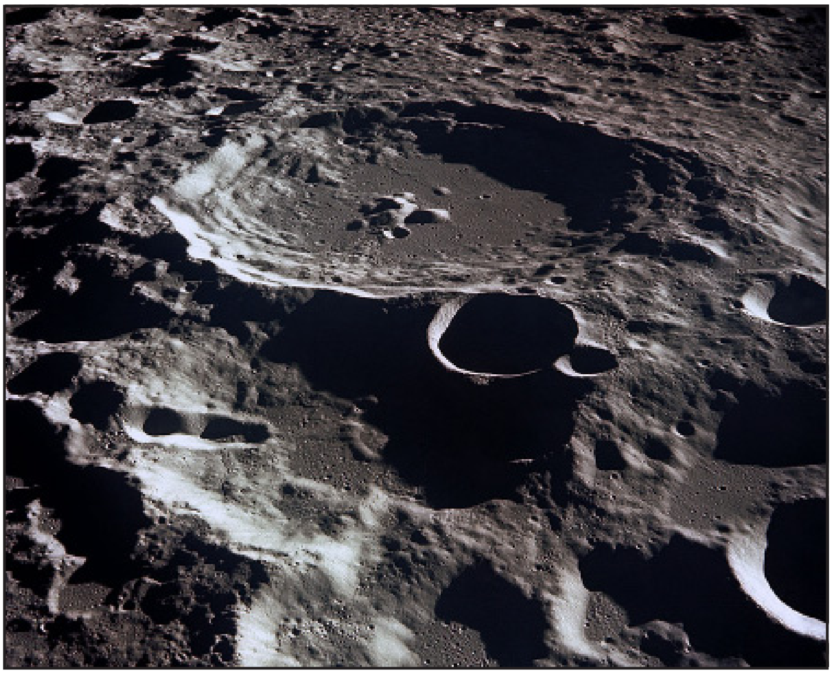
Variations in impactor flux to the Moon and Earth after 3.85 Ga

Sanna Holm

Examensarbeten i Geologi vid
Lunds universitet - Berggrundsgeologi, nr. 224
(15 ECTS)



Geologiska institutionen
Centrum för GeoBiosfärsvetenskap
Lunds universitet
2008

Variations in impactor flux to the Moon and Earth after 3.85 Ga

Bachelor of Science Thesis

Sanna Holm

Department of Geology
Lund University
2008

Contents

Cover Picture: Lunar crater Daedalus.

Variations in impactor flux to the Moon and Earth after 3.85 Ga.

SANNA HOLM

Holm, S., 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga. *Examensarbeten i geologi vid Lunds universitet*, No. 224, 36 pp. 15 ECTS credits.

Abstract: An impact crater is the result of a collision between a large and a smaller body. On Earth most of the cratering record has been erased because of tectonic processes and weathering. The Moon, however, displays a nearly complete record of impact events over the last 2 Gyr, and evidence of impact cratering events nearly 4 billion years old.

The same family of impactors is responsible for the formation of impact craters on the planets and moons in the inner Solar System. Such crater forming bodies are asteroids from the main asteroid belt, and comets commonly originating from the Oort Cloud. Therefore, impact craters on the Moon can be used for measurements of the amount and frequency of infalling material to Earth.

This paper reviews the different views on the evolution of the impactor flux to the Moon and Earth after 3.85 Ga and the different methods used for calculations of changes in impactor flux over time. Common methods used for this purpose are; determining crater frequency on lunar surfaces through counting craters on photographs, determination of the optical maturity (OMAT) of crater rays and analyzing lunar impact spherules with the $^{40}Ar/^{39}Ar$ isochron technique, in order to retrieve the age of the impacts that created the spherules.

This paper also presents a new study in which the frequency of small craters on 12 lunar structures (11 craters and one mare surface) of different ages has been evaluated. The results of counting showed that there is a tendency for an increased impactor flux to the Moon in the last ~1 billion years. This contradicts the results of many other recent studies where a constant or decreasing impactor flux in at least the last one billion years has been favoured. The increase in impactor flux to the Moon over the last 0.8 to one billion years might be as much as a factor 6, compared to that of the period 1-3 Ga. However, in order to draw any definite conclusions on the history of impacts striking the Moon further studies are needed.

Keywords: The Moon, impact crater, impactor flux, OMAT-profile.

Sanna Holm, Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: holm_sanna@hotmail.com

Variationer i impaktfrekvens på månen och jorden efter 3,85 Ga.

SANNA HOLM

Holm, S., 2008: Variationer i impaktfrekvens på månen och jorden efter 3,85 Ga. *Examensarbeten i geologi vid Lunds universitet*, Nr. 224, 36 sid. 15 högskolepoäng.

Sammanfattning: När en stor himlakropp kolliderar med en mindre skapas en nedslagskrater. På jorden har den största delen av alla nedslagskratrar som bildats under 4,6 miljarder år försvunnit på grund av tektoniska processer och vittring. På månen däremot kan man hitta kratrar så gamla som 4 miljarder år. Nästan alla spår av kratrar från de senaste 2 miljarder åren finns bevarade.

Kroppar som kolliderar med planeterna och månarna i det inre solsystemet är asteroider från asteroidbältet och kometer som ofta har sitt ursprung i Oort molnet. Eftersom kroppar med samma ursprung skapar kratrar på månen och jorden kan kratrar på månen användas när man utvärderar impaktfrekvens på jorden.

Vanliga metoder som används när variationer i impaktfrekvens på månen och jorden efter 3,85 Ga ska bestämmas är att genom att räkna kratrar på fotografier bestämma frekvensen av kratrar på dessa på ytor på månen, fastställande av den optiska mognaden hos kratrars omkringliggande strålsystem och analyser av impaktsfäruler med $^{40}Ar/^{39}Ar$ metoden för att bestämma åldern av nedslaget som skapade sfärulerna.

I den här uppsatsen presenteras en ny studie där frekvensen av små kratrar på 12 strukturer (11 kratrar och en mare yta) på månen har utvärderats. Resultaten av studien visar att det finns en tendens till att impaktfrekvensen på månen har ökat under de senaste ~1 miljarder åren. Många andra studier har förespråkat ett konstant eller minskande flöde av kraterformande kroppar till månen och jorden under de senaste en miljard åren. Ökningen i impaktfrekvensen på månen under de senaste 0.8 till en miljard åren kan vara så stor som sex gånger jämfört med den under perioden 1-3 Ga. Om några definitiva slutsatser om hur mängden infallande projektiler till månen och jorden har förändrats ska dras så måste ytterligare studier bedrivas.

Nyckelord: Månen, impaktkrater, impaktfrekvens, OMAT-profil.

Sanna Holm, Geologiska Institutionen, Centrum för GeoBiosfärsvetenskap, Lunds Universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: holm_sanna@hotmail.com

1 Introduction

Possible changes in cratering rate and/or periodicity in the flux of crater-forming bodies to Earth has been much debated (e.g. Alvarez & Muller 1984; Culler et al. 2000; Grier & McEwen 2001). Leading hypotheses support either a constant decrease in the number of crater forming events since the formation of the solar system, or a variable cratering rate with shorter periods of significantly enhanced infall of material to the Moon and Earth (McEwen et al. 1997; Hartmann et al. 2007).

Impacts on Earth happen due to encounters with asteroids or comets (Grier & McEwen 2001). The asteroid belt is currently believed to be the source of most of the material hitting the Moon, Earth and the other bodies in the inner solar system (Zappalà et al. 1998). Many authors tend to favour dramatic asteroid break-ups as an important reason for an increase in the amount of impactors striking the Moon and Earth. Schmitz et al. (2003), amongst others, has linked an increased amount of extraterrestrial chromite grains in Swedish marine limestone from the Ordovician to a major asteroid break-up event that was recognized by Keil et al. (1994). However, Shoemaker (e.g. 1998) amongst others favoured comets as the primary impactor creating large craters on Earth. Comets reaching Earth may e.g. originate from the Oort Cloud. They were perturbed into Earth-crossing orbits by a combination of galactic tidal forces and gravitational impulses from passing stars (Shoemaker 1998).

Even though the formation of an impact crater on Earth is a rare event today, it has been an important process in the development of both Earth's surface and the surface of the Moon (Grier & McEwen 2001). Because of tectonic processes and the weathering cycle traces of most impacts have been erased on Earth. Reliable sources for information on terrestrial impacts are the stable continental cratons. These areas are however not enough for drawing conclusions on the impact history of the entire planet, since e.g., no impact structures from the ocean basins are known, and they cover ~70% of Earth's surface. Also, the locations where impact craters have been discovered on Earth reflect areas where geologists have had the opportunity to find them. On the other hand, our moon can be considered tectonically inactive, and therefore it is an excellent study object. It reveals evidence of cratering events as old as ~4 billion years and a cratering record of the last 2 billion years that is nearly complete (Grier & McEwen 2001).

Comparison of data from the lunar impact record with crater populations on the asteroids Gaspra and Ida show the same crater distribution curve. This is a strong implication for that it is a common population of bodies that impact the planets, moons and asteroids in the inner Solar System (Neukum & Ivanov 1994). Thus, a determination of the cratering rate on the Moon is believed to reflect the cratering rate on Earth. Scaling effects may introduce a factor of 2 or 3 uncertainty in absolute age cratering estimates (Hartmann et al. 2007). This uncertainty is according to Neukum & Ivanov (1994) less than a factor of 2. However, this still means that the Moon is a reliable source for data when interpreting the impactor flux to Earth through geologic time, as long as the major parameters affecting the impact process are taken into account. These are e.g. gravity, atmospheric characteristics, crustal strength and density (Neukum & Ivanov 1994).

Through extensive research we have learned that the cratering rate on the Moon decreased rapidly during the first 1-1.5 billion years of lunar history (Neukum et al. 1975). This was proved by Hartmann as early as in 1965, when he presented a paper in which he based on crater counting had given the lunar maria an age of approximately 3.6 billion years, which is very close to the ages the lunar maria are given today; between 3 and 3.8 billion years (Neukum & Ivanov 1994). This would mean, considering the high density of craters on the lunar highlands, that there must have been a very rapid decrease in impact cratering in the first one billion years of lunar history (Hartmann 1965). This has been confirmed by later works by Hartmann (1970), Neukum (1983, see Neukum & Ivanov 1994) and Hartmann et al. (2007) amongst others.

During the time between ~4.1 to ~3.8 Ga a number of basins whose ages have been reasonably well-determined formed on the Moon. This time is referred to as the late heavy bombardment (Bottke et al. 2007b). After this, the amount of impactors striking the Moon decreased rapidly from ~3.8 to ~3.1 Ga (Hartmann et al. 2007). Bottke et al. (2007b) describes two main explanations for this apparent increased flux of basin-forming projectiles. One could be a terminal cataclysm caused by a spike in the inner Solar System impactor flux between 4.0 to ~3.8 Ga. This topic was first introduced by Tera et al. in 1974, (see Bottke et al. 2007b) as an explanation for why there were no lunar rocks with isotopic recrystallization ages of >4.0 Ga. However, the late heavy bombardment could also define the end of a monotonically decreasing impactor population, supported by Neukum & Ivanov (1994) amongst others. Bottke et al. (2007b) concluded, through modeling "the collisional and dynamical evolution of the post-planet formation population", that the most likely explanation for the lunar late heavy bombardment is a terminal cataclysm scenario.

In later time, some sort of constant cratering rate has been reached. This is accepted by the vast majority of researchers in this field. It is when discussing fluctuations around the steady cratering rate after ~3 Ga that the results of various types of methods in evaluating this subject disagree.

The objective of this paper is to evaluate the current view on changes in the production rate of impact craters on Earth since 3.85 Ga by looking at studies of the more complete impact record on the Moon. A study of the distribution of craters on selected lunar structures whose ages have been reasonably well-determined has been made.

2 Cratering on the Moon

The surface area of the Moon is only about 7% of that of Earth, 3.79×10^7 km^2. This can be compared with the surface area of the continent of Africa, which is 3.0×10^7 km^2. Craters of different types cover almost the entire surface of the Moon because of its inactive tectonic nature and lack of atmosphere.

2.1 Crater Morphology

Craters are classified according to their size and morphology. Melosh (1989) explains that all craters can be described as "circular rimmed depressions", but the individual morphological details for each crater depends on the size of the impactor, features of the material the impactor hits, planet (or moon) and the age of the crater. Wilhelms (1987) points out that generally, crater morphology gets more complex as crater size increases. For this paper Melosh's (1989) classification will be used.

Simple Craters: A small impactor striking the Moon will form a simple crater. These types of craters have characteristic bowl-shaped interiors without a central flat floor. The pit is surrounded by a raised rim. Simple craters display this morphology because of a small-scale collapse of the initially steep crater rim.

Complex Craters: Lunar craters are classified as complex when the crater's diameter reaches 10-20 kilometers. The transition from simple crater to complex crater is dependent on gravity. On Earth, which has six times the Moon's gravity, the transition takes place between crater diameters of 2 and 4 kilometers.

Complex craters have walls that slope steeply down from the rim, flat floors that are often covered with landslide deposits from the crater walls, and central peaks. The peak is not just a result of material sliding down from the walls and piling up in the center of the crater, but studies of terrestrial complex craters have shown that the central peak is composed of rocks that were uplifted underneath the crater floor. When complex craters reach sizes of about 140 kilometers in diameter or bigger, central peaks are replaced by peak rings.

Multiringed Basins: When describing extremely large impact structures called multiringed basins Melosh (1989) uses Orientale Basin on the Moon as an example. The outer part of the structure is defined by the inner edge of the Cordillera Mountain ring, approximately 900 kilometers in diameter. Inside of this outer mountain ring three more mountain rings occur. The Rook Mountains form the biggest ring of these. The center of the basin lies 2 to 3 kilometers below the level of the distant surrounding plains.

The rings form when rock is uplifted as a result of the impact. In the largest of these multiringed basins up to five rings may be found (Summerfield 1991).

Aberrant Crater Types: Craters that do not fit any of the classes above are called aberrant craters. This type of crater can, e.g. be elliptical because of a low-angle impact or display wide terraces because of debris sliding down from areas that were topographically high before the impact.

2.2 Ejecta Deposits

During an impact strong horizontal compressive forces cause rock underneath the crater center to get squeezed out- and upwards, creating a crater rim. On top of the uplifted rock ejected debris forms the upper part of the crater rim (Melosh 1989). This is because the material is thrown out of the crater at such low velocity, that close to the rim one often finds the same stratigraphy in the ejected debris as in the underlying rock, only inverted.

The ejected debris is continuous for about one or two crater radii from the crater rim, independent of crater size, before it thins out (Melosh 1989). This continuous layer of ejected debris is called an ejecta blanket.

