

Martian Crater Dating through Isochrons

Introduction

The universe is a vast and seemingly-endless array of space and matter that harbors many mysteries. Through advances in technology, scientists have been able to explore space and advance mankind's understanding of the world around us. Arguably the most studied object in the universe besides Earth is the planet Mars. The Mars Global Surveyor (MGS) is an orbiter that was launched in 1996 by N.A.S.A. and is designed to study the climate, atmosphere, topography, gravity, and other properties of Mars while also providing high resolution images of the surface. Unlike Earth, Mars has been largely geologically inactive for a few billion years, which is reflected in the abundance of craters on the surface. Although craters may seem like mere holes in the ground, they serve the important function of being able to help scientists date planetary surfaces through crater dating. This process involves counting the number of craters in an area and using this to approximate the age of the planetary surface. A large number of craters indicate an older surface while few craters suggest that the surface has been altered recently.

Crater dating is an important process for two main reasons. First, it allows scientists to be able to accurately date past stages of geologic activity on a planetary

surface. For example, if a surface is particularly saturated with craters and can be roughly dated, then it is possible to estimate the last eruption of a nearby volcano. As a result, scientists can determine if a planet is geologically active at all due to the presence of craters. Second, crater dating is a way to test various theories about the formation of the solar system as well as stages within those theories. The heavy bombardment is a period near the end of the formation of the solar system when large planetesimals slammed into the surfaces of planets and their moons. A surface that is extremely saturated with craters, which is the result of being unaltered since heavy bombardment, is evidence for the heavy bombardment stage of the widely accepted Nebular Theory. These theories can then be applied to other various solar systems in the universe. Due to crater dating, the local testing of theories can be applied to systems throughout the galaxy.

A convenient way to plot the measurements of craters is through the use of isochrons. An isochron is a plot of crater size vs. crater density for one particular age. Parallel curves are created when multiple ages are plotted. When plotting isochrons, the log of both the crater size and crater density is used to produce a straight isochron. The isochrons that I am using were derived by William K. Hartmann. Hartmann attempted to create more precise isochrons and created the ones he used in his testing based on data from the Moon. One fact about craters accepted by scientists is that smaller craters should be more abundant than larger ones. Therefore, an inverse relationship exists

between crater size and crater density. The main goal in my experiment of counting craters is to have my data lie on an isochron or between two isochrons, which would allow me to estimate the age it best represents. It is particularly difficult to have my data match up exactly to an isochron that is plotted or that can be estimated because of the small size of my sample. However, if by eye, my data is generally linear once it is plotted, then I am able to approximate the various ages of the surfaces I sampled.

Data

All of the data I used in my testing originates from the Malin Space Science Systems (MSSS), which extensively analyzed the data sent back by the MGS. The images referenced were taken by the Mars Orbital Camera (MOC) and then MSSS derived the various measurements applicable to the images, such as the length and width (in meters), pixel to meter conversion, and latitude and longitude of the image to name a few. These various derivations were placed into tables along with the images, which were given a name that I will reference. Particular information regarding MSSS and the MOC can be ascertained from the MSSS website at http://www.msss.com/moc_gallery/. The following is information listing the crater name and the applicable data used that was gathered from MSSS.

Crater Name	M03-00005	R02-00837	M01-00392	R10-04230	M12-00992	M07-05058
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Longitude of image center	180.10° W	6.46°W	280.63° W	356.76° W	299.41° W	269.43° W
Latitude of image center	34.76°S	29.56°S	20.98°S	30.05°S	29.32°N	1.40°N
Scale pixel width (meters)	237.88	247.17	235.31	246.85	254.19	242.42
Scaled image width (kilometers)	176.34	119.88	253.18	119.73	123.27	117.38
Scaled image height (kilometers)	253.72	119.93	1014.96	118.82	117.07	118.84

Analysis

Measurement of Crater Sizes

The first step towards plotting my crater sizes involved physically counting and measuring the craters in the various images. Since I measured the craters by hand, the craters had to physically be large enough in order to ascertain a proper measurement.

Therefore, I had to create a limit as to how small the crater could be in order for my eyes to distinguish it properly. The smallest craters I decided to include in my data are around 3-4 pixels in size. I used a tool for measuring distances, in pixels, in an image editing program called GIMP (<http://www.gimp.org>). In order to be as accurate as possible, I

measured the diameter of the perceived long side of the crater and then the diameter of the angle perpendicular to the previous measurement. I then took the average of those two numbers.

