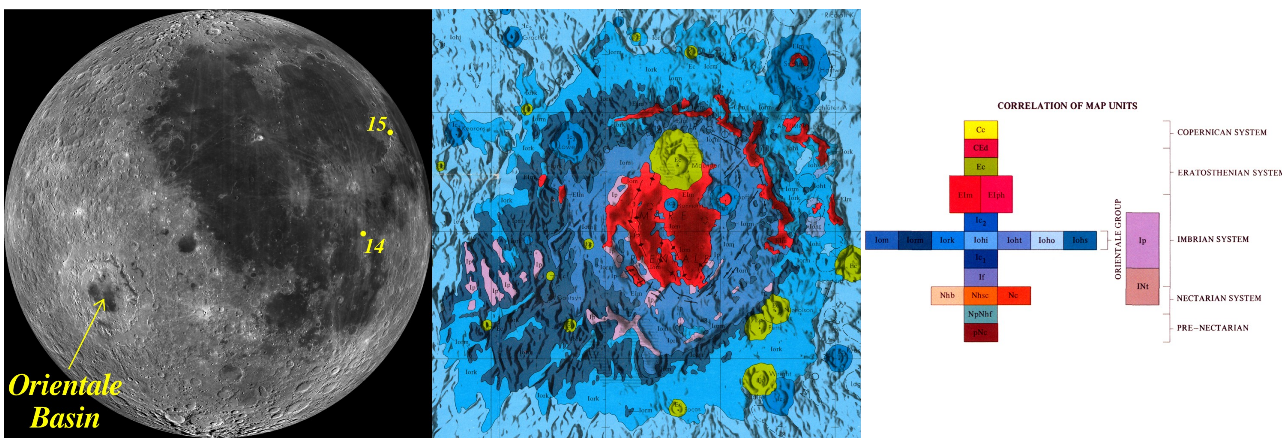

Figure 9.2: The Orientale impact basin. (Left) The location of the Orientale impact basin on the western edge of the near side. The landing sites of Apollo 14 and 15 are shown for reference. LRO mosaic [NASA/GSFC/Arizona State University]. (Center) A detail of the geological map of the center of the Orientale impact basin (Scott et al., 1977). (Right) The key for the geological map, indicating the geological eras.

The ages of features determined using the lunar geological time line can be very approximate, particularly in the Copernican and Eratosthenian Eras. There is a far more accurate method available, a method, like the geological time scale, that was calibrated by the Apollo samples.

Crater Counting

A glance at the Moon's surface shows that the number of impact craters is not uniform. The younger surfaces have far fewer impact craters than the older surfaces (Figure 9.3). The number of craters in a given area of lunar surface (number of craters per square kilometer) is called the *crater density*. The relative ages of surfaces can be established by comparing the crater densities: the surfaces with more craters are older.

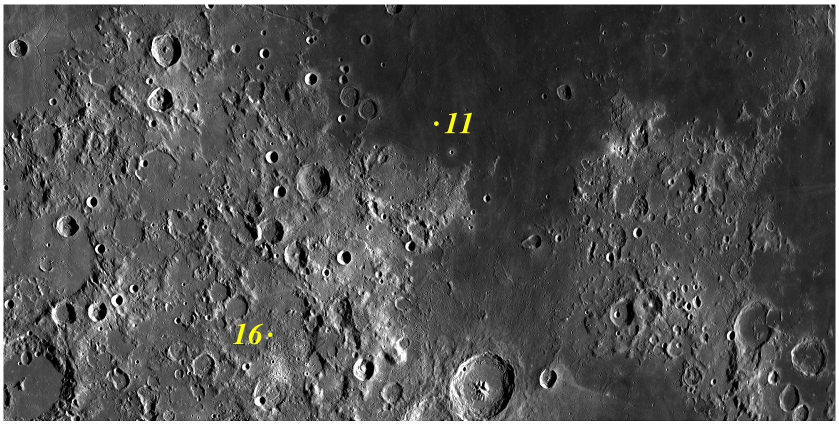

Figure 9.3: The equatorial region of the lunar near side, illustrating the contrast in crater densities between the younger mare landing site of Apollo 11 and the older highlands site of Apollo 16. LRO near side mosaic [NASA/GSFC/Arizona State University].