Secondary Crater Fields: Some of the ejected material may form secondary craters around the primary crater. The ejected debris that creates one of these craters impacts at low velocity because of the 2.4 km/s lunar escape velocity (Wilhelms 1987), above which ejected fragments will leave the moon. The low-velocity impact will result in the formation of asymmetric craters, which together form a secondary crater field recognizable beyond the ejecta blanket (Melosh 1989). Secondary craters can be hard to distinguish from primaries, especially when they expand several crater radii from their primary crater. According to Wilhelms (1987) the main difference from primaries is the tendency for secondaries to group together. Some ejected fragments may, however, separate enough and form what may look like a random primary crater. One way to determine if a distant crater is secondary is to look for an elongated dune lying between two secondaries (Melosh 1989). This dune forms when the secondaries strike, at nearly the same time, and the ejected material of these craters run into each other. When the ejected fragments collide they fall down and create the dune between the craters.

Crater Rays: Crater rays are bright radial or subradial features that extend from impact craters, often several crater radii from the parent crater. They consist of deposited material that was ejected from the crater center and from secondary craters during impact.

Rays extending out from fresh craters are bright because they consist of fresh, high-albedo material which contrasts greatly with the mature surfaces around. When lunar soils are bombarded by meteoritic particles and exposed to solar wind, the optical properties of the soil changes (Lucey et al. 1998). With time, fresh lunar soils, displaced by different processes linked to impact cratering, mature and become indistinguishable from its surroundings as the material approaches optical maturity (Hawke et al. 2004).

It has been generally belived that rays fade and become indistinguishable after approximately one billion years. Craters lacking bright rays are generally thought to belong to the Eratosthenian system and craters with bright rays are generally thought to belong to the Copernican system that began ~1 Ga (see e.g. Melosh 1989). McEwen et al. (1997) explain that some of the craters with bright rays on the lunar nearside might in fact be significantly older than one billion years. If rays consist of highland-rich ejecta that is deposited over mare surfaces they will remain visible because of the contrast in albedo, even after the rays have reached full maturity. These rays will become indistinguishable only when the highland material is mixed significantly with mare material (Hawke et al. 2004). In contrast, only immature rays are visible on the lunar farside because of its more homogeneous composition.

3 Age Determinations and Methods for Determining Impactor Flux

The stratigraphic record of the Moon is separated into five periods: Pre-Nectarian, Nectarian, Imbrian, Eratosthenian and Copernican.

The pre-Nectarian period started with the formation of the Moon ~4.6 billion years ago. By definition, the pre-Nectarian period ended with the formation of the Nectaris basin (3.9 Ga; Hörz et al. 1991, see Grier & McEwen 2001), which also naturally defines the beginning of the Nectarian period. The impact resulting in the Imbrian basin (3.85 Ga; Wilhelms 1987, p. 279) separates the Nectarian period from the Imbrian period. The Imbrian period is divided into the Early Imbrian epoch and the Late Imbrian epoch which ended at 3.2 Ga. The Eratosthenian period is named after the crater Eratosthenes, and lasted ~2 billion years, from 3.2 to ~1 Ga.

The definition of the end of the Eratosthenian period, and the beginning of the Copernican period (~1 Ga to present) has been debated. Wilhelms (1987) placed the boundary between these periods at 1.1 Ga based upon an assumption of a constant cratering rate over the past 3.2 billion years. Hawke et al. (2004, 2006) and Grier et al. (2001) suggested that the duration of the Copernican period should be equal to the time required for a surface to reach full optical maturity, which is approximately 0.8 billion years. This means that craters older than Copernicus (810 Ma) should be assigned to the Eratosthenian period.

If it was possible to visit every lunar crater and bring samples back to Earth for radiometric dating it would obviously be the best way for determining if there has been any variations in the flux of impactors in post-Nectarian times, since the relative or absolute age of a crater is needed in order for analyzes of this purpose to be made. This however is not practicable. Instead, craters not visited and radiometrically dated are assigned to one of the stratigraphic systems based on e.g. their relationship to other craters and lunar surface features, the density of craters on their floors, changes in crater morphology and the optical maturity of crater rays.

3.1 Crater Counting

Variations in crater frequency can be determined through counting craters, generally on photographs, in order to determine possible fluctuations in cratering rate (McGill 1977). Apollo, Lunar Orbiter and Clementine missions have all provided photographs that can be used for this purpose.

If crater distribution is to be used as a dating method two general assumptions must be made (McGill 1977). The first one is that the rate at which craters form on a body (the Moon) is uniform at each place all over the body. The other assumption is that the rate of processes destroying craters must be much slower than the rate at which new craters form. If processes would destroy craters at a faster rate than the rate at which new ones form, the surface of the Moon would look more like Earth's surface. Neukum et al. (1975) explains that below a diameter of a few hundred meters, older populations of craters on the Moon are in fact being destroyed at the same rate as new craters are being formed. This means that these small craters do not represent all craters that have formed. Instead, the density of craters of this size, or smaller, has reached equilibrium (also called saturation). Thus, in order to determine a size-frequency distribution on these older surfaces, only the larger craters can be used. Neukum & Ivanov (1994) concluded that, e.g., craters of diameters <300 meters and ages >3.5 Ga or diameters <1 kilometer and ages >4 Ga are in a state of equilibrium.

Aside from these general assumptions it is also important, when applying this method, to make sure that the area on which the craters are to be counted is accurately determined and that it is one "homogeneous geologic unit" (Neukum & Ivanov 1994), and that the craters counted on a specific structure to be dated are superimposed, so that no craters from an underlying older unit are measured (Neukum & Ivanov 1994). An example of this is that when counting on mare surfaces one often can see the rims of older craters that have been covered with basaltic lavas during the formation of the mare.

Volcanic activity can lead to the formation of features that may look similar to impact craters. These craters are especially hard to separate from impact craters if they are small and degraded. Volcanic and/or secondary craters can strongly bias the results of counting on a small scale if they are not separated from the primary ones (McGill 1977).

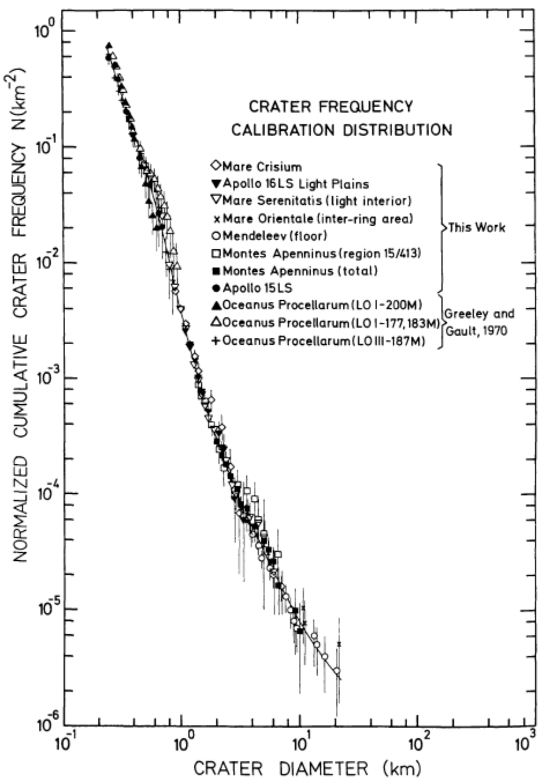


Fig. 1. The lunar standard size distribution curve from Neukum et al. (1975).

After counting craters and taking into account all of these parameters described above, the resulting crater size-frequency distribution is the same as, or close to, the production size-frequency distribution of a crater population. That means that it reflects the size-frequency distribution of the impactors and therefore it can be used for describing the history of impactors striking the Moon.

By counting craters over areas of different ages, >3 billion years old, Neukum et al. (1975) have compiled a general lunar size distribution for impact craters. They concluded, when the data was normalized to the frequency of Mare Serenitatis Light Interior, that "all crater populations investigated follow one general distribution behavior within the range of the statistical errors" (Fig. 1). This lunar standard size distribution curve has been frequently used in later works by e.g. McEwen et al. (1997), who compared their results of crater counting with the ones of Neukum et al. (1975). As can be seen in Fig. 7, there is great correspondence between these two curves.

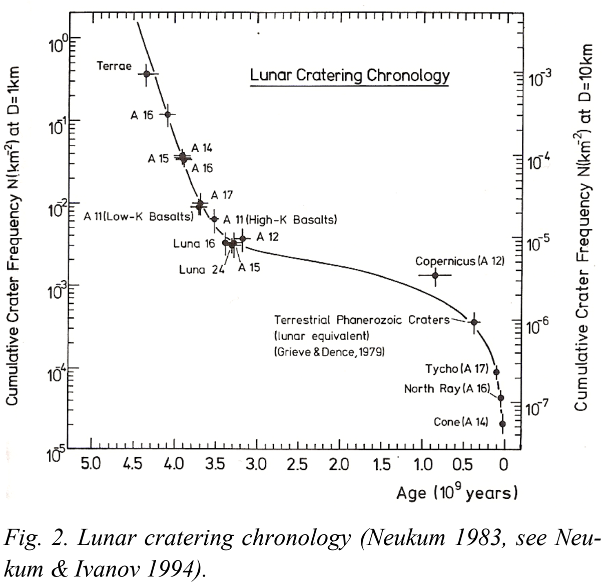


Fig. 2. Lunar cratering chronology (Neukum 1983, see Neukum & Ivanov 1994).

Neukum & Ivanov (1994) took the research further and concluded that through correlation of crater frequency with radiometric age data, an empirical determination of the impact chronology can be obtained (Fig. 2). The impact chronology is, therefore, "the functional dependence of the accumulated crater frequency on age or exposure time" (Neukum & Ivanov 1994). This functional dependence makes the absolute age of a lunar feature possible to determine from measurements of crater frequencies on images (Fig. 2, solid line), and the cratering rate as a function of time possible to derive (Neukum & Ivanov 1994). Neukum & Ivanov have, in their work, used the correlation between crater frequencies and radiometric ages from Neukum (1983). Then, in order to calculate the lunar cumulative impact rate one uses a mathematical function that gives the time derivative (rate of change) of the impact chronology relationship, $\partial N / \partial t$ = cumulative impact rate (Fig. 3).

3.2 The Optical Maturity (OMAT) Profile Method

Dating lunar craters solely based upon the assumption that craters with bright rays are young can be misleading since it is now clear that bright rays may in fact be older than one billion years (McEwen et al. 1997). The optical maturity profile method can provide more reliable relative ages for recent lunar craters.

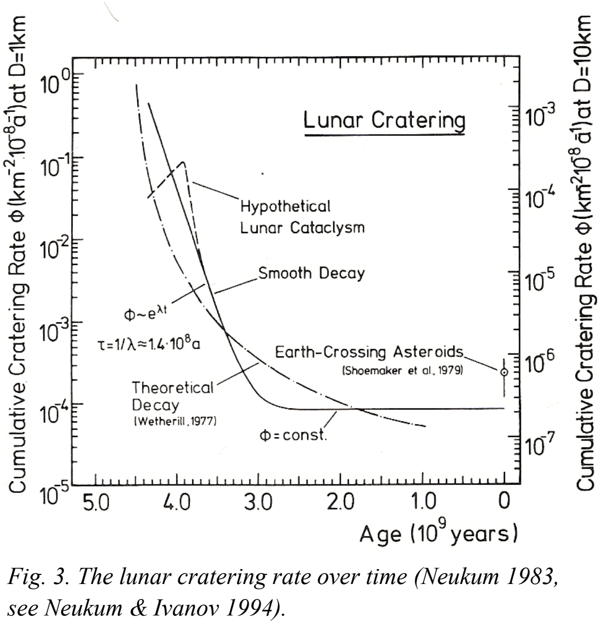


Fig. 3. The lunar cratering rate over time (Neukum 1983, see Neukum & Ivanov 1994).

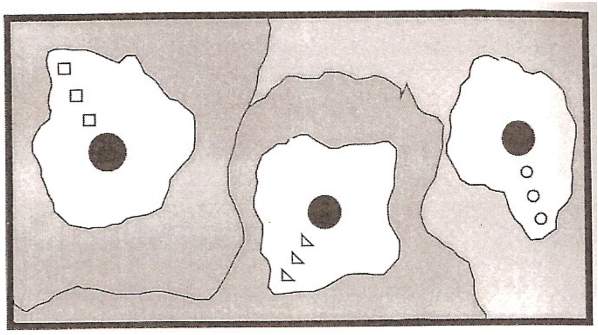


Fig. 4. The black circle represents a crater and the surrounding white area its ejecta blanket. The underlying terrains (grey areas) have different FeO content. The reflectance have been measured on several different places (squares, triangles and circles) and when plotted, it points to a hypothetical most-mature origin. "The OMAT parameter for any given point is the simple distance on the plot from the point to the mature origin". (Grier & McEwen 2001).

During the Clementine mission, launched in January 1994, the Moon was mapped by an ultraviolet-visual camera in five spectral bands with effective wavelengths of 415 nm, 750 nm, 900 nm, 950 nm and 1000 nm. This made it possible to examine the overall maturity level of the ejecta of each crater, because the "technique is sensitive to the spectral variation in soil samples of the same bulk chemical composition when exposed to lunar surface processes" (Grier & McEwen 2001). Grier & McEwen (2001) described the optical maturity (OMAT) parameter for any given point, defined by Lucey et al. (1998, 2000, see Grier & McEwen 2001), as "the simple Euclidean distance from the hyper-mature origin to each point on a trend" (see Fig. 4).

Grier et al. (1999) developed a way for large craters (≥20 kilometers) to be given a relative age based on their OMAT profiles (Fig. 5), a profile based on the OMAT value around craters. Each profile fell into one of three bins based on the absolute ages of a few lunar craters, including Tycho and Copernicus.

- Young: The crater's profile is characterized by high OMAT values near the rim that decreases steeply as the distance from the crater center increases.
- Old: OMAT values near the rim are very low and the profile has practically no slope. The ejecta is indistinguishable from the background.
- Intermediate: The ejecta is distinguishable from background some distance away from the crater, resulting in a somewhat flat profile with moderate OMAT values near the rim.