Conversion to Kilometers

All of the measurements that were made were done in pixels. Therefore, I had to convert the various pixel sizes into kilometers before I plotted my data. As previously stated, MSSS provided all of the necessary conversion information so I simply had to use the scaled pixel width to convert all of my measurements. The scaled pixel width was in meters, which required me to convert the meters into kilometers and then multiply the average pixel size of each crater by the scaled pixel width in kilometers. For example, one crater in the image M03-00005 averaged 14 pixels in size with a scaled pixel width in meters of 237.88. Therefore, the calculation to convert the crater size into kilometers is simply $(14 * (237.88 / 1000))$, which is 24.72 kilometers.

Binning Method

The process of binning involves placing the craters into various categories based on their size. This is done in order to reduce the significance of each data point by mitigating the effects of an error in size measurement. I created eight different categories of crater sizes in kilometers as follows: a) $0.25 < 0.5$, b) $0.5 < 1$, c) $1 < 2$, d) $2 < 4$, e) $4 < 8$, f) $8 < 16$, g) $16 < 32$, h) $32 < 64$. Once each crater was placed into its respective bin, I

counted the number of craters corresponding to each bin and calculated the average size of the craters in that bin. The average size of the craters in each bin would be the number used in plotting each bin along with calculating the error of each point that was plotted.

Error Calculation

As with any experiment, there is a degree to which error is a possibility in explaining the results. In this case, there is a degree to which the number of craters counted for a particular surface as well as their sizes is incorrect. I chose to treat my data as a Poisson distribution in determining the error. A Poisson distribution assumes that the observances in any situation are largely random. Therefore, I applied Poisson's theory by assuming the number of craters in each bin was random within a particular area observed. Poisson derived the value for the error as the \sqrt{N} (where N is the number).

However, the average sizes in each bin only correspond to specific area. The error then is now $(\sqrt{N})/A$ (where A is the area). For each bin the crater density therefore becomes $N/A \pm (\sqrt{N})/A$. When the log of the entire equation is taken, the error is not symmetric so it results in an upper and lower limit. The upper limit then becomes the log $(N/A + (\sqrt{N})/A)$ and the lower limit is the log $(N/A - (\sqrt{N})/A)$. For example, in the image M03-00005, the bin for sizes of $1 < 2$ km has 11 craters. Therefore, the crater density is N/A , which equals $11/44740.98 \text{ km}^2$ or 0.00024586 per km^2 and the log of that is -3.60931 . The error of $(\sqrt{N})/A$ equals $(\sqrt{11})/44740.98 \text{ km}^2$ or $7.41\text{E-}05$ per km^2 . The

upper limit becomes $\log(0.00024586 + 7.41E-05) = -3.49486$ and the lower limit is the $\log(0.00024586 - 7.41E-05) = -3.76515$. In some cases where the number of craters in a bin was equal to one, when deriving the lower limit it would turn out that N/A and $(vN)/A$ were equal, which would produce an indeterminate result since the log of 0 is undefined. When this was the case, I made the lower limit equal to the upper limit in order to have an error to plot.

Isochron Plotting and Age Determination

M03-00005

The image M03-00005 is located at longitude 180.10°W and latitude 34.76°S. On a map of Mars, this puts it in the southern hemisphere and east of Terras Cimmeria. The corresponding image is figure 1 and the plot of crater density vs. the number of craters on the isochrons is figure 2. By analyzing the points on the plot, it becomes apparent that the middle points are parallel to an isochron, but not all of the points follow the expected relation. An occurrence in this image and many others were points that deviated from the general linear plot that resulted. These points are characteristic of both the under-representation and over-representation of certain craters. As I stated previously, it is generally the case that smaller craters should be more abundant than larger craters due to the fact that there were many more small objects than large ones in the solar system. However, this image has both an abnormally low crater density for the smallest bin and an

abnormally high crater density for the largest bin. This observance reflects a problem mentioned earlier about limiting factors in crater counting.

Since I performed crater measurements by hand, I had to set a minimum pixel limit so that I could properly see all sides of the crater and produce an accurate measurement. However, figure 1 has many small craters that I simply did not have the capacity to measure, and I also may have missed measuring some craters that were near my minimum pixel size threshold. These craters that were not counted resulted in the smallest bin being under-represented. In addition, there are several fairly large craters in the image, which is an over-representation for the large bins. As a result, the two outside plots on the graph are void due to their inaccuracy. The remaining three points can be used to estimate by eye a best fit line and the corresponding age measurement based on other isochrons. These points roughly fall in between the isochrons of 1 billion and 3 billion years old, which would make the age estimation around 2 billion years old, but the error on the smaller bin is significantly lower than the error on the larger bin. As a result, this point is weighted more heavily, and I arrive at an estimation corresponding to an age of about 1.5 billion years old. Since the image is in the southern hemisphere, it would be expected that the surface would be much older, which will be the case in the other images. However, there are explanations that can account for this unusually young age.