This technique is very powerful, since it allows us to compare surfaces that are far apart, even if the surfaces have no common features that would allow us to determine their stratigraphic relation. Many mare surfaces on the near side are isolated and do not overlap other mare surfaces, making stratigraphic relations hard to determine. In such cases, we can use crater densities to determine their relative ages.

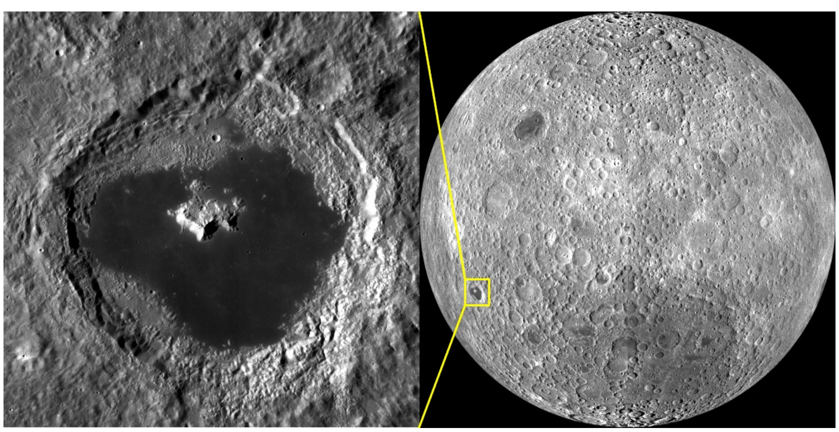

Figure 9.4: Tsiolkovsky impact crater on the lunar far side. LRO mosaic [NASA/GSFC/Arizona State University].

An extreme example is the case of the mare in the Tsiolkovskiy impact crater on the far side of the Moon (Figure 9.4).[104] The Tsiolkovskiy crater location means that there is absolutely no

[104] The Tsiolkovskiy crater mare was Jack Schmidt's favorite candidate landing site for Apollo 17. The very complicated logistics of a far side site, including the need for a communication satellite in lunar orbit, ruled it out early in the selection process (see Chapter 7 of Wilhelms (1993)).

physical overlap with any near side mare surfaces, so comparing crater densities with near side mare surface is the only way to determine its relative age. Crater counts on the Tsiolkovskiy mare determined that it has a slightly higher crater density than the Imbrium mare at the Apollo 15 site, but not as high a crater density as Mare Tranquillitatis at the Apollo 11 site.[105] This result is important as it established that the mare on the far side formed in the same era as the mare on the near side. The formation of mare surfaces happened at about the same time all across the lunar surface.

[105] Tyrie (1988)

From Relative to Absolute Ages

There are many different ways to quantitatively represent the crater density of a surface. One of the most commonly used representations is called the *cumulative size-frequency distribution*. In this representation, we choose an area and count the total number of craters larger than a diameter D. In its simplest form, the cumulative size-frequency distribution of a surface can be reduced to a single number by choosing a specific diameter and a specific amount of surface area. This allows us to easily compare the crater densities between two surfaces by simply comparing two numbers.

One of the most commonly used values for cumulative size-frequency distributions are a 1 km for the crater diameter (D) and 1 km^2 for the area. The resulting number is usually represented as N(1), and is read as “the total number of craters that have a diameter equal to or greater than 1 km per square km.”

Table 9.3 lists the $N(1) \times 10^{-4}$ values for the lunar surfaces that our six samples came from.