The OMAT curve of a crater of known age can then be compared with an OMAT curve of a crater of unknown age. Copernicus has a generally accepted age of 810 million years determined by radiometric dating. Grier et al. (1999) explains that the ejecta of crater

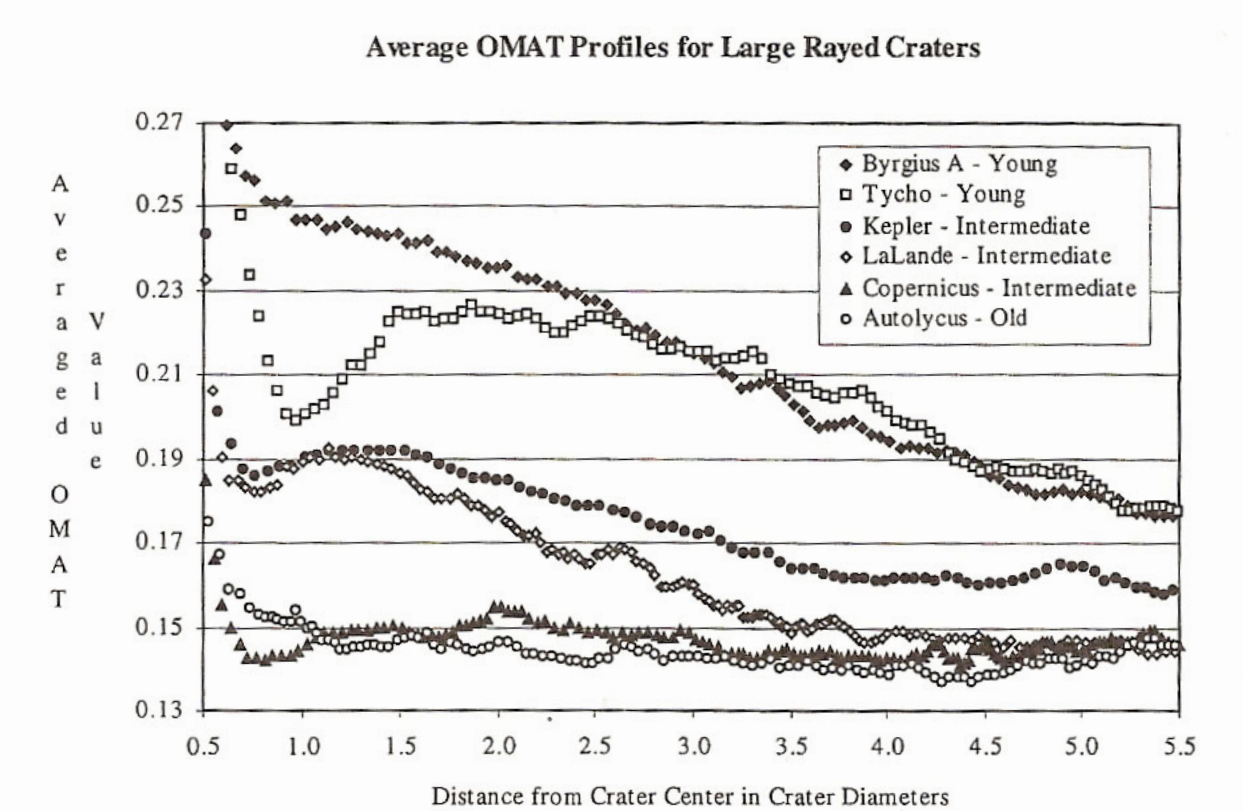


Fig. 5. Average OMAT-profiles for selected lunar craters. Differences in value and slope allows for classification of craters as either young, intermediate or old. (Grier & McEwen 2001).

Copernicus is almost entirely mature, resulting in a somewhat flat OMAT profile (see Fig. 5). Copernicus is either Old or on the old side of Intermediate, and has defined the upper limit of the OMAT profile technique. Thus, the method can only be used to date craters younger than about 800 million years (Grier et al. 1999).

3.3 Dating of Glass Spherules

Lunar spherules are "small glass beads that are formed mainly as a result of small impacts on the lunar surface" (Culler et al. 2000). The beads can also form due to volcanic eruptions, but these can be separated from the spherules of impact origin through different processes that will not be further discussed here. By analyzing the spherules with the $^{40}Ar/^{39}Ar$ isochron technique the ages of the impacts that created the spherules can be determined.

4 Impactor Flux Over the Past ~3.85 Billion Years

The impact record of both the Moon and Earth need to be studied in order to draw any definite conclusions on the impactor flux in the Earth-Moon system after ~3.85 Ga.

4.1 Changes in Impactor Flux; Evidence From the Moon

Today there are many ways, as described above, to evaluate the cratering record of the Moon in order to determine if there has been any change in the cratering rate in the past ~3.85 billion years. The techniques are different, but they have one thing in common. None of them has given a definite answer to if there has been any change in flux of crater forming bodies during this time.

Hartmann et al. (2007) evaluated earlier work on the cratering rate of the Moon by Neukum (1983, see Hartmann et al. 2007) and adjusted the crater production rate that Neukum (1983) had derived from counting craters. This was done in order to match the trends in recent work from different authors, e.g. the glass spherule data from Culler et al. (2000). The new curve presented by Hartmann et al. (2007) shows that there has been a decline in impact cratering from 2.3 billion years ago until today, of about a factor 3 (Fig. 6). Note that the curve is a plot of cumulative numbers of craters as a function of time and not a plot of cratering rate versus time. This curve (Fig. 6), presented by Hartmann et al. (2007), follows an equation from ~2.3 Ga to present:

Production rate (craters of D >1 km/km^2 per 200 Myr) $= 4.66(10^{-5})T + 5.59(10^{-5})$,

where D is diameter and T time in Gyr.

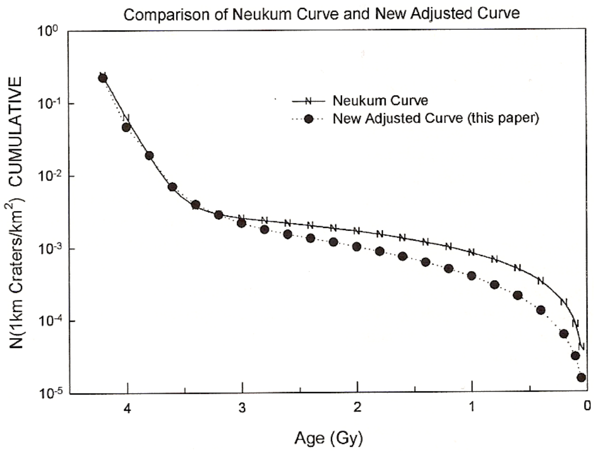


Fig. 6. Time dependence of the cumulative number of craters on the Moon (Hartmann et al. 2007).

In order to get an understanding of the impact cratering rate in recent time, McEwen et al. (1997) inspected the lunar farside and counted craters larger than 10 kilometers in diameter, which had rays that could be separated from the surroundings because of their higher albedo. The craters counted by McEwen et al. (1997) were then combined with nearside craters from Wilhelms (1987) to create a cumulative distribution, as seen in Fig. 7.

McEwen et al. (1997) created several possible solutions on the cratering rates of the Copernican and Eratosthenian periods, depending on the duration of the Copernican (Table 1). As described above, if the average Copernican cratering rate is equal to the average Eratosthenian cratering rate, the age of the Copernican has to be ~1 Ga. In the work by McEwen et al. (1997) they suggest that all craters on the farside with immature rays are no older than Copernicus. This suggestion is strengthened by the fact that Hawke et al. (2004, 2006) and Grier et al. (2001) suggested that the Copernican period could be defined by the time required for a fresh surface to reach optical maturity, as described above. Therefore, the oldest farside rayed craters must be approximately 0.8 billion years old, which is consistent with an average Copernican cratering rate ~35% higher than the average Eratosthenian cratering rate (Table 1).

The results of McEwen et al. (1997) need to be corrected, since several large craters that were assigned to the Copernican system are now known to have optical mature ejecta (Grier & McEwen 2001). Two of these craters are Eudoxus and Aristillus, which both were used in the study of McEwen et al. (1997).

System Durations, b.y.		Production of Craters ≥20 km, 10^{-15} km^{-2} yr^{-1}	
Copernican	Eratosthenian	Copernican	Eratosthenian
0.6	2.6	4.2 ± 0.6	2.1 ± 0.1
0.8	2.4	3.1 ± 0.5	2.3 ± 0.1
1.0	2.2	2.5 ± 0.3	2.5 ± 0.2

Table 1. Copernican and Eratosthenian crater production rates on the Moon. (McEwen et al. 1997)

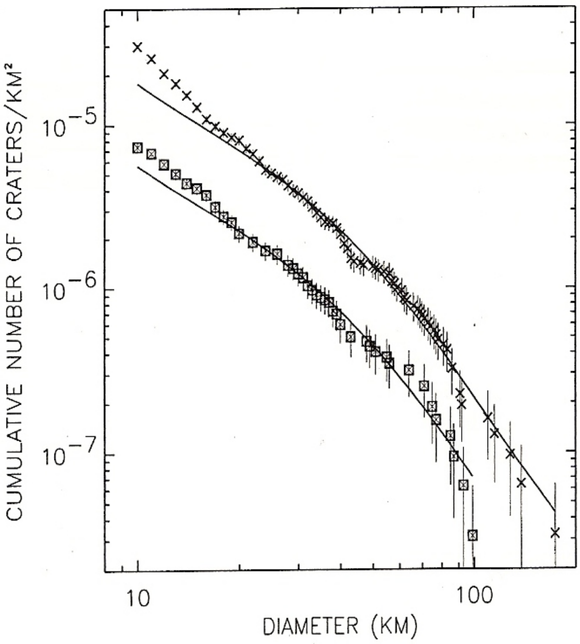


Fig. 7. Comparison of cumulative size-frequency distributions from the Copernican (squares) and combined Copernican and Eratosthenian craters (crosses from Wilhelms et al. 1978, see McEwen et al. 1997). The curves are the standard lunar distribution from Neukum et al. (1975). (McEwen et al. 1997).

This means that the average Copernican cratering rate, as suggested by McEwen et al. (1997), need to be adjusted and can no longer be ~35% higher than the average Eratosthenian cratering rate (Grier & McEwen 2001). Instead, when using the OMAT-profile method to identify craters of young age, Grier & McEwen (2001) concluded that the difference in crater rate between the last 0.8 billion years and that of the past 3.2 to 0.8 billion years is less than 10%. It is not yet possible however, from the data of Grier & McEwen (2001) to analyze any possible variations in cratering rate over time scales shorter than 100 million years. These results are supported by a study of Grier et al. (2000) in which they concluded that there have been no major changes in the flux of impactors to the Moon and Earth in at least the last one billion years. The results came from a study of OMAT-profiles of several both large and small lunar craters.

A constant cratering rate over the past 3 billion years was also supported by Neukum & Ivanov in their paper from 1994 (Fig. 3). The lunar cratering history shown in Fig. 3 was calculated by Neukum (1983) and shows a decrease in the cratering rate from 4.5 to 3.5 Ga, followed by a stable amount of infalling material. Neukum & Ivanov (1994) also used the lunar cratering history to calculate the history of impacts on Earth for the last 400 million years. The resulting average time between impacts creating craters that are one kilometre in diameter is about 1600 years for the whole Earth, and about every 6000 years for the continents. For craters 100 kilometres in diameter, the corresponding number is one event every 27 million years for the surface of the whole Earth.

Data from Culler et al. (2000) show that the production of lunar impact spherules from 3.5 Ga to the present has not been constant. The results of $^{40}Ar/^{39}Ar$ analysis of lunar impact spherules from a soil sampled during the Apollo 14 mission show that there has been a decrease in cratering rate from 3.0 Ga to 0.5 Ga, followed by a factor 4 increase over the last 0.4 Ga (Fig. 8). Hörz (2000) argued that the results of Culler et al. (2000) need to be tested further by analyzing spherules from additional lunar soils, sampled at different locations, before a definitive cratering rate can be established. Hörz (2000) also drew attention to the fact that the soil sampled by Apollo 14 may be effected by a local recent impact that led to the distribution of spherules to be concentrated in the last 0.4 billion years of lunar history. Further, Hörz (2000) said that recently produced impact spherules may be favoured by the fact that they have not been exposed to space weathering for as long as the average lunar soil.

Culler et al. (2000) did mention two possible biases in their work. The first one was the possibility that an excess amount of spherules from the sample were produced in the near by Cone impact, 25 Ma. To test the bias, Culler et al. (2000) removed the spherules whose ages were consistent with, or close to, 25 Ma. When removed, an increase in cratering rate of about a factor of ~2 was still present. The second bias mentioned by Culler et al. (2000) was the possible presence of younger material emplaced on top of the ejecta from the Cone crater. To test this bias, spherules with ages ranging from 0-25 Ma were removed. The spherules removed happened to be the same as the ones removed earlier, so the increase in cratering rate was still present.

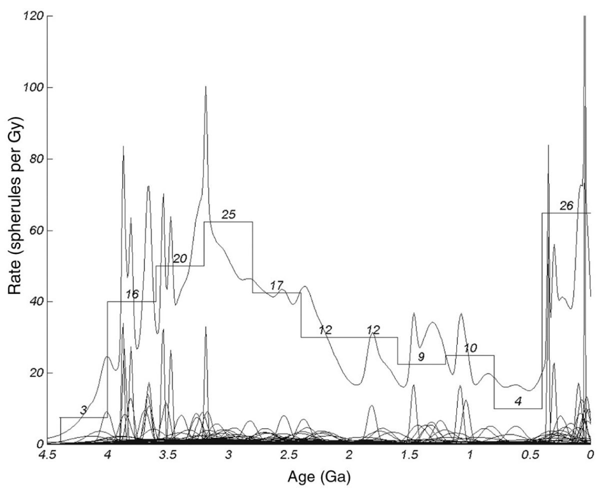


Fig. 8. Age distribution of 155 spherules. Each peak on the bottom represents a single spherule and the width corresponds to its age uncertainty. The line represents a summary of the peaks. The histogram has 0.4 Gyr bins normalized to the number of spherules formed per one billion years. Numbers above bins represents the number of spherules in that bin. (Culler et al. 2000).

Additional $^{40}Ar/^{39}Ar$ analyses have been made since Culler et al. (2000) presented the results of their research. Levine et al. (2005) used the technique to determine the ages of lunar spherules from a soil sampled during the Apollo 12 mission. Their results also showed an abundance of spherules younger than 400 million years, which is consistent with an increase in cratering rate in the inner Solar System, supporting the results of Culler et al. (2000). This can be seen in Fig. 9. Levine et al. (2005) noted, that even though their data is consistent with an increased infall of material on to the Moon, it "does not require this explanation".

4.2 Changes in Impactor Flux; Evidence From Earth

Generally, studies of the cratering record on Earth are more positive towards an increased cratering rate in recent time. Grier & McEwen (2001) pointed out that there is evidence for changes and/or periodicities in the infall of material to Earth in recent time. The four largest impact craters on Earth that are younger than 150 million years each correspond to a mass extinction. Grier & McEwen (2001) assume that no more than 15 % of such craters have been found because of the active geologic nature of Earth. If all mass extinctions are caused by impacts, a large crater should have been found at only one of six recent extinctions. If some mass extinctions are unrelated to infall of extraterrestrial material impact craters should have been found at less than one of the six recent extinctions (Grier & McEwen 2001). An explanation for this could be, according to Grier & McEwen (2001), that large impacts can be clustered in time. Evidence supporting this is the occurrence of two large craters at the Eocene-Oligocene boundary (see Fig. 12). Montanari et al. (1998) also provided evidence supporting this theory, as described below.

