Introduction

When we gaze at the Moon from the earth, we observe that only one hemisphere is constantly visible to us. This is owing to tidal locking. It is because the gravitation between Earth and Moon has, in effect, caused the Moon's rotational period to equal the time it takes for the Moon to revolve around Earth. Tidal forces in the long run caused the rotation of the Moon to decelerate until it became equal to the period of revolution, and this led to one hemisphere only being visible from the earth.

On the near side of the Moon, we can see numerous black spots of basalt rock which are a result of ancient volcanic activity. These dark features are termed maria, after the Latin for "seas" because astronomers who saw them first thought that they were seas. The samples which were returned back to the earth during the Apollo mission tell us that the maria developed around 3.5 billion years ago. The Moon itself, however, was created nearly 4.5 billion years ago. Due to the absence of an atmosphere, liquid water, and active tectonics, the Moon's surface has not changed over billions of years. As a result, the surface of the Moon is pockmarked with impact craters from a few millimeters to a few hundred kilometers.

The maria cover about 16% of the Moon's surface and contain significantly fewer craters than the lunar highlands, also known as terrae. The highlands are the lighter regions composed of less dense, anorthositic rocks. They solidified when the Moon cooled and are older than the maria, preserving records of craters dating back to the early history of the Solar System. By studying the age of the maria and the distribution of craters across the lunar surface, we can calculate the rate of asteroid impacts over time. The evidence suggests that the impact rate has significantly decreased since the formation of the maria.

Understanding the frequency and scale of asteroid impacts on the Moon provides valuable insights into the history of our Solar System and the potential hazard of asteroid impacts on Earth.

Objective

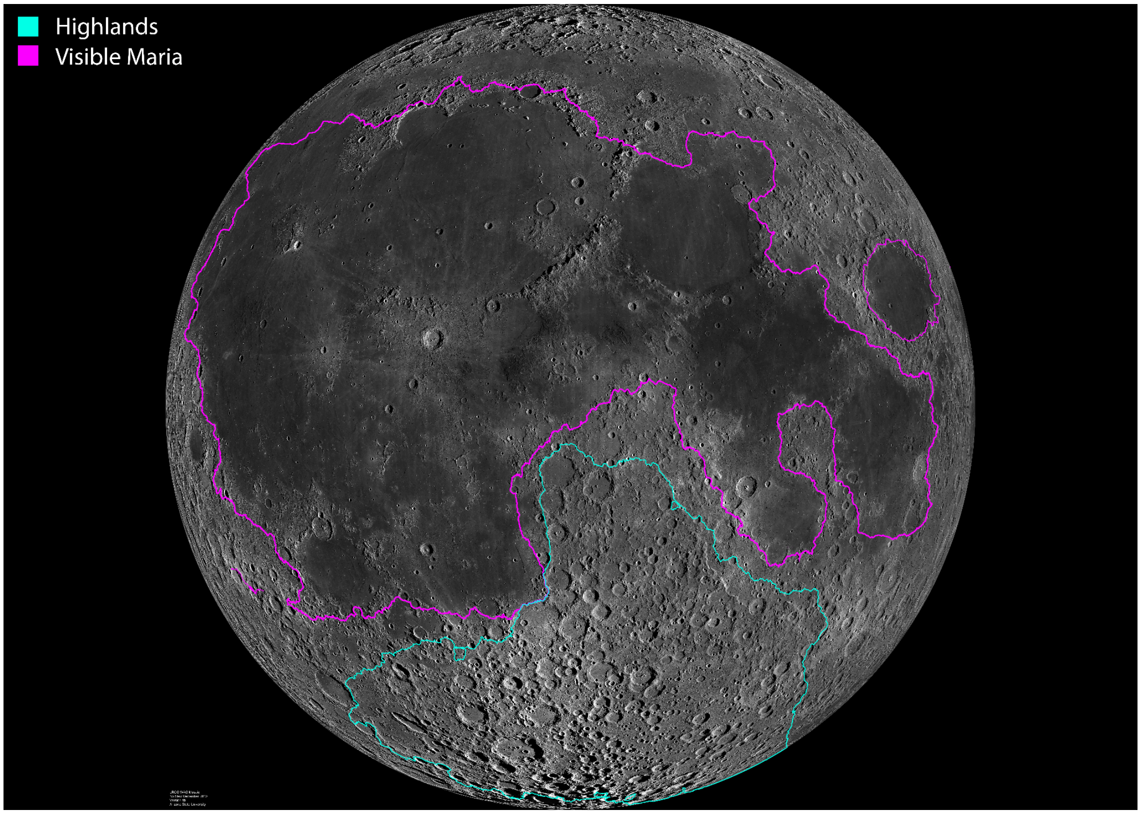
The objective of this lab was to observe the craters and maria on the Moon in order to determine impact rates on both the Moon and the Earth. By studying the lunar surface features, we aim to gain insights into the history of asteroid impacts in our Solar System and understand how planetary surfaces evolve over time.