The possibility exists that craters in the image have been destroyed. By analyzing

the features in the image, it can be determined if this is a likelihood. In the upper right hand corner of figure 1, a white streak is observed to run from a large crater. This streak could be outflow in the form of a dried up river channel or a cliff. These types of features distort or even destroy craters. In addition, a few craters in the image seem shallow and appear to be covered in dust. These craters could simply have been covered up by the large amounts of dust that gets strewn about Mars. As a result, smaller craters would be the first to be erased, which further emphasizes the under-representation of small craters.

R02-00837

At a location of longitude 6.46°W and latitude 29.56°S , the image R02-0083 lies in the southern hemisphere of Mars and slightly northeast of Argyre Planitia. The image and crater density vs. the number of craters plot on the isochrons is figures 3 and 4 respectively. Similar to the case in the previous image, there is both an under-representation of the smallest bin and over-representation of the larger bin. However, in this image the second largest bin is also over-represented, which makes it void as well. In addition, there are many small craters that were below my required pixel size and several large craters, which explain this problem. Please see the previous section for an explanation of this occurrence. Therefore, the remaining four points can be used to estimate the approximate age. These points all hover around an isochron corresponding to an age of roughly 3.2 billion years with minimal error in two of the four points. Since

the image is in the southern hemisphere, this age seems appropriate. Throughout figure 3 there appears to be cliff or mountain-like structures, and these could possibly have destroyed several small craters. Impacts that occur on these structures can be severely distorted and destroyed quicker than if they had hit on a flat surface.

M01-00392

The image M01-00392 is located in the southern hemisphere at a longitude of 280.63°W and latitude of 20.98°S and northeast of Hellas Planitia. Figures 5 and 6 represent the image and the plot of crater density vs. the number of craters on the isochrones respectively. Figure 5 demonstrates that there is an under-representation of the two smaller bins. The remaining points seem to coincide generally on a line so an argument can be made that the two smaller points would also fit that line if those bins were not under-represented. However, only the smallest bin is void in this instance since it deviates extremely from the other points. This image is the most difficult to estimate an age for since the points with the smallest error do not seem to line up. In this case it is best to not only use points with the smallest error but to also visualize where the relevant points should be since they are more scattered than in other images. The four larger bins in the image generally fall on a line corresponding to 3.5 billion years, and the smaller point on the line of 3 billion years is under-represented and would most likely correspond to that age as well if it had more craters in that bin. As a result, I arrive at an age

estimation of approximately 3.5 billion years. This age seems appropriate due to the image being located in the southern hemisphere. In figure 4, many of the craters appear to be shallow, and it is possible that dust has largely filled in these craters and even completely erased smaller ones.

R10-04230

At longitude 356.76°W and latitude 30.05°S, the image R10-04230 is north of Noachis Terra in the southern hemisphere of Mars. Figure 7 is the image and figure 8 is the plot of crater density vs. the number of craters on isochrons. As figure 8 demonstrates, there is once again an under-representation of the smaller bin. The remaining four points generally fall in the same region. However, the smallest bin included has a much smaller error than the larger bin, which results in it being weighted heavier. As a result, I chose an age estimation corresponding to 3.2 billion years. This age seems appropriate for its location.

The presence of wind in this image is essential in understanding the large under-representation that was in the smallest bin. In figure 7, there are white streaks extending out the right side of many craters. This is indicative of the fact that the presence of dust due to the wind could possibly have destroyed small craters. In addition, there are a large number of shallow craters. Dust seems to have filled in these craters, and even some of the smallest craters are becoming difficult to discern in the image.

M12-00992

The image M12-00992 is located at longitude 299.41°W and latitude 29.32°N. It is northeast of Isidis Planitia in the northern hemisphere of Mars. The corresponding image is figure 9 and the plot of crater density vs. the number of craters on isochrons is figure 10. In this image, there is a slight under-representation of the smaller bin, and a large over-representation of the larger bin. When looking at figure 9, it is apparent that there are many large craters and very few small craters, which distorts the representation of the bins when plotted. There are so many large craters in this image that the large bin actually passes the saturation line. However, this bin is so over-represented, and since it is impossible for a point to pass the saturation line in theory, the larger bin is void in this case. The three remaining points hover around a line corresponding to 3.4 billion years, which is the age I have chosen. This age seems old based on the fact that this image lies in the northern hemisphere. Although, figures 1 and 2 prove it is not unlikely for an image's age to not reflect the general knowledge about that terrain.

When looking at figure 9, several striking features are present that help explain the unexpected old age of that particular area. There appears to be a series of large craters in a row. One explanation is that a rather large object hit this area on Mars and actually broke up into several different pieces that resulted in chain impacts. These large impacts would have erased many craters that were in the area. In addition, a large crack

runs though almost the entire image, which could represent a cliff or mountain. This crack could have also erased small craters from this image. As a whole, this image is rare anomaly in the sense that there is an extreme over-representation of large craters, which even passed the established saturation line.