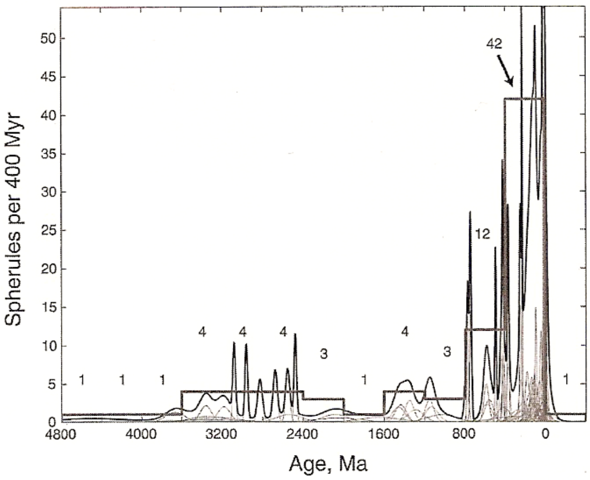


Fig. 9. Age distribution of 81 spherules. Each peak on the bottom represents a single spherule and the width corresponds to its age uncertainty. The line represents a summary of the peaks. The histogram has 0.4 Gyr bins normalized to the number of spherules formed per one billion years. Numbers above bins represents the number of spherules in that bin. (Levine et al. 2005)

In 1984 Alvarez & Muller presented a study of impact craters on Earth, with evidence for a periodic nature of the flux of impactors. For the study, Alvarez & Muller (1984) used a compilation of craters on Earth with diameters ≥10 kilometers, and ages between 5 and 250 million years. Fig. 10 is a statistical representation of the history of impacts resulting in craters ≥10 kilometers on Earth during this time interval, presented by Alvarez & Muller (1984). The arrows are placed at ~28 million year intervals, indicating a periodicity.

Alvarez & Muller (1984) also tested the occurrence of a periodicity with a method devised by S. Perlmutter. Montanari et al. (1998) describes how to use this method; "this test consists in computing all the time differences between any pair of dated events, and then representing the frequency with which any given value occurs in the data, as a function of the time difference itself". Each time difference is plotted as a peak, with the two errors of the corresponding ages combined in quadrature and these peaks then superimposed (Alvarez & Muller 1984). A periodicity of 28.4 million years is evident (Fig. 11).

In 1998 Montanari et al. presented a study in which they had investigated the cratering record on Earth with the same methods, only slightly modified and with more data, as Alvarez & Muller did in 1984. Montanari et al. (1998) concluded that there is no evidence for any periodicity in the flux of impactors to Earth in the last 150 million years based on 33 craters with diameters larger than 5 kilometers, and ages less than 150 million years.

Montanari et al. (1998) pointed out that even though their results show no convincing evidence of periodicity, there is an apparent clustering of craters closely spaced in time occurring on several places in the crater record (Fig. 12). There are four clusters of craters in Fig. 12; 1-5, 10-13, 15-19 and 21-24. To find out whether these clusters are random or not, Montanari et al. (1998) applied the Poisson formula, with which one can calculate the probability of a number of

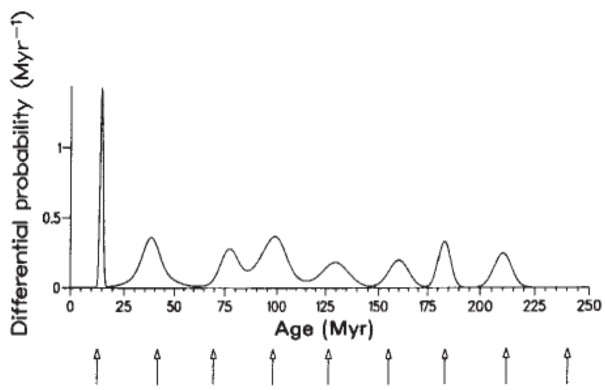


Fig. 10. Craters on Earth with ages between 5 and 250 million years. Arrows are placed at ~28 million year intervals. (Alvarez & Muller 1984).

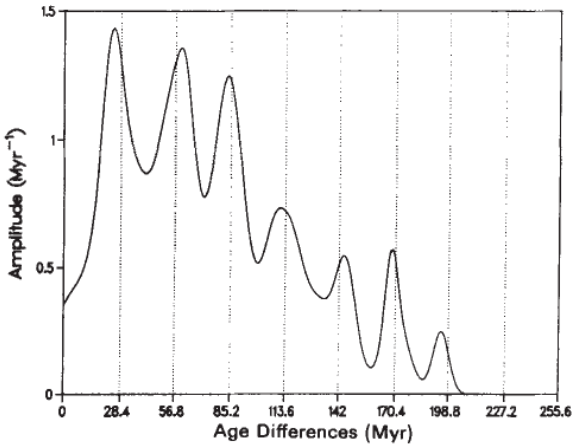


Fig. 11. Distributions of age differences between terrestrial craters. The difference in age between two craters was plotted as a peak. All the peaks resulting from the test were then added, resulting in the curve. Vertical lines indicate periodicity. (Alvarez & Muller 1984).

events (the number of craters) to occur in a time interval where a certain number of events are expected on average (the average number of impacts over e.g. 50 million years). The result was that these events had a priori probability of less than 10 percent chance to occur randomly. The youngest craters, number 1-5, are favoured by their young age and they have not been considered in the study.

4.3 Reasons for changes in the flux of impactors

Culler et al. (2000) concluded that there is evidence for an increase in the amount of impactors in the Earth-Moon system in recent time. The main reasons for an increased flux of impactors, suggested by e.g. Bottke et al. (2007) and Shoemaker (1998), may be due to collisions in the main asteroid belt and variations in the amount of comets reaching the inner Solar System originating from the Oort cloud.

Hartmann et al. (2007) drew attention to the fact that the increase in glass spherule production around 500 million years ago, detected by Culler et al. (2000) and Levine et al. (2005), corresponds to a breakup event in the asteroid belt. The peak in spherule production can be seen in both Culler et al. (2000) and Levine et al. (2005), here in Fig. 8 and 9. Evidence of the breakup event was detected in the results of Bogard (1995) who dated L-chondrite meteorites, and in the results of Schmitz et al. (1997, 2001 and 2003).

Bottke et al. (2007) suggests that an increase in the flux of crater-forming bodies in recent time is due to a break-up of a ~170-kilometer sized body in the innermost region of the main asteroid belt, producing the Baptistina asteroid family (BAF), approximately 160 million years ago. This break-up could have, according to the numerical simulations of Bottke et al. (2007), resulted in an increase in the population of near-Earth

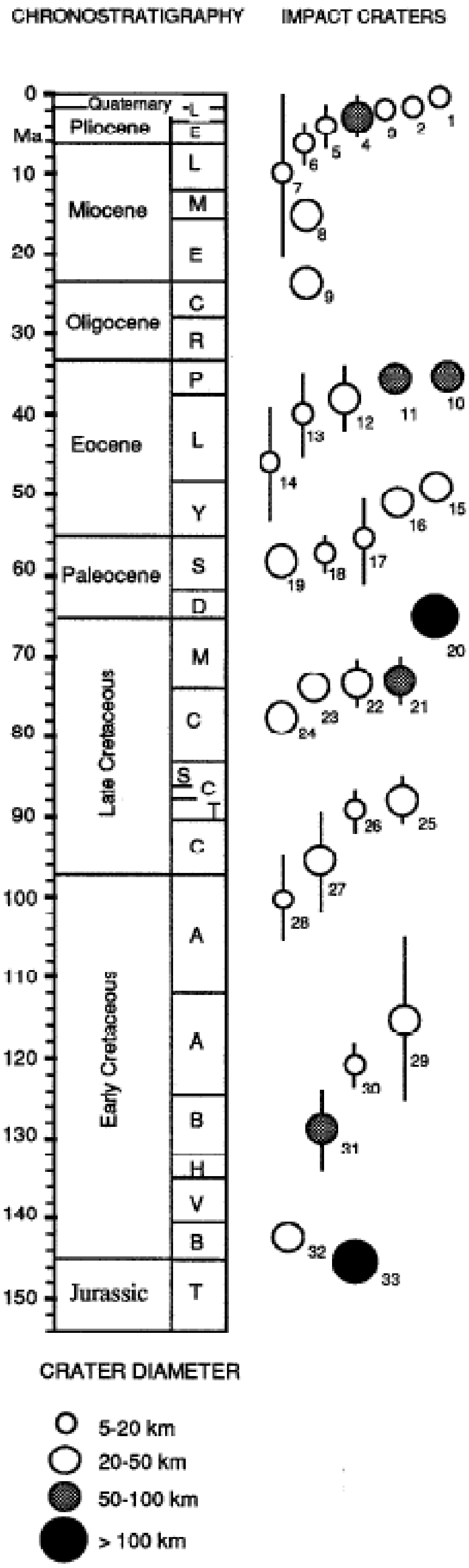


Fig. 12. Distribution of terrestrial craters through time. The craters have numbers, but they are not listed in this paper. (Montanari et al. 1998, modified).

objects (NEOs) for about 100 million years. Bottke et al. (2007) argue that the BAF is the source for the impactors that produced the Cretaceous/Tertiary impact on Earth and the Tycho crater on the Moon. However, according to Grier & McEwen (2001), Tycho crater would have formed even without the increased flux of NEOs noted by Bottke et al. (2007). According to statistics, one crater larger than 50 kilometers in diameter should have formed in the past 109 million years, and Tycho is the only one (Grier & McEwen 2001). The data came from a OMAT-value comparison of the cratering rates over the last 109 Myr with that of the past 810 Myr.

The break-up of large main-belt asteroids, causing occasional increases in impact crater production rate in the Earth-Moon system, is expected to occur every few hundred million years according to Shoemaker (1998). Further, Shoemaker (1998) say that about ten major break-up events are likely to have occurred in the last 3.2 billion years, in which Wilhelms (1987, p. 272) expected the cratering rate to be constant. Shoemaker (1998) assume that the timing of these events is random, causing the number of large craters produced by asteroid impacts to vary from each billion year interval to the next. Impact cratering as a function of comets entering the Earth-Moon system is, on the contrary, according to Shoemaker (1998) expected to be time variable. An explanation for an increase in the cratering rate may be a decrease in the amplitude of the motion of the Sun normal to the galactic plane, causing comets from the Oort cloud to be perturbed into Earth-crossing orbits. This was modeled by Matese et al. (1995). The results of this modeling showed a periodic nature of the flux of Oort cloud comets that directly cross Earth's orbit and those Jupiter-dominated comets that do not cross Earth's orbit. The mean period is, according to Matese et al. (1995), 33 million years, with a standard deviation of less than 5 million years.

5 Discussion

Cratering rate in the Earth-Moon system is studied in order to obtain information on the evolution of our planet, the evolution of life, what causes mass extinctions and the current impact hazard on Earth. Although speculative, there is a chance that Earth in a not to distant future will be struck by an object that is large enough to cause a biological and social crisis.

5.1 Impactor Flux

Evaluations of the crater record of the Moon by crater counting are often based on studies performed two or three decades ago. The articles of Neukum et al. (1975) and Neukum (1983) are the most frequently used ones. Hartmann (2007) explained why these data are considered so reliable: "we assume the cratering rate from Apollo/Luna sites, being simply and directly observed from cumulative craters on surfaces of well-characterized age". However, mistakes are made today and they were definitely made two decades ago.

If the infall of material on a body in the inner Solar System is not randomly distributed all over the body, but under the influence of a latitudinal effect, as suggested by Le Feuvre & Wieczorek (2006), the results of crater counting are biased. If there is a higher amount of impactors striking either the high latitudes, or the equatorial region of a planet, crater counting on a geologic formation in one of these areas would result in biased ages. Where there is a greater infall of material, the age of the formation would be estimated to be too old, and a formation where there is less infall of material would have an estimated age younger than its true age. However, since several production size-frequency distributions have been determined for the Moon, where the data from several lunar craters actually fit the same curve a latitudinal effect cannot be expected to have a major impact on crater distribution.

Neukum & Ivanov (1994) calculated the recurrence interval of large impacts to be 27 million years on Earth, based on the cratering record on the Moon. Alvarez & Muller (1984) suggested that the formation of a large crater (≥10 kilometers in diameter) occur every ~28 million years. This is a strange coincidence that should be further tested to see if there is in fact some sort of periodic nature of impacts in the inner Solar System. These results of Neukum & Ivanov (1994) and Alvarez & Muller (1984) could indicate that the comet-flux modeling of Matese et al. (1995) is right, and that comets are responsible for many large impacts on the Moon and Earth, just as Shoemaker (e.g. 1998) suggested.

The studies of OMAT-profiles presented in this paper indicate that no major changes in the impactor flux in the Earth-Moon system has occurred in at least the last one billion years. It is not clear however if the results of an OMAT-profile study can be considered reliable since there are several possible sources for biased results. Lucey et al. (1998b) noted that when an OMAT-profile is used as an absolute age determination tool that is coupled with crater densities, for determinations of impactor flux, the technique "would actually measure the differential rate between the macrometeorite flux and the processes controlling optical maturity, which is some combination of solar wind gas and micrometeorite flux with unknown relative weights". This would mean that during periods of high solar wind activity the optical properties of the lunar regolith might change faster than currently believed, resulting in an age bias.

The results of Grier & McEwen (2001) and Grier et al. (2000) have been considered as implications for a stable cratering rate during at least the last one billion years. It is interesting that none of the OMAT studies show any evidence for the asteroid break-up events at ~500 Ma and ~160 Ma, even though the first event might explain the results of the spherule dating studies of both Culler et al. (2000) and Levine et al. (2005), and that it has in fact been confirmed by high amounts of extraterrestrial chromite grains from decomposed meteorites in Swedish marine limestone (e.g. Schmitz et al. 2003). The events not being seen in the results of OMAT studies can be explained by the fact that Grier & McEwen (2001) said that no variations over time scales shorter than 100 Ma could be detected. However, the apparent increase in impactor flux starting at about 500 Ma, suggested by Culler et al. (2000) should be evident in OMAT-profile studies if it is real. It is not though, and if the results of the OMAT studies are true, a possible explanation for this could be that impact spherule dating only is reliable for recent spherules, because older ones (>500 Ma?) are destroyed or altered by space weathering, as Hörz (2000) suggested. Another possible explanation could be displacement of lunar soils due to later impact events. Why Fig. 8 and 9 look so different before ~500 Ma is probably a combination of sampling on different locations and the method having these weaknesses. The high amount of spherules younger than ~500 Ma may also reflect the formation of some other crater nearby between 25-500 Ma. The Cone crater is probably not the only crater that has formed during that time period. How to explain the abundant amount of chromite grains without an increased amount of infalling material to Earth is harder though.

A declining curve of impactor flux or cratering rate in the inner Solar System was presented by Hartmann et al. (2007). Actually, the main tendency for the impactor flux should be to slowly decline since with time, there will be less material left to impact the planets. As the asteroids in the asteroid belt becomes less and less, collisions causing smaller asteroid-pieces to form an increased amount of craters on the Moon and Earth during a short period of time (e.g. 50 million years), will become more rare. Around the steady declining main curve for impactor flux there should be occasional peaks with more impacts occurring during time intervals.

Neukum & Ivanov (1994) supported the results of Neukum (1983). A constant cratering rate since 3.0 Ga (Fig. 3) seems unlikely since the effects of at least one major asteroid break-up event has been observed on Earth (e.g. Schmitz et al. 2003). Unless a constant amount of asteroid break-up events has happened throughout history, causing the impact cratering rate curve to be flat from 3.0 Ga, the results of Neukum (1983) must be wrong. Either way, the curve should be up for re-evaluation since it is so old.