Sample	Source	Age [billion yrs]	N(1)	Ref
10022	Mare Tranquillitatis	3.59	64 ± 20	NI94
12033	Copernicus Crater	0.80	6.68 ± 1	H12
14321	Imbrium Crater	3.87	370 ± 70	NI94
14321	Cone Crater	0.025	0.21 ± 0.05	NI94
15415	Ancient Lunar Crust	4.15	$3{,}600 \pm 1100$	NI94
67015	Descartes Formation (Nec?)	3.92	340 ± 70	NI94
67015	North Ray Crater	0.047	0.39 ± 0.17	H12
72535	Serenitatis Crater (Imb??)	3.89	100 ± 30	NI94
72535	Tycho Crater	0.096	0.6 ± 0.17	H12

Table 9.3: Cumulative crater densities of the surfaces sampled. References: NI94 (Neukum and Ivanov, 1994), H12 (Hiesinger et al., 2012).

The data in Table 9.3 is very powerful since it allows us to turn relative ages into absolute ages across the entire lunar surface. We can use the crater density measured on surfaces with well-established absolute ages (the Apollo landing sites) to calibrate crater densities across the surface of the entire Moon.

Figure 9.5 plots the values for the Age vs. N(1) from Table 9.3. The red line is a fit to the data from *all* of the lunar samples.[106] Finding the absolute age of a surface can now be reduced to finding the total number of craters larger than 1 km on the surface, dividing that number by the total area of the surface, and then using the fit in Figure 9.5 to find the absolute age.

[106] The six Apollo missions were not the only missions to return samples from known locations on the lunar surface. The Soviet Union landed three robot missions on the Moon (Luna 16,20, and 24) that returned samples from surfaces that were not visited by the Apollo missions. A nice summary of the Luna missions can be found on Wikipedia: http://en.wikipedia.org/wiki/Luna_programme.

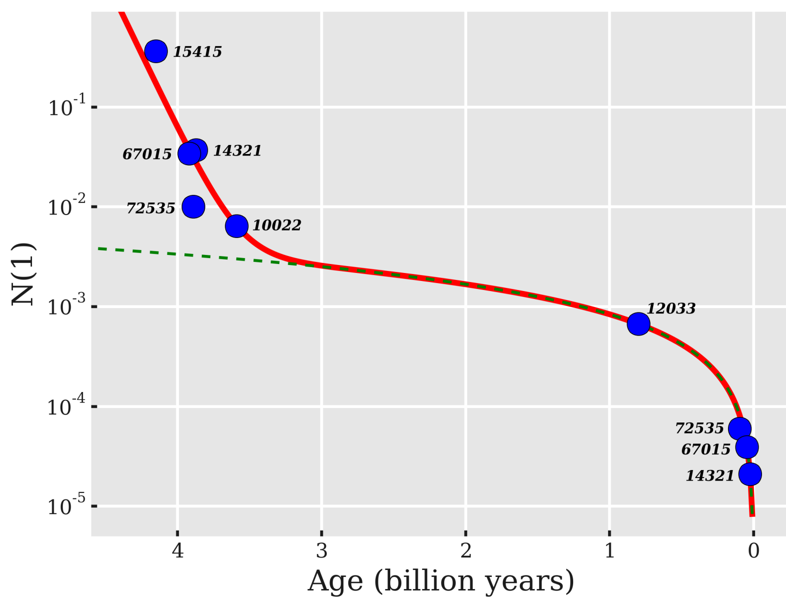

Figure 9.5: Lunar cratering chronology. A plot of Age vs. N(1) for the data in Table 9.3. The red line is a fit to all of the lunar sample data from Neukum et al. (2001) and the green dashed line is a fit for a constant cratering rate.

A concrete example: The relative age of the Tsiolkovskiy mare (Figure 9.4) was established by comparing its crater density to that of the Apollo landing sites. Since the crater densities have been calibrated, the absolute age of the Tsiolkovskiy mare can be estimated. Recent crater counts of the Tsiolkovskiy mare, using high-resolution data from the Lunar Reconnaissance Orbiter, have determined that the crater density [N(1)] is 33×10^{-4}.[107] Using Figure 9.5, we can see that this value of N(1) corresponds to an age of about 3.2 billion years. That is how old the Tsiolkovskiy mare is.