Procedure

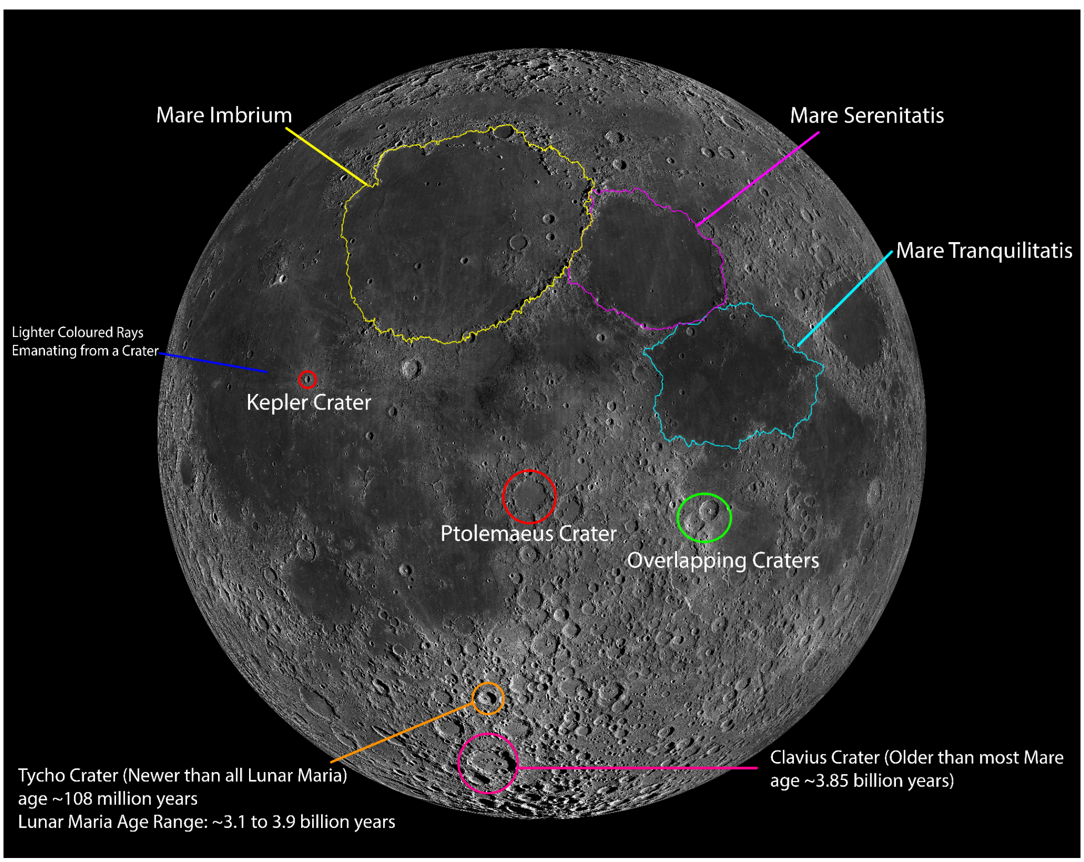
The first step was to download GIMP image manipulation software. I opened the high-resolution lunar image—a 10,000 by 10,000 pixel JPEG file—in GIMP. I scanned the Moon's surface and identified three prominent craters. I circled and labeled these craters on the image. Similarly, I identified and labeled three maria and three spacecraft landing sites. I used different colors for each group and created a legend at the top of the image to distinguish them.