In spite of the fact that the cratering record on Earth is very much incomplete, many studies on cratering rate has been made with the, at the time, known craters on Earth as background data. Two such studies are presented in this paper; the one by Alvarez & Muller (1984) and the one by Montanari et al. (1998). Since Montanari et al. (1998) used the same data as Alvarez & Muller, plus additional craters, they should have presented the same results, but they did not. Additional evidence supports the results of Alvarez & Muller (1984), as described above, indicating that their study might be right. However, no recent studies of crater counting on the Moon, impact spherules or OMAT-profiles of craters that support the occurrence of periodic impactors have been found. The results of Montanari et al. (1998) are convincing when they show that there is some sort of correlation between groups of impacts over intervals of several million years. A large percentage of the total amount of craters striking the Earth during the last 150 Ma is missing, but Montanari et al. (1998) concluded that these events would have had a less than 10 % chance to occur randomly. Even if there is no periodic nature of the flux of impactors to the Moon and Earth, there might have been time intervals of several million years during the history of the inner Solar System when the flux of crater-forming bodies has been many times greater than the average. A variable cratering rate as a result of asteroid break-ups and maybe changes in the cometary flux is highly likely. No information on the spread in time of large impacts on the Moon has been found because of the time limit. If there is no such research it would be interesting to study the occurrence of large craters on the Moon to see if there is a tendency for them to be clustered in time.

More studies of other bodies in the inner Solar System are needed in order to draw conclusions on the evolution of the impactor flux. Hopefully, new photographs of Mercury will allow for OMAT-studies and crater counting studies, that can answer questions about the impactor flux in the inner Solar System.

6 The Study

The research projects discussed in this paper clearly generally give very different results. The implementation of a new study of crater counting on lunar structures with available age data would hopefully provide new information on how to interpret the results of previous studies and maybe reveal tendencies of the impactor flux to the Moon that need to be further tested. Therefore, such a study was performed.

12 lunar structures were chosen for the study (Table 2). All visible craters inside the main structure were counted, in order to evaluate the history of impacts during the time since the main structure formed.

6.1 Method

For this study pictures from the “Lunar Orbiter photographic atlas of the near side of the Moon”, by Byrne (2005), have been used. Most of the pictures in the book were produced by the Lunar Orbiter Mission 4, launched in august 1967. The pictures from Byrne (2005) were generally the most suitable ones available because of their high quality. However, they were not always of good enough quality, especially for the smaller structures. The photographs of Alphonsus, Plato, Copernicus, Kepler and Triesnecker (see chapter 9 for references) were taken from the internet.

Time Unit (Period)	Time Unit (Epoch)	Age (Ga)	Craters (diameter in km)	Reference
Copernican		0.1	Tycho (85)	Grier & McEwen 2001
			Triesnecker (25.7)	Grier & McEwen 2001
			Kepler (31.8)	Grier & McEwen 2001
			Stevinus (71.3)	Grier & McEwen 2001
		0.8	Copernicus (92.5)	Grier & McEwen 2001
		~0.8-1	Eudoxus (67.1)	Grier & McEwen 2001
Earatosthenian				
			Aristoteles (87)	Byrne 2005
			Hercules (69)	Cook 2005 (size), Byrne 2005 (age)
		3.2		
Imbrian	Late Imbrian		Plato (101)	Byrne 2005
			Mare Humorum(?)	North 2007
	Early Imbrian			
		3.85	Alphonsus (119)	Wilhelms 1987
Nectarian				
			Endymion (125)	Cook 2005 (size), Byrne 2005 (age)
		3.9		
Pre-Nectarian				

Table 2. Lunar stratigraphic systems and structures chosen for the study.

Each photograph has been reduced and is presented in Appendix 1A-L. For Eudoxus, Aristoteles, Stevinus, Kepler, Triesnecker and Tycho additional photographs from different angles and in different lighting were used. The reason why these structures were chosen is simply because of the available age-data on them, their spread in time and the possibility of counting craters of the smallest possible diameter. There are of course many more structures that could have been chosen but the time limit only allows for counting on these 12 structures.

Each photograph of a chosen structure was covered with a transparent overlay and then craters were measured and counted. No craters smaller than 1 mm in diameter were counted on any structures. After each crater was counted it was crossed over on the overlay in order to avoid counting the same crater more than once. The total counting area was calculated with simple geometry, resulting in what could be a minor area bias for craters, since they are not perfect circles. For later comparison of different surfaces, two unit areas (10^8 km^2 and 1 km^2) were divided by the total counting area in order to obtain a normalizing factor for the surface. The millimeter diameter of each crater was converted into the equivalent real km-diameter before the total number of craters of a certain diameter was multiplied by the normalizing factor.

In order to find out how the amount of craters on each structure is related to the structure's age the number of craters per 1,000,000 km^2, in the diameter interval 1-2 km, was divided by the age of the structure itself to obtain the average number of craters that formed on this area per one billion years.

The diameter interval 1-2 kilometers has been used because there are not enough craters in the bigger diameter intervals for all main structures, and because of the possibility of comparing the results of this study with those of others, in which craters of one kilometer in diameter are most often plotted and analyzed.

6.2 Results

Craters of small diameters are far more abundant than larger ones on the 12 structures (Appendix 2A-C). This results in curves that decline towards larger crater diameters, to the bottom right (Fig. 13). Craters having too few data points (Hercules, Stevinus and Tycho) do not form curves. Craters Kepler and Triesnecker did not reveal any small craters inside the main structure, and therefore they are not included in the diagrams and tables (Appendix 2C).

The number of craters in the diameter interval 1-2 kilometers is higher for craters of greater age (Fig. 14). An exception from this is crater Endymion, which has the greatest age but not the highest total number of craters in this interval (Fig. 14).

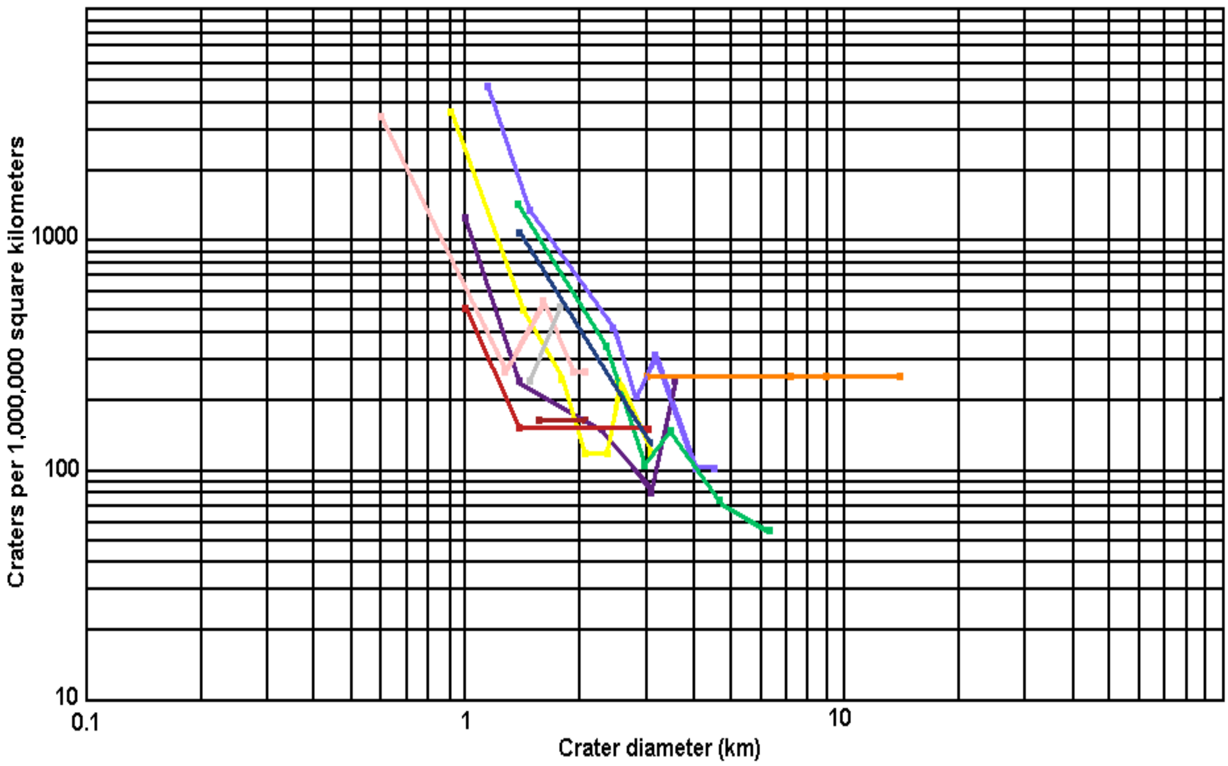
Crater Plato was plotted both with only the craters in the interval 1-2 km included, and with these craters plus the interval 0.795-1.06 km included (Fig. 14, yellow data points). The interval 0.795-1.06 km should however not be included since that clearly makes the values for Plato too high (Fig. 14).

Generally, the data from this study is similar to that presented in earlier studies (Table 2), e.g. Neukum et al. (1975), McGill (1977) and Neukum (1983, see Neukum & Ivanov 1994). An imaginary curve connecting data points from this study (Fig. 14) would have many similarities with the results of Neukum (1983, see Neukum & Ivanov 1994), seen in Fig. 2, if crater Endymion had the highest number of craters in the interval 1-2 km.

The average number of impactors striking the main structures per one billion years since the formation of the structure has not been stable through time (Table 4). The young structures have high values, and the old structures have lower values. An exception from this is Alphonsus, which has values that are similar to those of the younger structures (Table 4).

6.3 Discussion of the Study

There are some uncertainties in the results of this study, mainly because an age bias. Aristoteles and Hercules are Eratosthenian in age according to Byrne (2005), but the Eratosthenian period lasted at least 2.2 billion years. Further, Eudoxus is Old and Stevinus Intermediate/Old according to their OMAT-profiles (Grier & McEwen 2001). In this paper they have been given the same age as Copernicus, but they could in fact be younger, especially Stevinus. Since Copernicus has defined the upper limit of the OMAT-profile tech-



Color	Crater	Age
Purple	Endymion	Nectarian
Blue	Alphonsus	Early Imbrian
Green	Mare Humorum	~3.2 Ga
Yellow	Plato	Late Imbrian
Orange	Hercules	Eratosthenian
Red	Aristoteles	Eratosthenian
Pink	Eudoxus	Old (OMAT-profile)
Dark blue	Copernicus	Intermediate/Old (OMAT-profile)
Grey	Stevinus	Intermediate/Old (OMAT-profile)
Dark red	Tycho	Young (OMAT-profile)

Fig. 13. Number of craters per 1,000,000 km² (data from Appendix 2A-C).

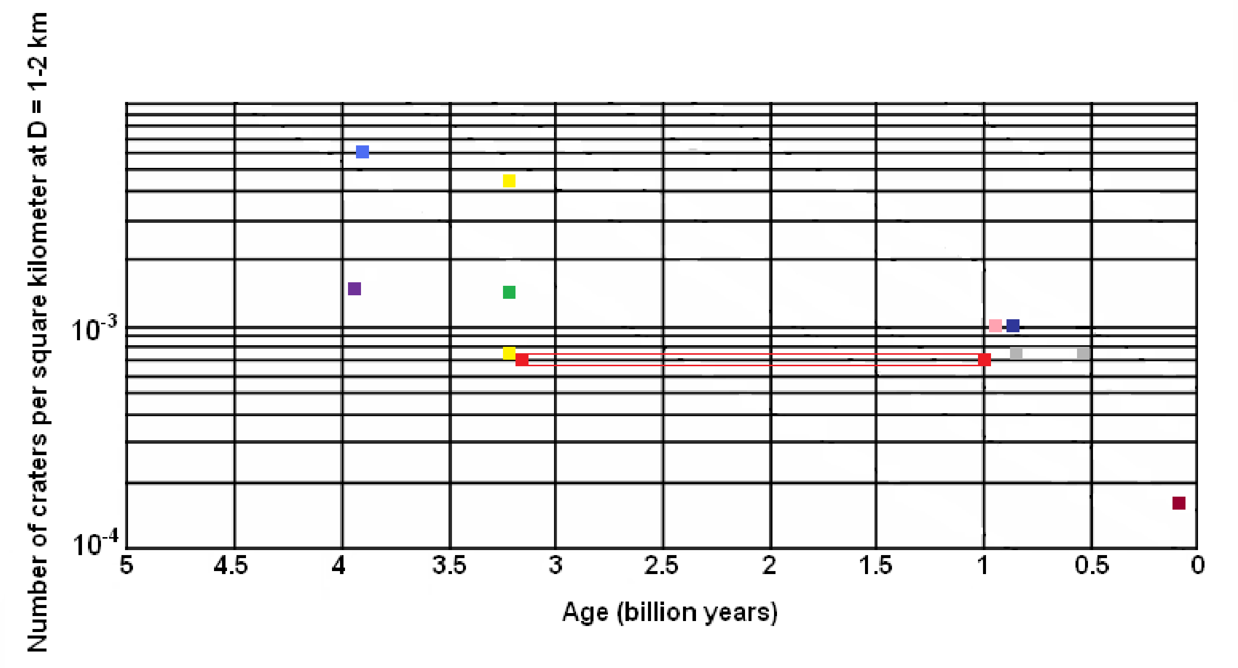


Fig. 14. The number of small craters (diameter 1-2 km) inside the 12 main structures per one km² plotted against the age of the main structure. Elongated data points (red and grey) represent age uncertainties. See Fig. 13 for legend.

nique they were not considered older than 0.8 Gyr. There has also been a too small amount of structures chosen for counting in order to retrieve results that would be statistically significant. Also, on some pictures it was hard to identify certain craters and some might have been missed, while others of the same diameter were counted. In spite of these three aspects, the study gave results similar to earlier ones.

The general declining tendency for Fig. 13 is a natural reflection of smaller impactors more commonly striking the surface of the Moon, and younger structures having smaller total amounts of craters is a natural reflection of the time they have been exposed to impact cratering.

As explained above, crater Endymion has too few craters inside the main structure for its old age. This could be a reflection of the bad quality of the available pictures of Endymion, compared with those of, e.g., Alphonsus. Triesnecker and Kepler having no visible craters inside the main structure may either be because there are none, or because of the photographs not being good enough. Tycho is younger than both these craters but it had at least two small craters inside. However, Tycho is more than twice as big as Kepler and more than three times as big as Triesnecker, and therefore it is more likely to have been struck by an impactor since its formation.