[107] Williams et al. (2013)

Cratering Rate

The data in Figure 9.5 reveals another very important part of the story of the lunar surface. The green dashed line in the plot is what you would expect the crater density to be if the rate of impactors hitting the Moon *today* were representative of the rate for the entire history of the lunar surface. The green dashed line fits pretty well for about the most recent 3 billion years of lunar history. This implies that the current rate of impactors hitting the Moon today has been pretty much the same over the last 3 billion years.

The story before that was much different. Prior to 3 billion years ago, the rate of impactors hitting the Moon was much higher than it is today. The first 1.5 billion years of lunar history was a time of an extremely high rate cratering. The initial anorthosite-rich crust of the Moon was subjected to a very high rate of impacts and this high rate continued as the last of the large impact basins were formed. The impactor rate started to lessen as the first mare surfaces started to form, and the impactor rate dropped to the current rate as the last of the mare surfaces cooled.

The calibrated crater densities of the lunar surface are the best data we have for how the cratering rate in the inner solar system has changed over time. This cratering history is shared by all surfaces in the inner solar system. This has some important implications for the Earth's earliest history. The earliest evidence of life on the surface of the Earth dates back to about 3.5 billion years ago.[108] Data from the Moon is our best evidence that the earliest life on the Earth had to survive and evolve on a surface that was subject to an intense rate of impacts.

108 Allwood et al. (2009)

Crater Population

A slightly different way to describe the crater density of a surface is to group the measured crater sizes into a number of discrete size bins. This technique essentially creates a histogram of the craters counted on a surface. This way of describing the crater density is called an *incremental size-frequency distribution*. This distribution makes it easy to see the relative number of craters of different sizes.

Figure 9.6 shows the incremental size-frequency distribution of the average crater densities of the highlands and mare on the lunar near side. Two facts are easily evident from the data:

1. The highlands have at least 10 times more craters at *every* size range than the mare do.

2. Small craters *greatly* outnumber larger craters on both surfaces. For example, on both surfaces there are about 100 times more 4-km craters than 40-km craters.

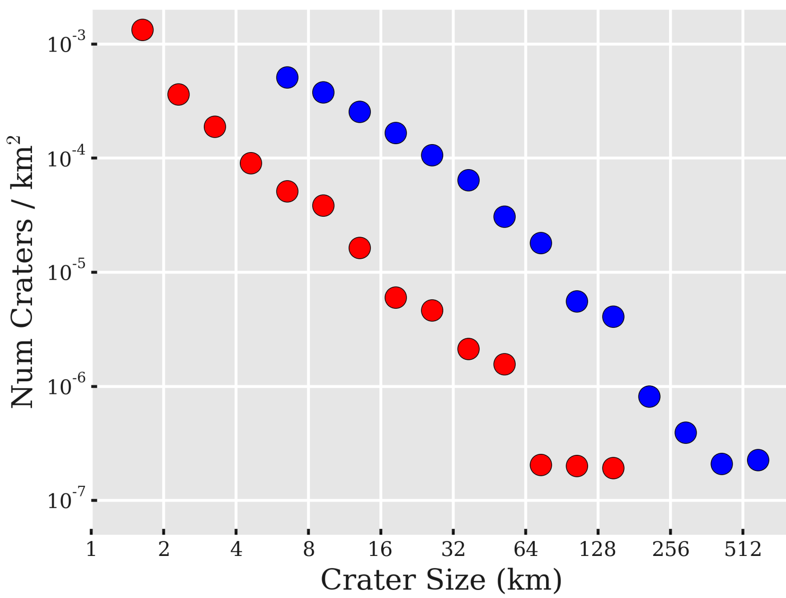

Figure 9.6: The crater densities of the lunar mare (red) and highlands (blue). The mare data is an average over the near side mare, and the highlands data is an average over the near side highlands. All data from chapter 8 of Basaltic Volcanism Study Project (1981).