In a new GIMP window, I opened another copy of the high-resolution JPEG lunar image. I located overlapping craters and labeled them as I did in the first image. I also identified and labeled a crater that was formed before a mare and one that was formed after. Additionally, I found and labeled three craters that appeared lighter and had streaks radiating from them.
To determine the scale of the digital image, I divided the actual diameter of the Moon in kilometers by its diameter in pixels on the image. Using this scale, I calculated the actual diameters in kilometers of one small crater (Kepler) and one large crater (Ptolemaeus). Applying the rule of thumb that craters are typically 10 to 50 times the size of the impacting asteroid, I estimated the possible sizes of the asteroids that created these craters.
Next, I found and labeled three craters of similar sizes to those listed in Table 1 in the lab manual. Using the online tool Impact Earth, I calculated the sizes of craters that would be created if asteroids such as 99942 Apophis and Swift-Tuttle were to collide with Earth. I observed the simulated impacts, including potential tsunamis, using the collision calculator provided by Impact Earth. I also used the website to determine the crater size that would be produced by a 1-kilometer-diameter asteroid.
Using the diameter of the crater as a guideline, I counted the number of craters of that size or larger on the maria of the Moon from the high-resolution JPEG image. Due to limitations in accurately measuring the sizes of the smallest craters, my count may have included craters formed by asteroids smaller than 1 kilometer in diameter. My estimated uncertainty for this count was ±50. I then counted the number of similar-sized craters on the maria using the lunar maps provided in class. Due to the lower quality of the printed maps and potential reflections affecting visibility, my estimated uncertainty for this count was ±40.
Based on the number of craters counted, I calculated the total number of craters on the Moon created since the maria were formed. By dividing the age of the maria by the crater count, I determined the rate at which asteroids equal to or larger than 1 kilometer in diameter have impacted the Moon since the formation of the maria. I then calculated the number of such asteroids that have hit the Moon each year over this period. Finally, I compared the impact rate on the Moon to Earth's surface area to estimate the probability of a 1-kilometer or larger asteroid colliding with Earth in a given year.

Answers


Highlands
Visible Maria

1)


Mare Imbrium
Mare Serenitatis
Mare Tranquilitatis
Lighter Coloured Rays
Emanating from a Crater
Kepler Crater
Ptolemaeus Crater
Overlapping Craters
Tycho Crater (Newer than all Lunar Maria)
age ~108 million years
Lunar Maria Age Range: ~3.1 to 3.9 billion years
Clavius Crater (Older than most Mare
age ~3.85 billion years)

2-6)

7-11) Table 1:

Image Scale [km/pix] = 3476 km/10000px = 0.3476			
Crater	Diameter [Pixels]	Diameter [km]	Meteorite Diameter [km]
Kepler	70	24.332	0.48664
Ptolemaeus	456	158.5056	3.170112

12-15)
Table 2: Impact Calculator Data

Near-Earth Object	**99942 Apophis (Asteroid)**	**Swift-Tuttle (Comet)**
Diameter [km]	0.325	26
Speed [km s^{-1}]	10	50
Impact Angle [°]	45	45
Density [kg m^{-3}]	2600	600
	Land Impact	
Target Density [kg m^{-3}]	2400	2400
Final Crater [km]	3.87	242
	Water Impact	
Water Depth [m]	3500	3500
Tsunami Height [km]	0.0063	1.7

Vancouver Island mainly comprises of sedimentary rocks (Minerals Ed, Canada) that range in density from 1500 ~ 3300 kg m^{-3} thus taking an average value for density, we use 2400 kg m^{-3}.

Swift-Tuttle (Comet) Impact on Earth:
“Depending on the direction and location of impact, the collision may cause a change in the length of the day of up to 13.5 milliseconds.”

Input Data for 99942 Apophis (Asteroid):
Distance from Impact: 300.00 km (= 186.00 miles)
Projectile diameter: 325.00 meters (= 1070.00 feet)
Projectile Density: 2600 kg/m3
Impact Velocity: 10.00 km per second (= 6.21 miles per second)
Impact Angle: 45 degrees
Target Density: 2400 kg/m3
Target Type: Crystalline Rock

Input Data for Swift-Tuttle (Comet):
Distance from Impact: 300.00 km (= 186.00 miles)
Projectile diameter: 26.00 km (= 16.10 miles)
Projectile Density: 600 kg/m3
Impact Velocity: 50.00 km per second (= 31.10 miles per second)
Impact Angle: 45 degrees
Target Density: 2400 kg/m3
Target Type: Crystalline Rock

16-19) Table 3:

Calculator Inputs	
Diameter [km]	1
Speed [km s^{-1}]	20
Density [kg m^{-3}]	3000
Impact Angle [°]	45
Crater Diameter	
Transient Crater [km]	11
Final Crater Moon [km]	22
Final Crater Moon [pix]	63.29

Projectile Density (3000 kg/m³):
Justification: This density represents a typical stony asteroid, which is common in the solar system. Stony asteroids are composed primarily of silicate minerals, and their densities range from about 2600 to 3500 kg/m³. Selecting 3000 kg/m³ is a reasonable average value for such asteroids.