M07-05058

The image M07-05058 is located at longitude 269.43°W and latitude 1.40°N. It is in the northern hemisphere of Mars and south of Syrtis Major Planitia. The corresponding image is figure 11 and the plot of crater density vs. the number of craters on isochrons is figure 12. Figure 12 demonstrates that both the smallest and largest bin are void due to under-representation and over-representation. The remaining three points largely deviate from a line, which makes it difficult to attribute them to a particular isochron. Therefore, it is appropriate to set a minimum age for this image since the data does not enable me to be more precise. The smallest of the three bins has a minor error compared to the rest of the data and is located at about 3.2 billion years old. However, the remaining two points are much closer between 3.6 billion years and 4 billion years. As a result, I am estimating the age of this surface to be at least 3.3 billion years old. The fact that two of the three bins represent a much older age than the third elevates the minimum age from 3.2 billion years to about 3.3 billion years. This age seems young since the image is located in the northern hemisphere. However, it is not too far from the

equator, which does not allow me to be as definitive with my assessment of the age being young since the differences in the terrains between the hemispheres is speculative at the equator.

Figure 11 is similar to figure 9 in that there are several large craters and a crack that runs through a large portion of the image. The high number of large craters explains the over-representation of the largest bin that crosses the saturation line. The crack in the image has probably erased several of the smaller craters, which attributes to the under-representation of the smaller craters.

Improvements for Future

After performing my research involving the dating of planetary surfaces based on crater counting, there are two main factors I have determined that should be considered in order to improve the results in future replications of this nature. In almost every image, I had some combination of the under-representation or over-representation of my small and large bins. As a result, I had to eliminate two data points in some cases from my age assessment. It is critical to choose images that have a large amount of craters so that the some of the results are not invalidated. Initially, I simply picked images because they were aesthetically pleasing, which often meant images with several large craters and was unaware as to how important small craters were. On this same note, I feel it is important to have a computer program actually measure the sizes of craters. A computer program is

much more accurate than measuring with a distance tool in a program similar to GIMP, especially in regards to craters that approached my size threshold. It is possible that I incorrectly measured many of the small craters because it was difficult for my eye to discern them properly. Even in regards to large craters, it was often hard to tell where the biggest diameters appeared to be due to the chaotic terrain in the images.

Conclusion

Although my experiment with crater counting had a few limiting factors, it was generally successful. I was able to plot the various bins and estimate the ages based on the isochrons that Hartmann derived because the points that I had generally coincided on or near a line. In the cases where my data was not as accurate, there were details within the images that allowed me to hypothesize the lack of particular sizes of craters in the images. It is definitely possible to replicate Hartmann's work, which is a testament to the validity of his isochrons. As crater counting becomes a more technical means of estimating the ages of planetary surfaces, its accuracy can only increase, and it will continue to provide insight about the mysteries that exist in our galaxy.