Neukum & Ivanov (1994) explained that the values of crater frequency for Copernicus appear to be somewhat too high, even though the crater frequency for it has been assured several times through measurements. This could, according to Neukum & Ivanov (1994) be because of its absolute age (given based on Apollo 12 data) being wrong. In Fig. 2 one can see that crater Copernicus lays above the line. In Fig. 14 and Table 4, made with data from this study, Copernicus actually seems to have values that are too high for its age. A comparison of the values of Copernicus and those of Eudoxus and Stevinus was made in order to conclude if the data for Copernicus is too high. Stevinus (age 0.8) has much lower values than Copernicus, if Stevinus is given an age of 0.5 Ga its values are high and Eudoxus have values that are high too. If Copernicus is in fact 810 million years old, the high number of craters may indicate a higher flux of infalling material in recent time, or at least during a shorter period of time in the last 0.8 Ga. If Copernicus is older than 810 million years that would explain the high values from Table 4. Tycho also has values that are very high compared to those of older craters. All these four craters have ~1000-1500 crater forming events per one billion years. It corresponds to about a factor 6 increase in impactor flux compared to the values of Plato and Aristoteles, and about a factor 3 increase compared to the values of Mare Humorum. It may however be a much bigger increase over a short period of time, resulting in the high numbers, maybe by as much as a factor 10. Even if Copernicus is given an age of 1 Ga its values are above 1000 (1041.66) craters on 1,000,000 km² per one billion years. The age of Eudoxus should be older than Copernicus, but the exact age is not known. Regardless whether the age is 0.8 or 1.0 Ga its values are still above 1000.

If the number of craters counted on, e.g., Aristoteles are too low then the values for the number of crater forming events per one billion years would go up. The values for a surface of the same age was retrieved from Fig. 2, which is about 1000 craters per

Structure	Number of craters D ~ 1 km (km^{-2}) (This study)	Number of craters D = 1 km (km^{-2}) (From Neukum 1983, see Neukum & Ivanov 1994)
Plato/Mare Crisium*	~3.74×10^{-3}	$(3.0 \pm 0.6) \times 10^{-3}$
Mare Humorum/Mare Crisium*	1.55×10^{-3}	$(3.0 \pm 0.6) \times 10^{-3}$
Copernicus	1.04×10^{-3}	$(1.3 \pm 0.3) \times 10^{-3}$
Tycho	1.76×10^{-4}	$(9.0 \pm 1.8) \times 10^{-5}$

* Compared to structure having the same age in Neukum (1983, see Neukum & Ivanov 1994).

Table 3. Comparison of selected data from this study with that of Neukum (1983, see Neukum & Ivanov 1994). For all but Mare Humorum the values of this study are the same as those of Neukum (1983, see Neukum & Ivanov 1994), within the uncertainties.

1,000,000 km^2 at D = 1 km. The resulting number of craters forming per one billion years is 400 if the age of Aristoteles is estimated to be 2.5 Ga and 344.8 if its age is estimated to be 2.9 Ga (Table 4). This means that the values for Copernicus, Eudoxus, Stevinus and Tycho are still too high.

The values for Alphonsus in Table 4 are close to those of Copernicus, Eudoxus, Stevinus and Tycho, indicating that the impactor flux was much higher around its formation, since the values are so low for Aristoteles. This could mean that the impactor flux was high around 3.8 Ga, lower around 2.5 Ga and then increased late in geologic time. It is likely that the impactor flux was low around 3.2 Ga, considering the values in Table 4 for Mare Humorum. Since these values are the average number of crater-forming events per one billion years, it does not necessarily indicate that the cratering rate has been constant for every one billion year interval since the time of the formation of the crater. It is more likely, as described above, that the impactor flux has varied.

In order to conclude if Copernicus has been given an age that is not true it needs to be sampled again, or crater counts of every main structure that has been given a relative age based on its OMAT-value can be performed to see how well those values correspond to those of Copernicus.

The results of this study can not be considered truly reliable since counting has been done on too few lunar structures. It has, however, revealed interesting tendencies of the impactor flux that should be further tested.

Crater (age in billion years)	Number of craters 1-2 km in diameter per 1,000,000 km^2	Average number of crater-forming events on 1,000,000 km^2 per one billion years
Endymion (3.9)	1629.28	417.76
Alphonsus (3.8)	6208.37	1633.78
Mare Humorum (3.2)	1546.16	483.18
Plato (3.3)	4493.37*	1361.62
Plato (3.3)	748.89	226.94
Aristoteles (2.5)[1]	672.87	269.15
Aristoteles (2.9)[1]	672.87	232.02
Eudoxus (0.8)	1131.16	1413.95
Copernicus (0.8)	1041.66	1302.08
Stevinus (0.8)[2]	751.37	939.21
Stevinus (0.5)[2]	751.37	1502.74
Tycho (0.1)	176.2	1762

* The interval 0.795-1.06 km also included.

[1] Different ages based on the uncertainty of the crater's age.

Table 4. Craters with calculated average amount of crater-forming events on 1,000,000 km^2 per one million years since the

7 Conclusions

Information about the flux of impactors in the inner Solar System can be retrieved from the crater record of the Moon. The record of impacts on Earth is too altered to be used for this purpose.

The methods currently used for evaluating the crater record of the Moon, such as the OMAT-profile method and dating of impact glass spherules needs to be refined. Currently, as a method for evaluation of impactor flux through time, crater counting must be considered as the most reliable. It is the only one that is based on direct observations of the lunar surface.

A constant impactor flux during the last 3 billion years is not likely as long as a constant amount of asteroid break-up events do not happen through time. The evidence of a variable cratering rate are convincing, especially since the results of the study performed for this paper has revealed tendencies for an increased impactor flux (maybe as much as a factor 6 increase) in the last 0.8-1 billion years.

8 Acknowledgements

I would like to thank my supervisor Birger Schmitz for his great commitment to this project. Thank you for taking the time to read manuscripts, answering questions and providing literature, and also for helpful discussions and making suggestions for improvements.

I would also like to thank everyone else that have supported me, especially Anders Cronholm and Carl Alwmark.

9 References

Alvarez, W. & Muller, R.A., 1984: Evidence from crater ages for periodic impacts on the Earth. *Nature 308*, 719-720.

Bogard, D.D., 1995: Impact ages of meteorites: A synthesis. *Meteoritics 30*, 244-268.

Bottke, W.F., Vokrouhlický, D. & Nesvorný, D., 2007: An asteroid breakup 160 Myr ago as the probable source of the K/T impactor. *Nature 449*, 48-53.

Bottke, W.F., Levison, H.F., Nesvorný, D. & Dones, L., 2007b: Can planetesimals left over from terrestrial planet formation produce the lunar Late Heavy Bombardment? *Icarus 190*, 203-223.

Byrne, C.J., 2005: *Lunar orbiter photographic atlas of the near side of the Moon*. Springer-Verlag, London. 329 pp.

Culler, T.S., Becker, T.A., Muller, R.A. & Renne, P.R., 2000: Lunar impact history from $^{40}Ar/^{39}Ar$ dating of glass spherules. *Science 287*, 1785-1788.

Cook, J. (editor), 2005: The Hatfield SCT lunar atlas: photographic atlas for Meade, Celestron and other SCT telescopes. Springer-Verlag, London. Unpaginated.

Grier, J.A., McEwen, A.S., Lucey, P.G., Milazzo, M. & Strom, R.G., 1999: The optical maturity of ejecta from large rayed craters: Preliminary results and implications. In Gaddis, L.R. & Shearer, C.K. (conveners) *Workshop on new views of the Moon II; understanding the Moon through the integration of diverse datasets*, 19-21.

Grier, J.A., McEwen, A.S., Milazzo, M., Hester, J.A. & Lucey, P.G., 2000: The optical maturity of the ejecta of small bright rayed lunar craters. Papers presented to the thirty-first lunar and planetary science conference, abstract number 1950.

Grier, J.A & McEwen, A.S., 2001: The lunar record of recent impact cratering. In Peucker-Ehrenbrink, B. & Schmitz, B. (editors) *Accretion of extraterrestrial matter throughout Earth's history*, 403-422. Kluwer Academic/Plenum Publishers, New York.

Grier, J.A., McEwen, A.S. & Lucey, P.G., 2001: Optical maturity of ejecta from large rayed lunar craters. *Journal of Geophysical Research 106*, 32,847-32,862.

Hartmann, W.K., 1965: Terrestrial and lunar flux of large meteorites in the last 2 billion years. *Icarus 4*, 157-165.

Hartmann, W.K., 1970: Lunar cratering chronology. *Icarus 13*, 299-301.

Hartmann, W.K., Quantin, C. & Mangold, N., 2007: Possible long-term decline in impact rates. 2. Lunar impact-melt data regarding impact history. *Icarus 186*, 11-23.

Hawke, B.R., Blewett, D.T., Lucey, P.G., Smith, G.A., Bell III, J.F., Campbell, B.A. & Robinson, M.S., 2004: The origin of lunar crater rays. *Icarus 170*, 1-16.

Hawke, B.R., Gaddis, L.R., Blewett, D.T., Boyce, J.M., Campbell, B.A., Giguere, T.A., Gillis-Davis, J.J., Lucey, P.G., Peterson, C.A., Robinson, M.S. & Smith, G.A., 2006: The composition and origin of lunar crater rays: Implications for the Copernican-Eratosthenian boundary. Papers presented to the thirty-seventh lunar and planetary science conference.

Hörz, F., Grieve, R., Heiken, G., Spudis, P. & Binder, A., 1991: Lunar surface processes. In Heiken, G., Vaniman, D. & French, B. (editors) *The lunar sourcebook: A user's guide to the Moon,* 61-120. Cambridge University Press, Cambridge.

Hörz, F., 2000: Time-variable cratering rates? *Science 288*, 2095a.

Keil, K., Haack, H. & Scott, E.R.D., 1994: Catastrophic fragmentation of asteroids: evidence from meteorites. *Planetary and Space Science 42*, 1109-1122.

Le Feuvre, M. & Wieczorek, M.A., 2006: The asymmetric cratering history of the terrestrial planets: Latitudinal effect. Papers presented to the thirty-seventh lunar and planetary science conference.

Levine, J., Becker, T.A., Muller, R.A. & Renne, P.R., 2005: $^{40}Ar/^{39}Ar$ dating of Apollo 12 impact spherules. *Geophysical Research Letters 32*, L15201.

Lucey, P.G., Blewett, D.T. & Hawke, B.R., 1998: FeO and TiO_2 concentrations on the South Pole Aitken basin: Implications for mantle composition and basin formation. *Journal of Geophysical Research 103*, 3701-3708.

Lucey, P.G., Taylor, J. & Hawke, B.R., 1998b: Global imaging of maturity: Results from Clementine and lunar sample studies. Papers presented to the twenty-ninth lunar and planetary science conference, abstract number 1356.

Lucey, P.G., Blewett, D.T. & Hawke, B.R., 2000: Imaging of lunar surface maturity. *Journal of Geophysical Research 105*, 20,387-20,402.

Matese, J.J., Whitman, P.G., Innanen, K.A. & Valtonen, M.J., 1995: Periodic modulation of the Oort cloud comet flux by the adiabatically changing galactic tide. *Icarus 116*, 255-268.

McEwen, A.S., Moore, J.M. & Shoemaker, E.M., 1997: The phanerozoic impact cratering rate: Evidence from the farside of the Moon. *Journal of Geophysical Research 102*, 9231-9242.

McGill, G.E., 1977: Craters as “fossils”: The remote dating of planetary surface materials. *Geological Society of America Bulletin 88*, 1102-1110.

Melosh, H.J., 1989: *Impact cratering: A geologic process*. Oxford University Press, New York. 245 pp.

Montanari, A., Campo Bagatin, A. & Farinella, P., 1998: Earth cratering record and impact energy flux in the last 150 Ma. *Planetary and Space Science 46*, 271-281.

Neukum, G., König, B. & Arkani-Hamed, J., 1975: A study of lunar impact crater size-distributions. *The Moon 12*, 201-229.

Neukum, G., 1983: Meteoritenbombardement und datierung planetarer oberflächen. Habilitation Dissertation for Faculty Membership, Ludwig-Maximilians-University of Munich.

Neukum, G. & Ivanov, B.A., 1994: Crater size distributions and impact probabilities on earth from lunar, terrestrial-planet, and asteroid cratering data. In Gehrels, T. (editor) *Hazards due to comets and asteroids*, 359-416. University of Arizona Press, Tucson.

North, G., 2007: Observing the Moon: A modern astronomer’s guide. Second Edition. Cambridge University Press, Cambridge/New York. 408 pp.

Schmitz, B., Peucker-Ehrenbrink, B., Lindström, M. & Tassinari, M., 1997: Accretion rates of meteorites and cosmic dust in the early Ordovician. *Science 278*, 88-90.

Schmitz, B., Tassinari, M. & Peucker-Ehrenbrink, B., 2001: A rain of ordinary chondritic meteorites in the early Ordovician. *Earth and Planetary Science Letters 194*, 1-15.

Schmitz, B., Häggström, T. & Tassinari, M., 2003: Sediment-dispersed extraterrestrial chromite traces a major asteroid disruption event. *Science 300*, 961-964.

Shoemaker, E.M., 1998: Long-term variations in the impact cratering rate on Earth. In Grady, M.M., Hutchison, R., McGall, G.J.H. & Rothery, D.A. (editors) Meteorites: flux with time and impact effects. *Geological Society, London. Special Publications 140*, 7-10.

Summerfield, M.A., 1991: *Global geomorphology*. Pearson, Harlow. 537 pp.

Tera, F., Papanastassiou, D.A. & Wasserburg, G.J., 1974: Isotopic evidence for a terminal lunar cataclysm. *Earth and Planetary Science Letters 22*, 1-21.

Wilhelms, D.E., Oberbeck, V.R. & Aggarwal, H.R., 1978: Size-frequency distributions of primary and secondary lunar impact craters. *Proceedings of the Lunar and Planetary Science Conference 9*, 3735-3762.

Wilhelms, D.E., 1987: The geologic history of the Moon. *U.S Geological Survey Professional Paper 1348*, 302 pp.

Zappalà, V., Cellino, A., Gladman, B.J., Manley, S. & Migliorini, F., 1998: Asteroid showers on Earth after family breakup events. *Icarus 134*, 176-179.