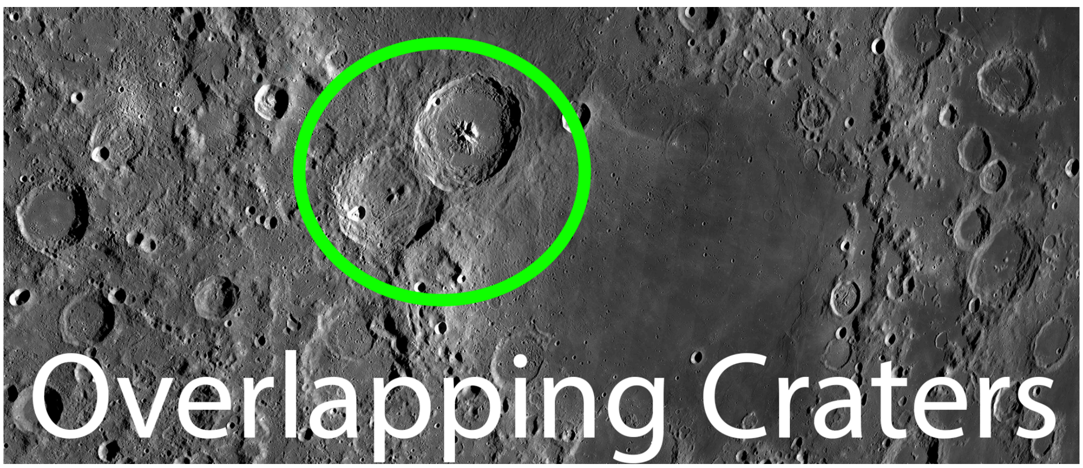
Impact Velocity (20 km/s):
Justification: The Moon lacks an atmosphere, so asteroids impact its surface at high velocities without significant deceleration. Typical impact velocities on the Moon range from 10 km/s to 25 km/s. An impact velocity of 20 km/s falls within this range and represents an average speed for asteroids in the inner solar system.

Impact Angle (45 degrees):
Justification: Due to the random nature of asteroid orbits and impact trajectories, the most probable impact angle is 45 degrees. This angle is statistically the most common and is used as a standard in impact modeling to represent an average scenario.

20-26)
Table 4:

Mare	Diameter [km]	Area [km^2]	Crater Count	Impact Density [craters/km2]
Imbrium	1146	1031475.974	400	0.000387794
Serenitatis	674	356787.5361	220	0.000616613
Tranquillitatis	875	601320.4689	180	0.000299341
			Average Impact Density:	0.000434583

Analysis

1) 

When two craters overlap, the one that formed first is the one that appears underneath or is partially covered by the other crater. In other words, the crater whose rim or floor is intersected or overlaid by another crater must have existed before the second crater formed. In this case that would be the left crater being formed first or being older.

2) Craters that formed before the mare (plural: maria) are typically covered or partially submerged by the mare's basaltic lava flows. These craters may appear as "ghost craters" with only parts of their rims visible above the mare surface. Craters that formed after the mare are superimposed on top of the mare and are clearly visible with well-defined rims and ejecta blankets spreading over the mare surface.
3) Based on observations of the lunar surface, more craters were formed early in the history of the Solar System. This is evidenced by the heavily cratered lunar highlands compared to the relatively smoother maria.
Reasons for this include:
    - Late Heavy Bombardment (LHB): Approximately 4 to 3.8 billion years ago, the inner Solar System experienced a period of intense asteroid and comet impacts, leading to a higher frequency of cratering events.

- Decline in Impact Rate: Over time, the number of impactors in the Solar System has decreased due to accretion onto planets, collisions, and ejections from the Solar System, leading to fewer impacts in the later history.
- Surface Age Differences: The maria are younger surfaces (~3.5 billion years old) and show fewer craters than the older highlands, indicating a decrease in impact frequency over time.