Appendix

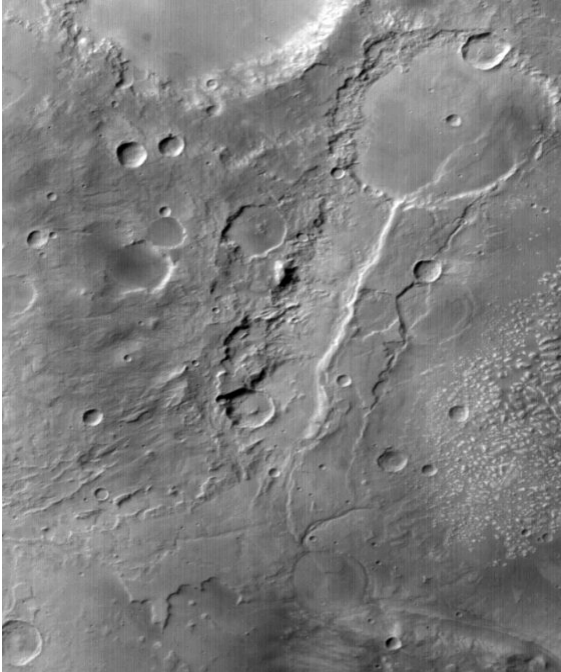


Figure 1

Age: 1.5 billion years

Figure 2

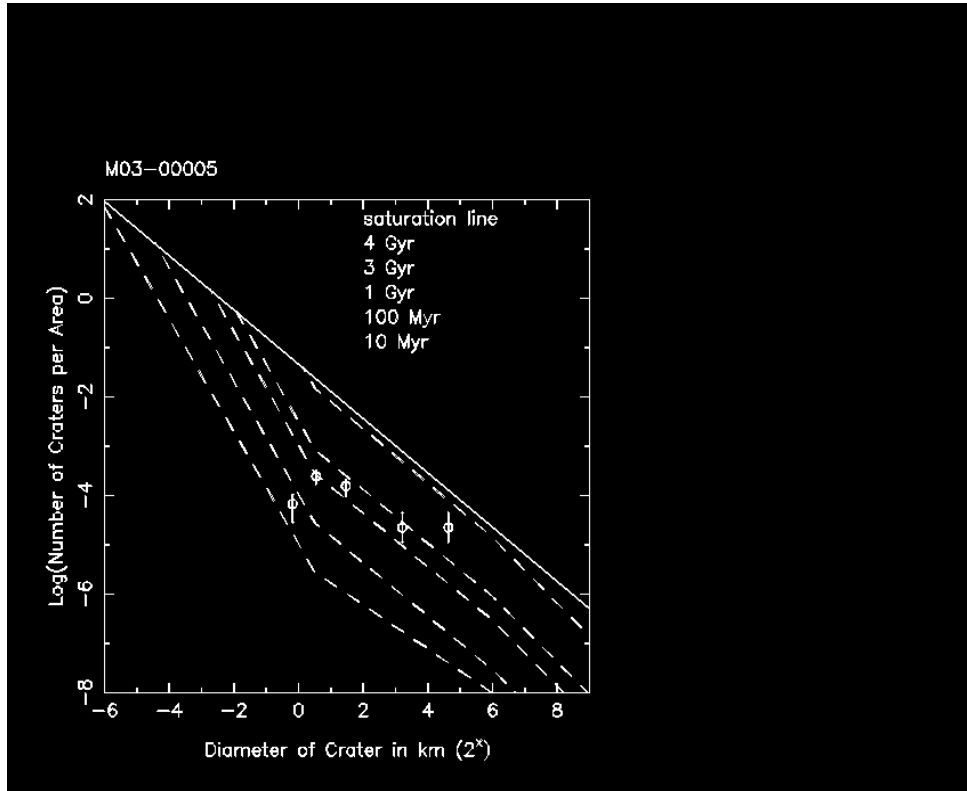
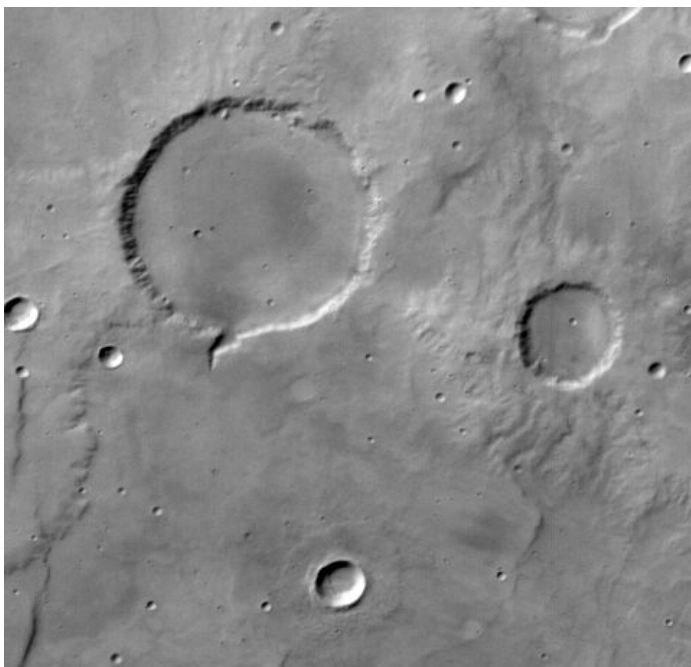