Internet Addresses:

http://upload.wikimedia.org/wikipedia/commons/thumb/f/f6/Lunar_crater_Daedalus.jpg/613px-Lunar_crater_Daedalus.jpg (080211)

http://www.damianpeach.com/barbados06/lunar/alphonsus_2006_04_20.jpg (080109)

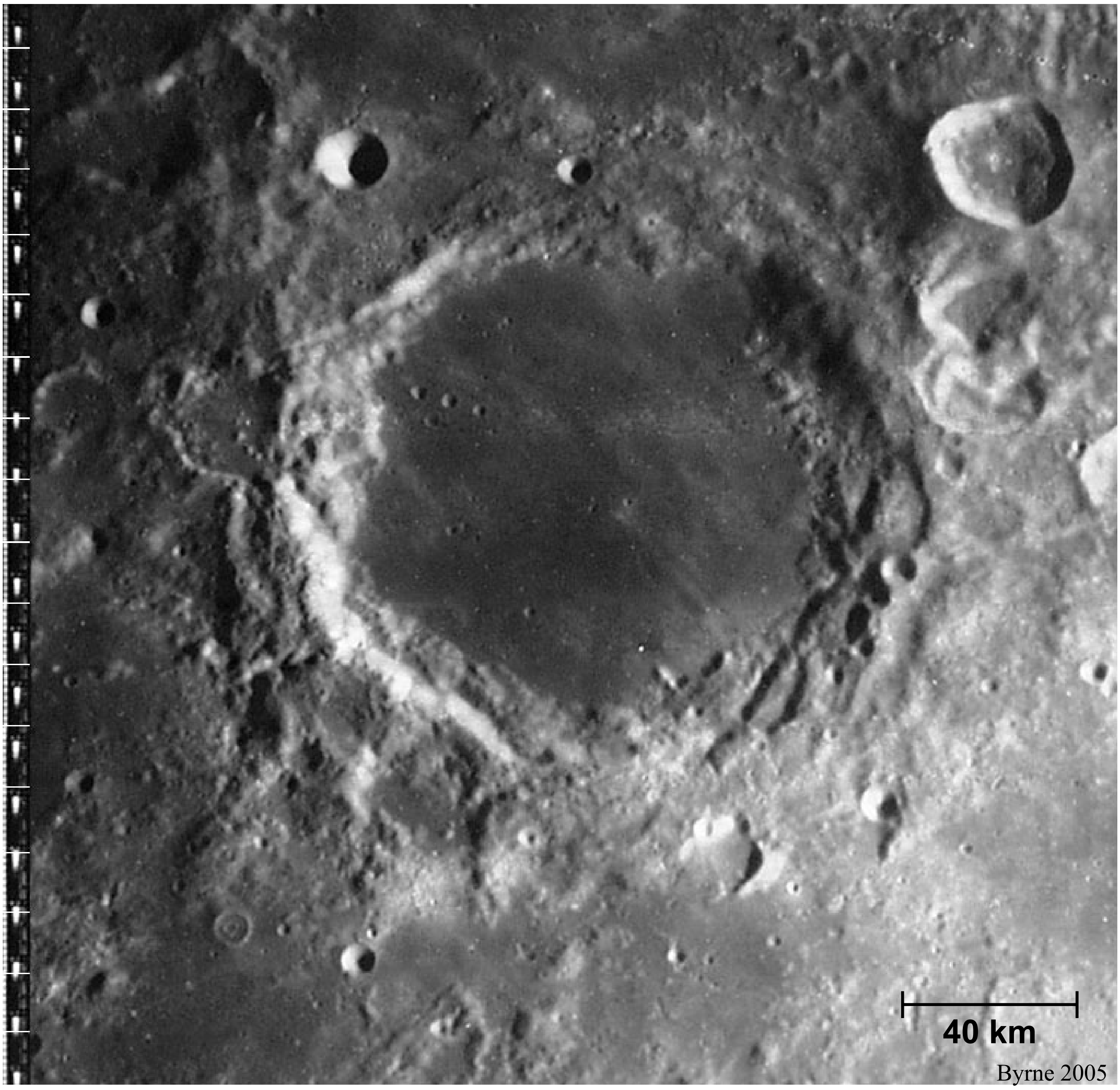
http://media.skyandtelescope.com/images/Plato_l.jpg (080109)

http://www.damianpeach.com/barbados06/lunar/copernicus_2006_04_20.jpg (080109)

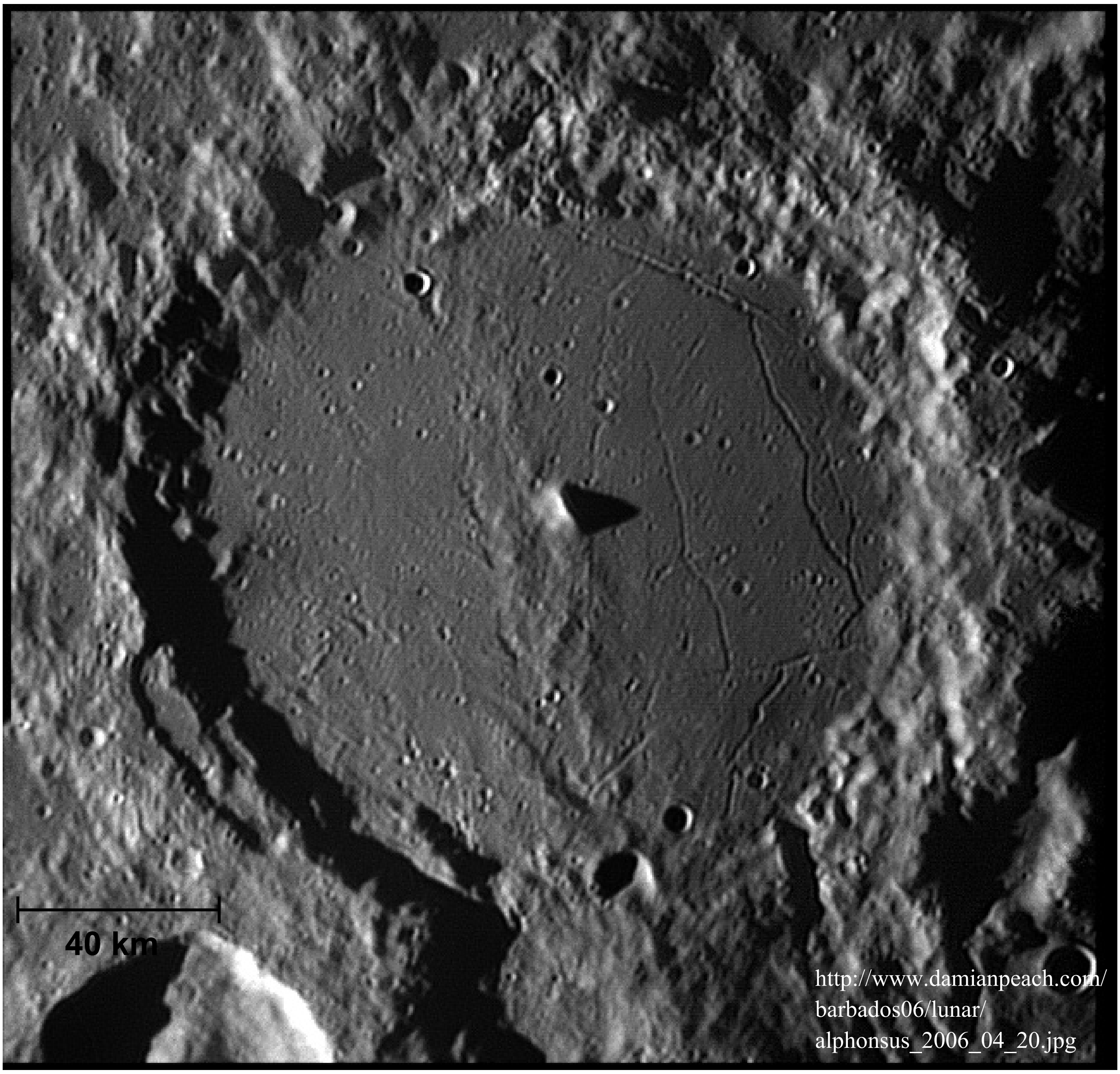
http://sci.esa.int/science-e-media/img/2b/lores_39467.jpg (080109)

http://www.damianpeach.com/lunartemp/triesnecker02.jpg (080109)

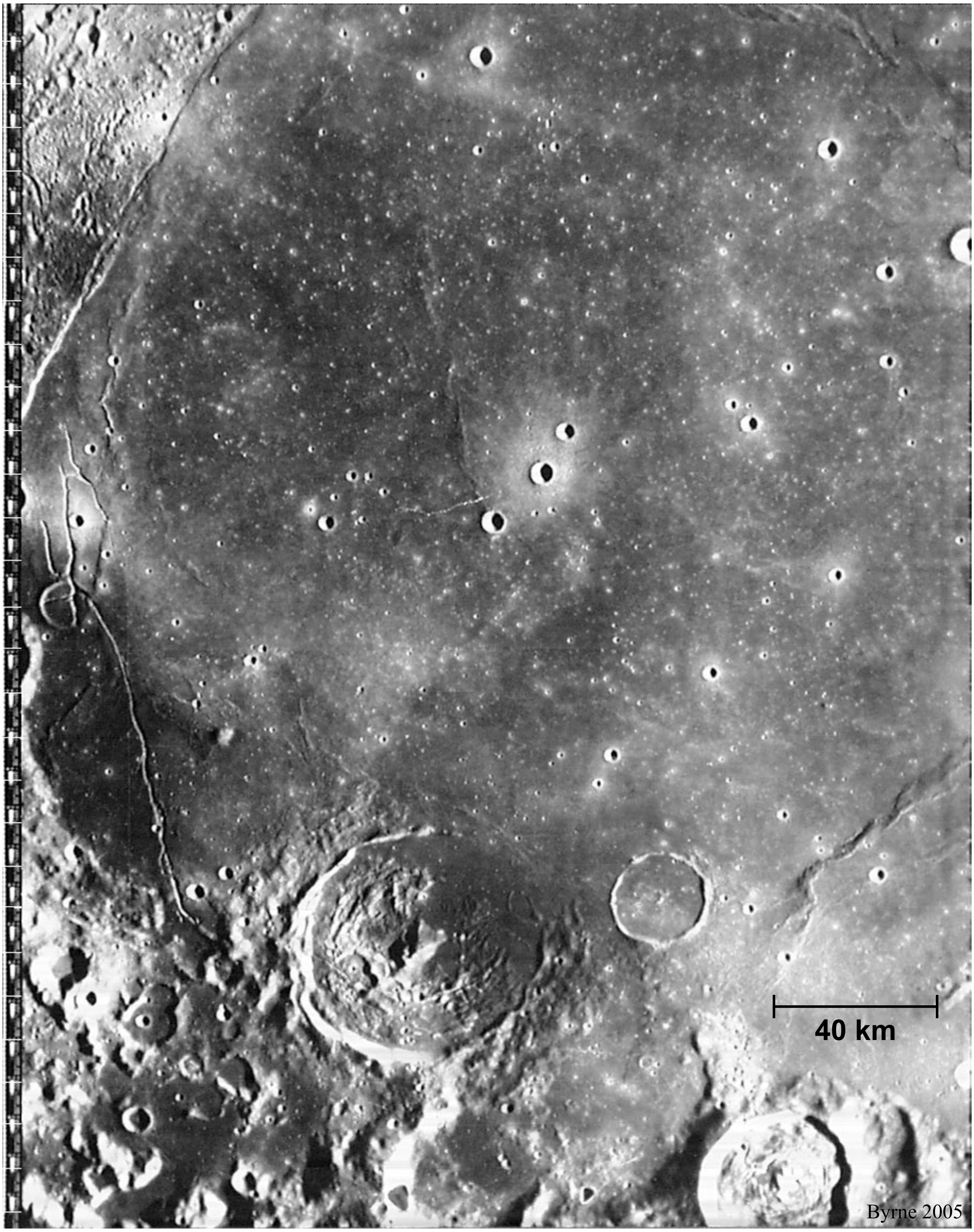
Appendix 1A. Endymion (~3.9 Ga)



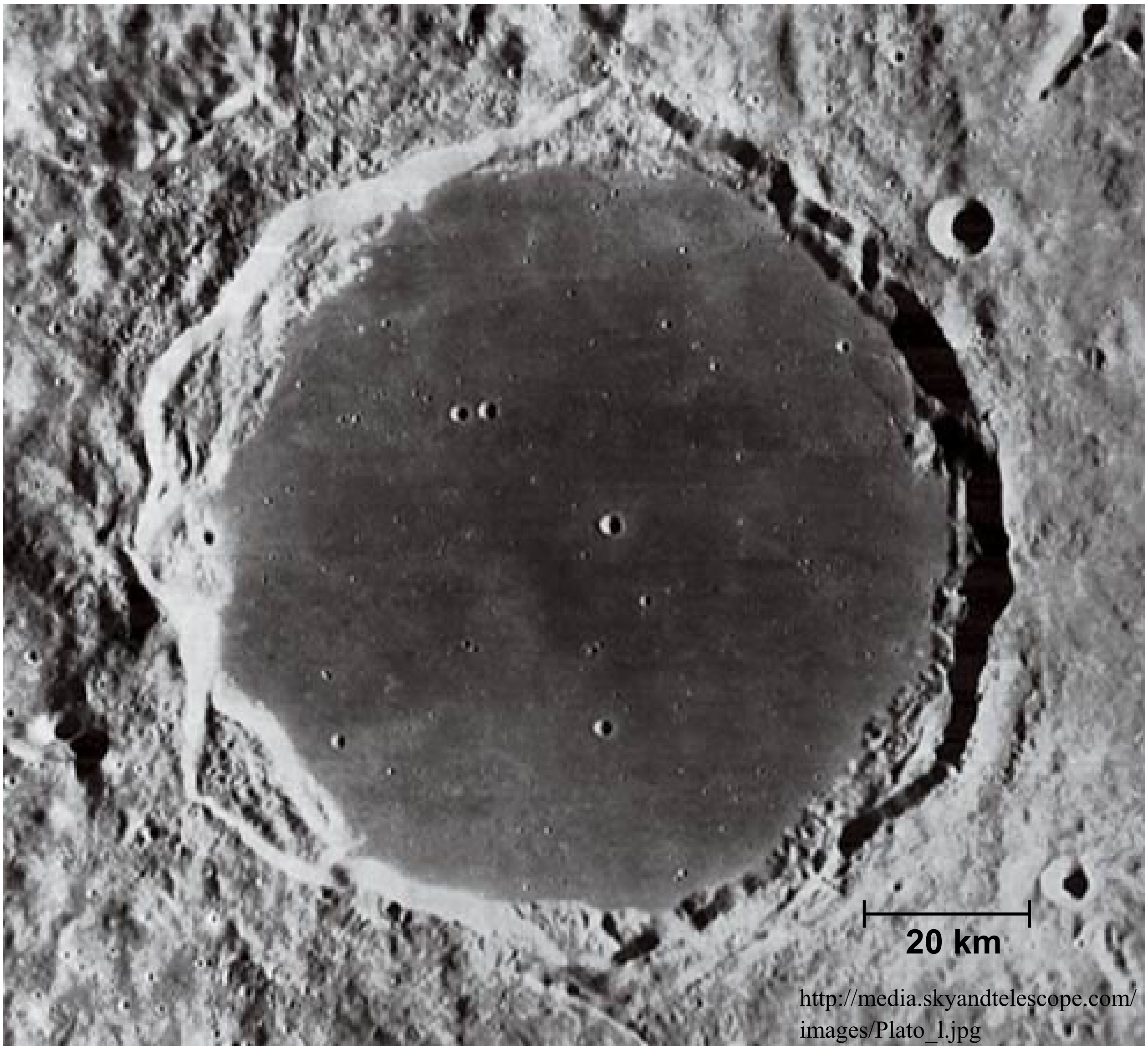
Appendix 1B. Alphonsus (~3.8 Ga)