4) Mount Doug (PKOLS), with a peak elevation of 210 meters above sea level, would likely be safe from the tsunamis caused by the water impacts of the Near-Earth Objects (NEOs) at the top of the mountain. From previous calculations:
   For 99942 Apophis (Asteroid): The tsunami height at 300 km distance was calculated to be around 2 meters.
   For Swift-Tuttle (Comet): The tsunami height at 300 km distance was calculated to be approximately 100 meters (0.1 km).
   Since both tsunami heights are significantly less than 210 meters, being at the top of Mount Doug would place us well above the maximum tsunami wave heights caused by either NEO impact.
5) At 300 km from either impact, you would need to be concerned about the following significant effects:
   Air Blast (Shock Waves):
   For Apophis: The air blast effects might include strong winds and overpressure that could cause damage to structures and windows within a certain radius.
   For Swift-Tuttle: The air blast would be much more intense, potentially causing severe structural damage, uprooting trees, and posing a risk to life even at 300 km distance.
   Seismic Shaking:
   The impact could generate seismic waves equivalent to a large earthquake, potentially causing ground shaking and damage to buildings and infrastructure.
   Thermal Radiation:
   The fireball generated by the impact could emit intense thermal radiation, possibly causing burns or igniting fires within a certain radius.
   Ejecta Fallout:
   Debris ejected from the impact site could fall back to the surface, posing hazards such as falling rocks or dust contamination.
   Atmospheric Effects:
   Dust and aerosols injected into the atmosphere could affect air quality and lead to climatic changes.
   Therefore, even if you are safe from the tsunami at the elevation of Mount Doug, these other effects could pose significant risks.
6) Yes, the crater caused by a 1 km asteroid matches the expectation that the final crater diameter is approximately 20 times the impactor diameter. Using Equation 1:
   $D = k \times d = 20 \times 1 km = 20 km$
   Our calculated crater diameter of 22 km is close to this estimation, confirming that the crater size aligns with the rule-of-thumb. Although it is slightly higher than the typical range of 15-20km.

7) N = p * a where a is surface of moon and p is average impact density
   P = 0.000434583 and a = 38 million km^2
   Therefore N = 16,515 craters
8) T = 3.5×10^9 years/16,515 = 211,936 years per impact
9) P = 1/211,936 = 4.72×10^{-6} impacts per year
10) Scaling factor = Surface Area of Earth/Surface Area of Moon = 510/38 = 13.42
    P earth = $4.72 \times 10^{-6} \times 13.42 = 6.34 \times 10^{-5}$ impacts per year
11) 1/ 6.43×10^{-5} impacts per year = 15,775 years per impact

Discussion

1)
In making this extrapolation, several key assumptions are involved:

Uniform Impact Density: We assume that the impact density (craters per unit area) measured on the three selected maria - Imbrium, Serenitatis, and Tranquillitatis—is representative of the entire lunar surface. This presumes that the maria we studied are statistically similar to other regions in terms of impact history.

Consistency Over Time: We assume that the impact rate has remained relatively constant over the 3.5 billion years since the maria formed. This means we are disregarding any significant variations in impact frequency that may have occurred due to changes in the Solar System, such as during periods like the Late Heavy Bombardment.

Similar Geological Surface Conditions: We assume that the physical characteristics of the maria are similar to the rest of the lunar surface, meaning that craters would form and be preserved in the same way across different regions.

Negligible Erosion Processes: We implicitly consider that all craters formed are preserved over geological time because the Moon lacks significant erosion processes. This allows us to count existing craters as a cumulative record of impacts.

Direct Scaling to Earth: When scaling from the Moon to Earth, we assume that the impact frequency is directly proportional to the surface area. This ignores factors like Earth's stronger gravitational pull and atmospheric effects that can influence impact rates.

Homogeneous Impactor Distribution: We assume that the population of impactors (asteroids and comets) is distributed uniformly throughout near-Earth space and that both the Moon and Earth are equally likely to be struck by these objects, aside from differences in surface area.

Negligible Atmosphere Effects on Large Impactors: For large impactors (like those creating 22 km craters), we assume that Earth's atmosphere does not significantly shield the planet, allowing us to compare impact rates directly with the Moon.

These assumptions simplify complex realities to allow for a manageable calculation, but they also introduce uncertainties and potential inaccuracies in the extrapolated results.

2)
Reasonableness of Estimation:

Preserved Impact Record: The Moon's lack of atmosphere, water, and tectonic activity means its craters are well-preserved, providing a valuable record of impacts over billions of years.
Shared Space Environment: Both the Earth and Moon reside in the same region of space and are subject to similar populations of near-Earth objects (NEOs).

Differences Affecting Impact Frequency:
Gravitational Focusing: Earth’s stronger gravitational field enhances its ability to attract passing objects, a phenomenon known as gravitational focusing. This increases the Earth's impact rate compared to the Moon beyond what surface area differences alone would suggest.

Atmospheric Entry: Earth's atmosphere can cause smaller meteoroids to burn up or disintegrate before reaching the surface. However, larger meteorites (such as those creating 22 km craters) are less affected, making the Moon's crater record more directly comparable for large impacts.