Figure 3



Age: 3.2 billion years

Figure 4

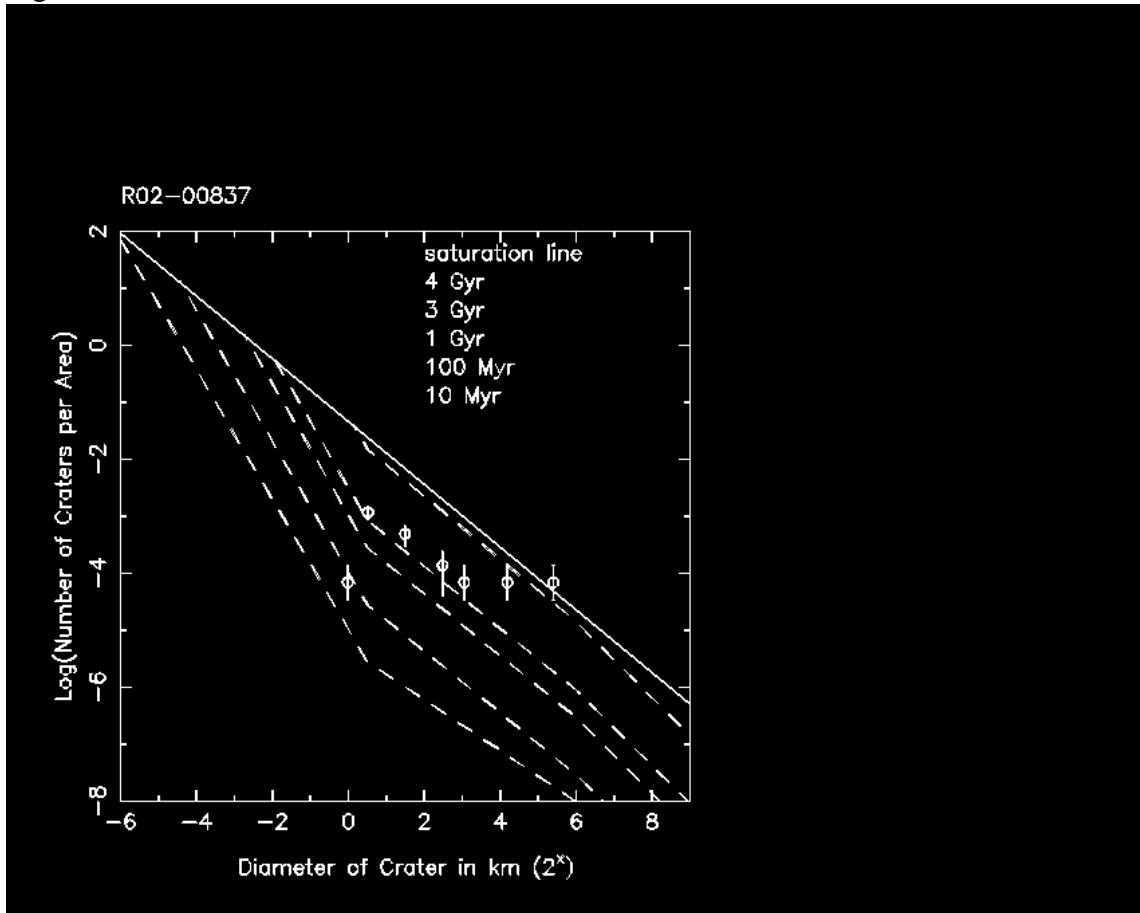


Figure 5



Age: 3.5 billion years

Figure 6

(missing figure)