The relative number of craters of different sizes on a surface is called the *crater population* of the surface. The crater populations of the mare and highland surfaces are dominated by small craters. In fact, the crater population of the mare and highlands look very similar. The straight-line fits to the data for the mare and highlands have a very similar slope (Figure 9.7). However, if you look closely at the data you can see that the difference between the data points and the straight line looks slightly different for mare data than it does for the highland data.

A final type of crater distribution makes these differences easier to see. Instead of plotting the number of craters at different sizes, you can plot the *difference* between the number of craters measured and the straight-line fit. This type of plot is called an *R Plot*. An R plot provides a useful interpretation: The value of a point in an R plot tells you the fraction of the surface area covered by craters of a particular diameter. For example, Figure 9.8 shows the R plots for the near side mare and highlands. The highlands are covered by mostly large craters, while the mare are covered by mostly small craters.

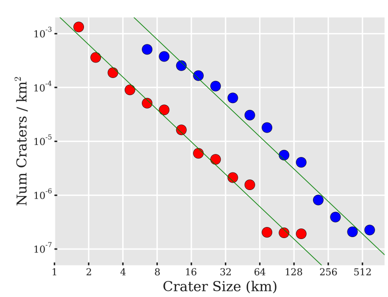

Figure 9.7: Same plot as Figure 9.6 but with a straight line fit to the data (green lines).

The R plots really emphasize the details of the crater population of a surface. The crater population of the highlands is different from the mare. The population of the impactors that

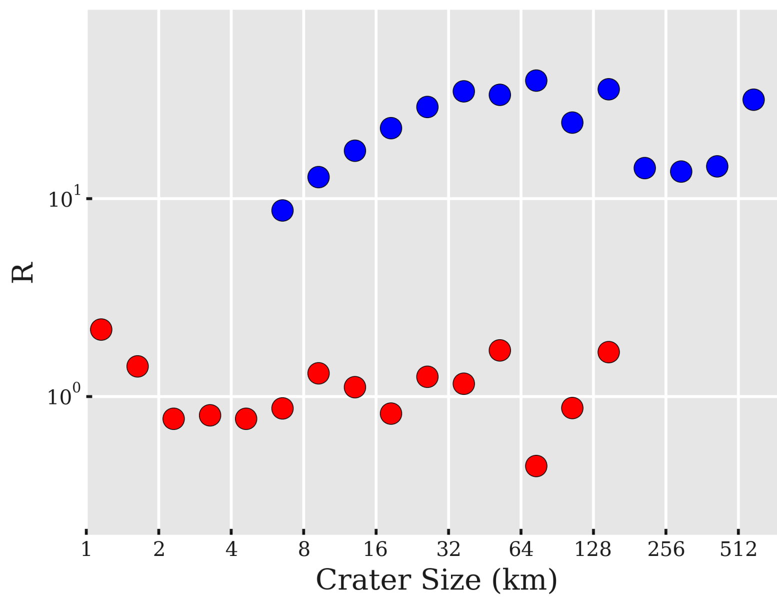

Figure 9.8: The R plot for the average near side mare (red) and highland surfaces (blue).

formed the craters on the highlands had a much higher proportion of large impactors than the population that formed the craters on the mare surfaces.

This difference is important because it tells us that the *population* of impactors changed over time. Early in the history of the solar system, the population of impactors was dominated by large objects. Over time, the population changed to the point (today) where small objects make up a much larger fraction of the impactor population.

Putting all three of our crater distributions together reveals a story of the evolution of the objects raining onto the surfaces in the inner solar system.[109] Very early in the solar system's history there was a very high rate of bombardment from a population with a large fraction of big impactors. As time went on, the rate of impacts decreased and the population changed to one made up of a larger fraction of small impactors.

[109] A detailed and very quantitative explanation of crater density distributions can be found in Chapter 10 of Melosh (1989).

The only data we have of the history and evolution of the impactor population in our solar system is the calibrated crater densities of the lunar surface.

Our story started with learning about specific samples at specific places on the Moon. This knowledge led to insight into the entire history of the solar system. *Ex Luna, Scientia*.