Impact Velocity: Objects impact Earth at higher velocities due to its greater gravitational acceleration, which can influence the frequency and energy of impacts.

The Earth is likely hit by meteorites more often than the Moon, not just because of its larger surface area but also due to gravitational focusing. Therefore, while the Moon provides valuable data, estimates of Earth's impact rate should account for these differences to improve accuracy.

3)
In Analysis Question (11), we calculated that an asteroid of this size impacts the Earth approximately every 15,775 years.

Comparison to Human Civilization:

Age of Civilization: Human civilization, characterized by the development of agriculture, cities, and writing, is about 6000 years old.
Time Between Impacts: The average interval between such catastrophic impacts is more than twice the entire span of human civilization.
Implications:
Rarity on Human Timescales: Such events are rare within the context of recorded history, which may explain why there are no known records or direct evidence of civilization-ending impacts in human history.
Existential Risk: Despite their rarity, the potential impact of such an event is immense, emphasizing the importance of monitoring NEOs and developing impact mitigation strategies.

Civilizational Vulnerability:
Technological and Social Impact: Modern civilization is more interconnected and technologically dependent, potentially increasing vulnerability to global catastrophes.
Awareness and Preparedness: Our ability to detect and potentially deflect hazardous asteroids has only developed recently, which could alter future outcomes compared to past civilizations.

The average interval between 1 km asteroid impacts is significant when compared to the age of human civilization, highlighting both the rarity of such events and the importance of vigilance in planetary defense efforts.

4)
Reasons for Fewer Craters on Earth:
Erosion and Weathering:
Atmospheric Effects: Earth's atmosphere leads to weathering processes, including wind, rain, and temperature fluctuations, which erode surface features over time.
Hydrogeological Activity: Rivers, glaciers, and oceans reshape the landscape, removing or burying impact craters.
Plate Tectonics:
Crust Recycling: Movement of tectonic plates results in subduction, where crustal material is forced into the mantle, effectively erasing surface features.
Mountain Building and Volcanism: Geological activity can distort or cover existing craters.
Vegetation and Sedimentation:
Covering Features: Soil accumulation, vegetation growth, and sediment deposition can obscure craters, making them harder to detect.
Human Activity:
Land Use Changes: Urban development and agriculture can modify the landscape, removing geological evidence of past impacts.
Only Large Craters Remain:
Resilience to Geological Processes: Larger craters (tens to hundreds of kilometers in diameter) are more likely to leave some discernible trace despite Earth's active geology.
Difficulty Detecting Small Craters: Smaller craters are more easily erased or hidden and may require geological surveys to identify.
Importance of the Moon:
Preservation of Ancient Impact Record:
Lack of Atmosphere and Water: The Moon lacks the erosive forces that modify Earth's surface, allowing craters to remain virtually unchanged for billions of years.
Static Geology: The Moon has no plate tectonics or significant volcanic activity to alter its surface extensively.
Studying Solar System History:
Impact Chronology: The abundance and distribution of lunar craters provide insights into the impact rate over time, helping to reconstruct the history of meteoritic bombardment in the inner Solar System.

Calibration Point: The lunar surface serves as a reference for dating planetary surfaces elsewhere, using crater counting techniques to estimate ages.
Understanding Earth's Early History: Since Earth's early surface record has been largely erased, the Moon offers clues about the environment and processes during the formative years of the Solar System.

Conclusion

The Moon is a crucial resource for understanding the impact history and geological evolution of the inner Solar System. Its well-preserved craters fill gaps in Earth's geological record, enabling scientists to study events that have shaped not only the Moon but also Earth and other terrestrial planets. By examining the Moon's surface and impact history, we gain valuable insights into the dynamics of our Solar System, the potential risks posed by NEOs, and the processes that have influenced planetary development over billions of years. This knowledge not only satisfies scientific curiosity but also informs efforts to protect our planet from future catastrophic impacts.

References

https://en.wikipedia.org/wiki/99942_Apophis
https://en.wikipedia.org/wiki/Comet
https://mineralsed.ca/site/assets/files/3451/victoriaareageotour_me.pdf
https://www.eoas.ubc.ca/courses/eosc350/content/foundations/properties/density.htm
https://gpg.geosci.xyz/content/physical_properties/physical_properties_density.html
https://maps.garmin.com/en-CA/marine?maps=garmin&overlay=false&key=c0xusj3k58s5
https://science.nasa.gov/solar-system/asteroids/facts/