Figure 7



Age: 3.2 billion years

Figure 8

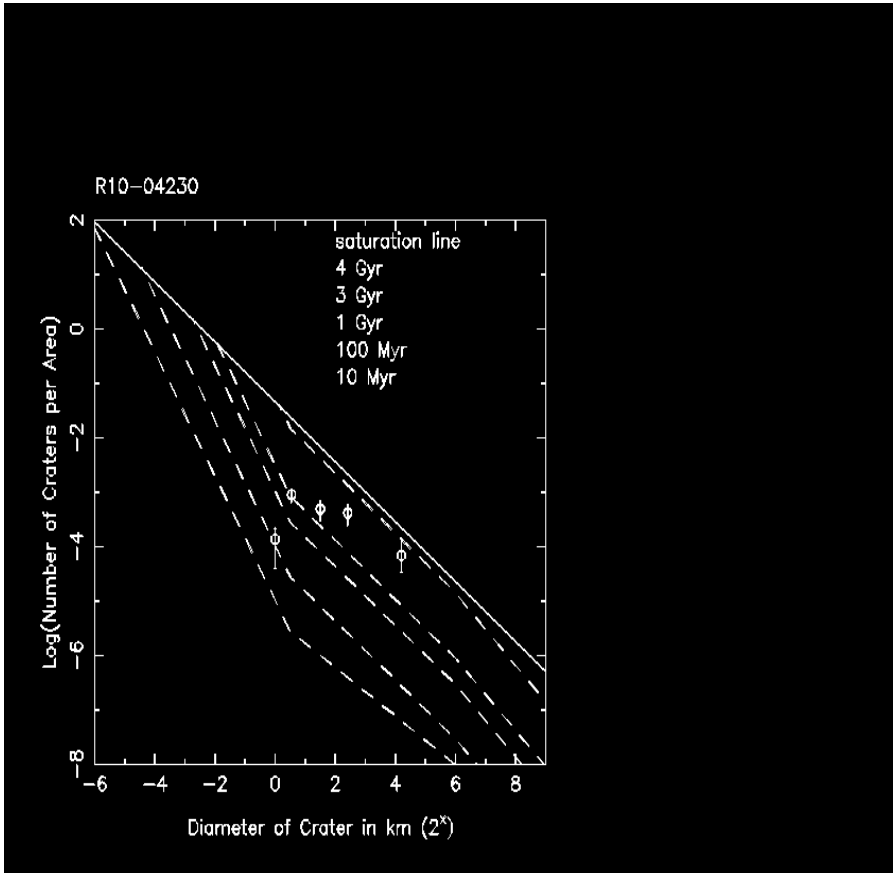
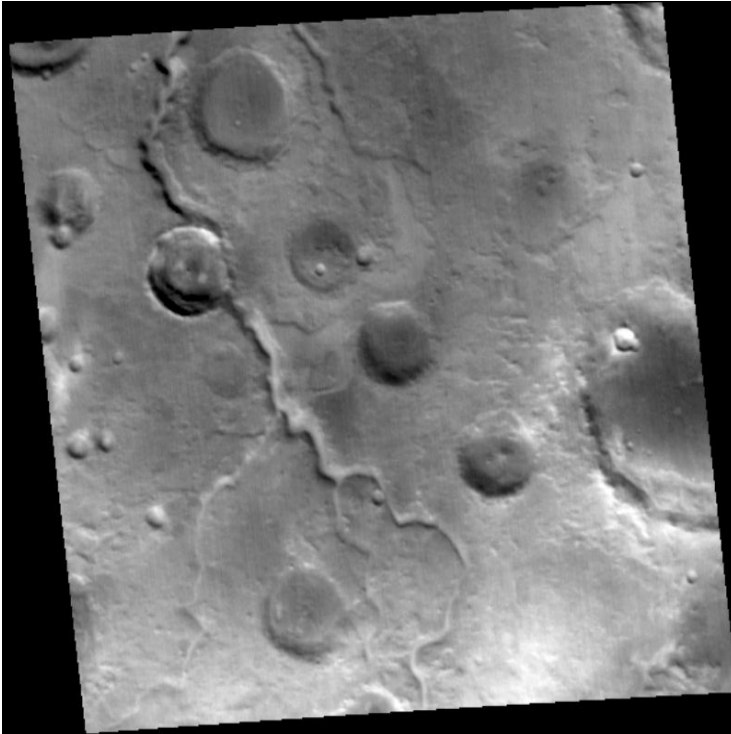


Figure 9



Age: 3.4 billion years

Figure 10

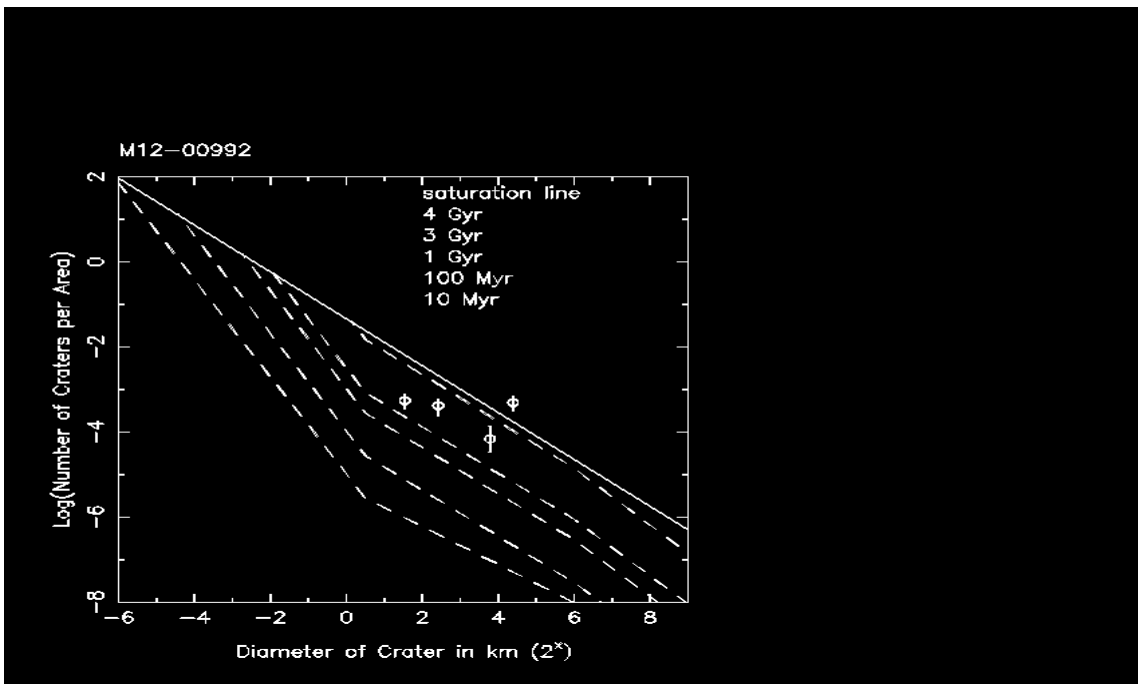
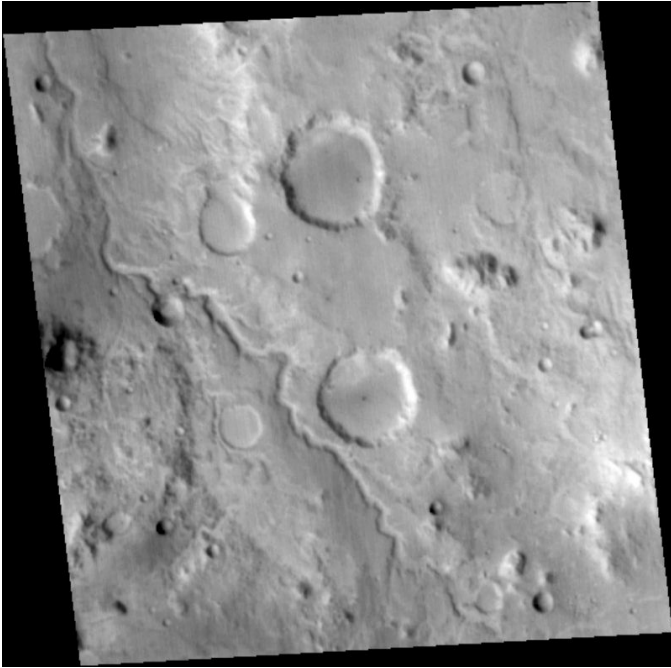
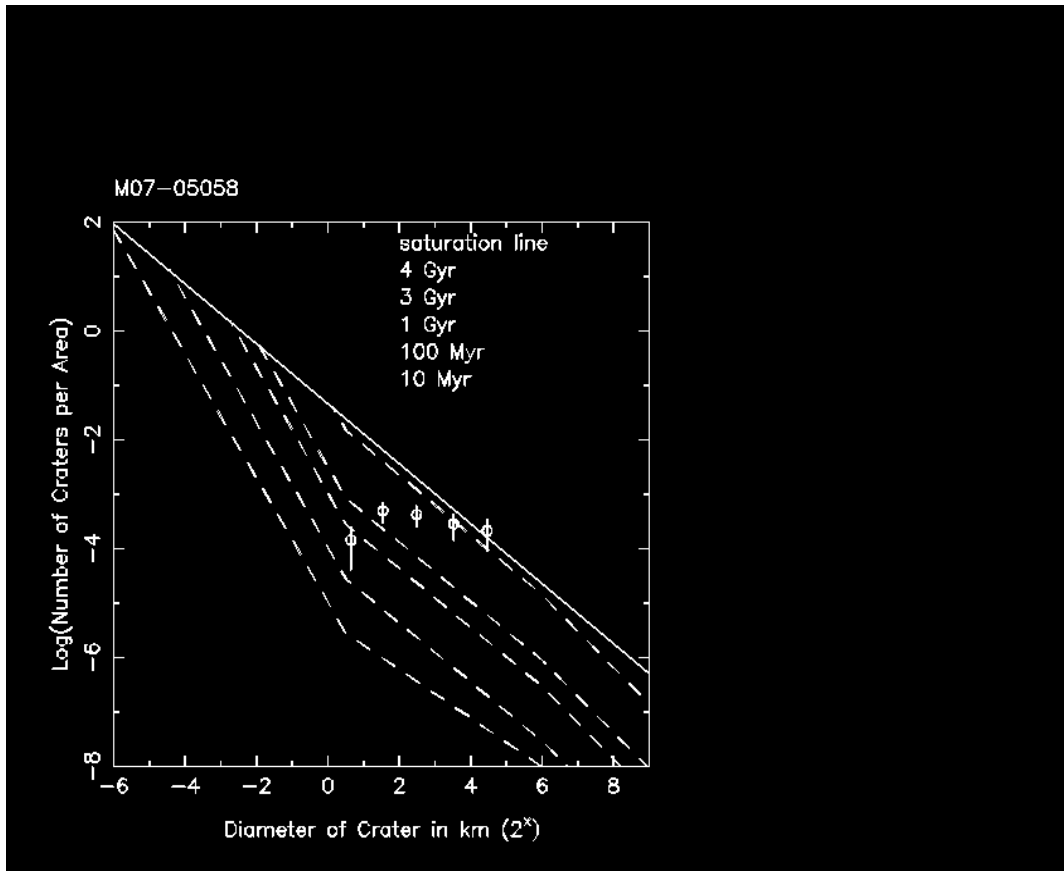


Figure 11



Age: 3.3 billion years

Figure 12



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