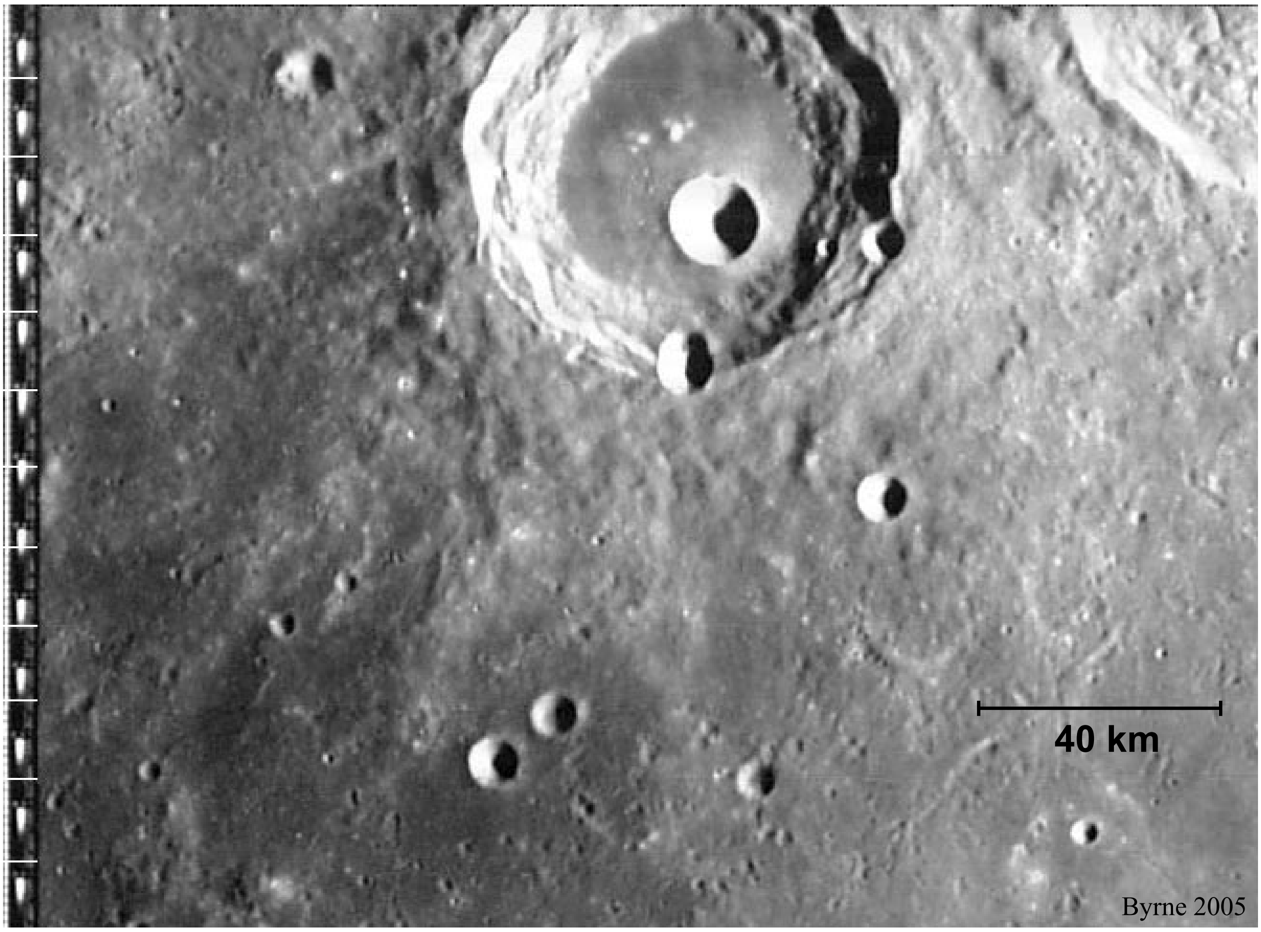
Appendix 1C. Mare Humorum
(~3.2 Ga)



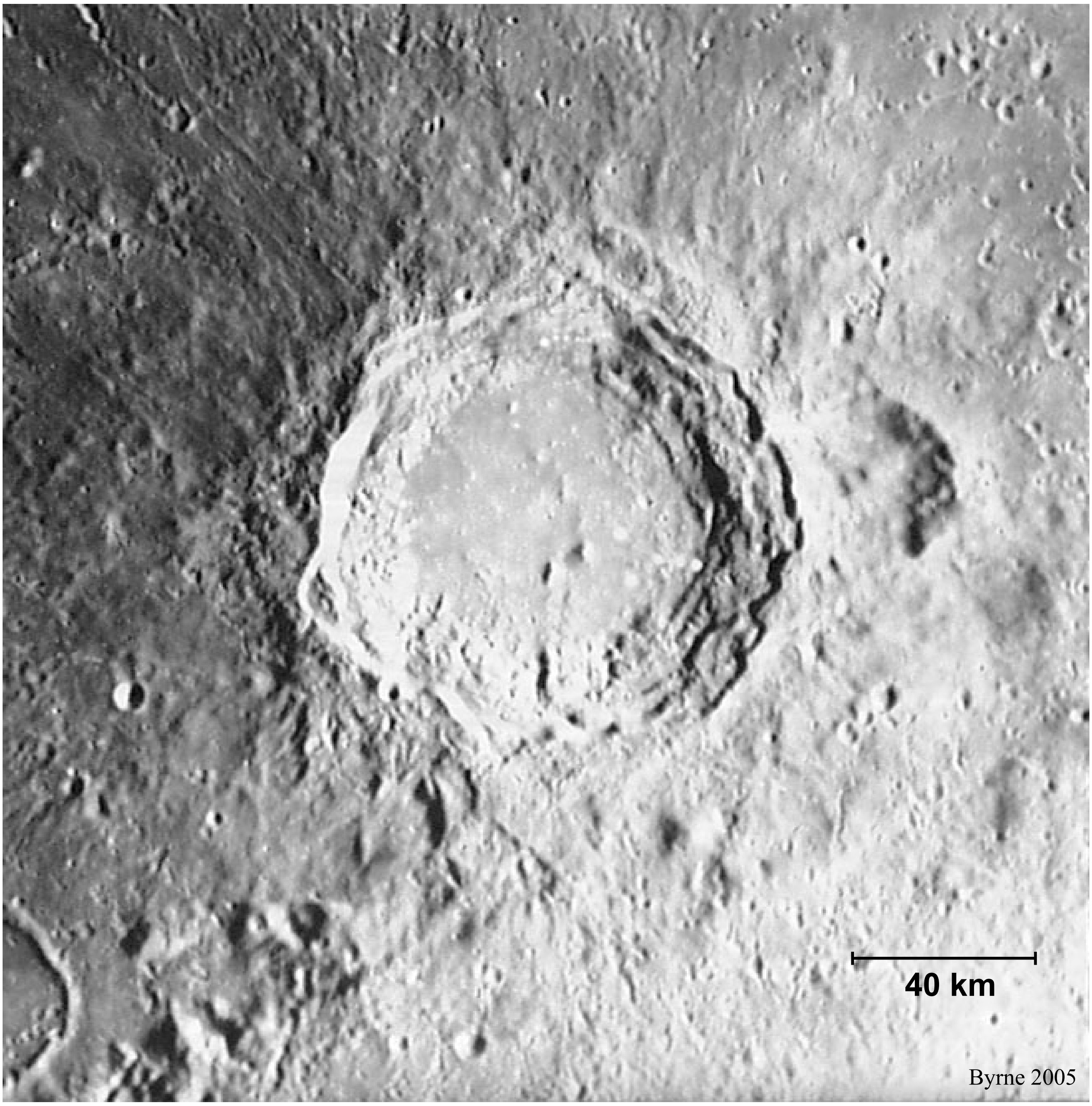
Appendix 1D. Plato (~3.3 Ga)



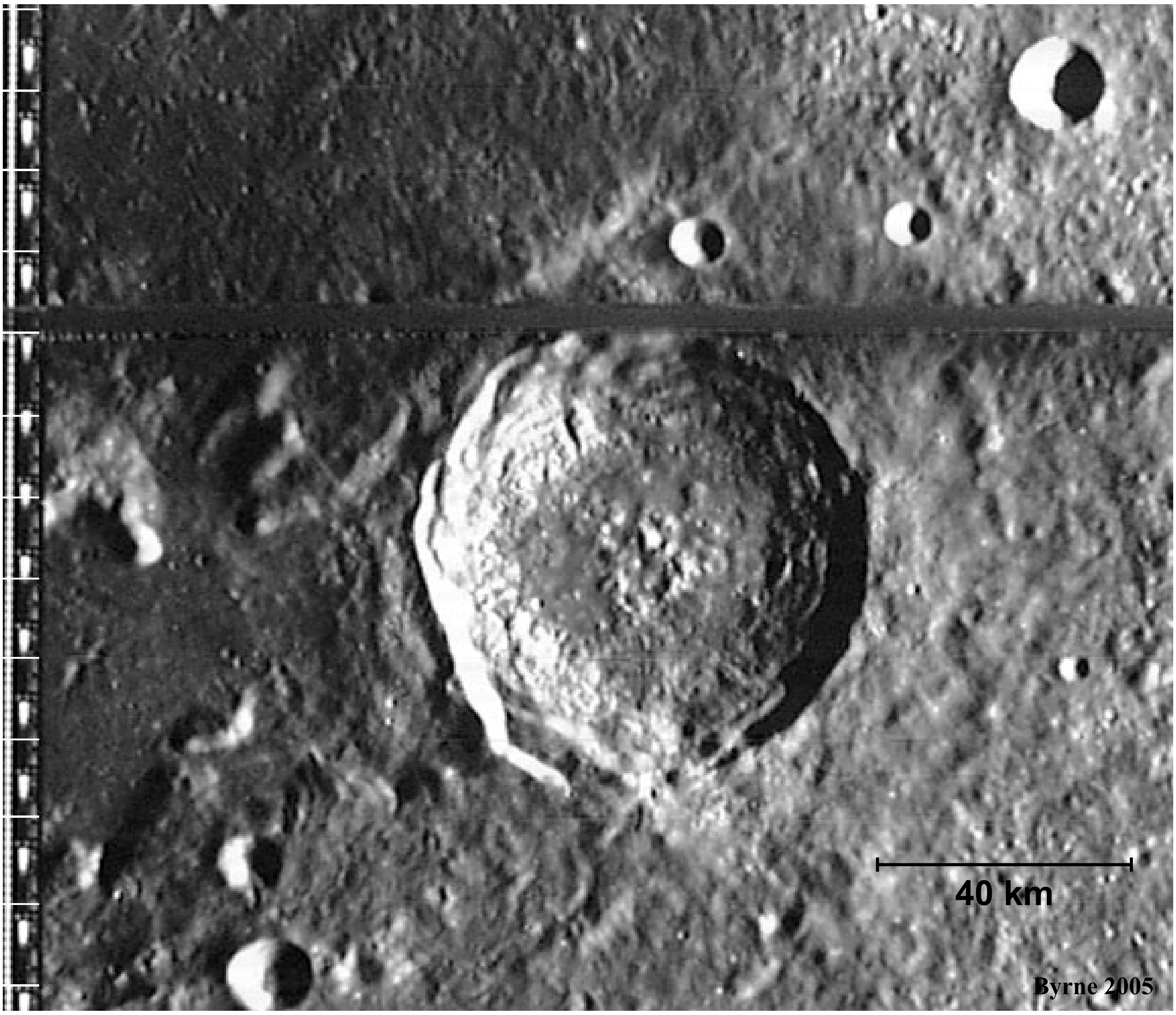
Appendix 1E. Hercules (~2.5 Ga)



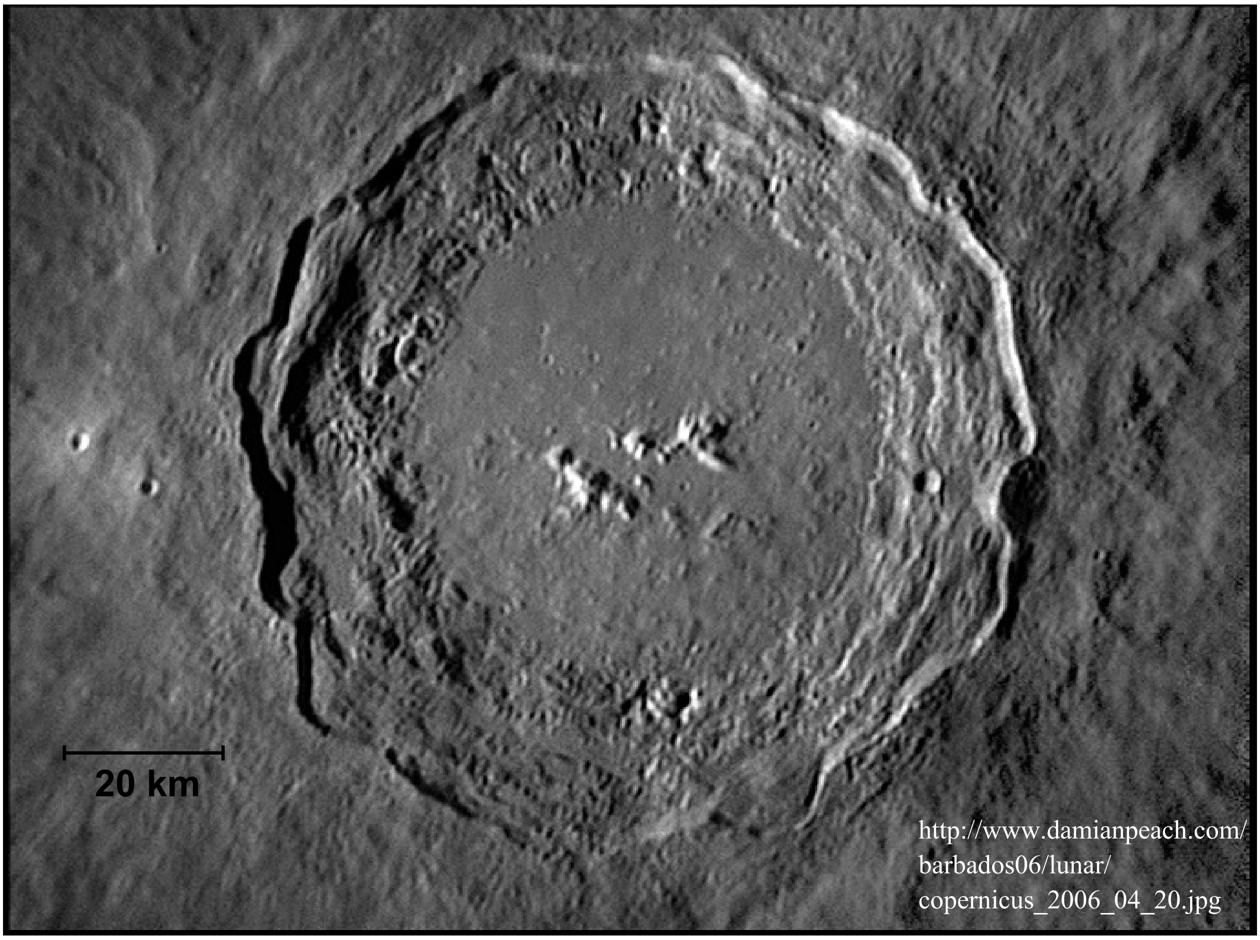
Appendix 1F. Aristoteles **(~2.5 Ga)**



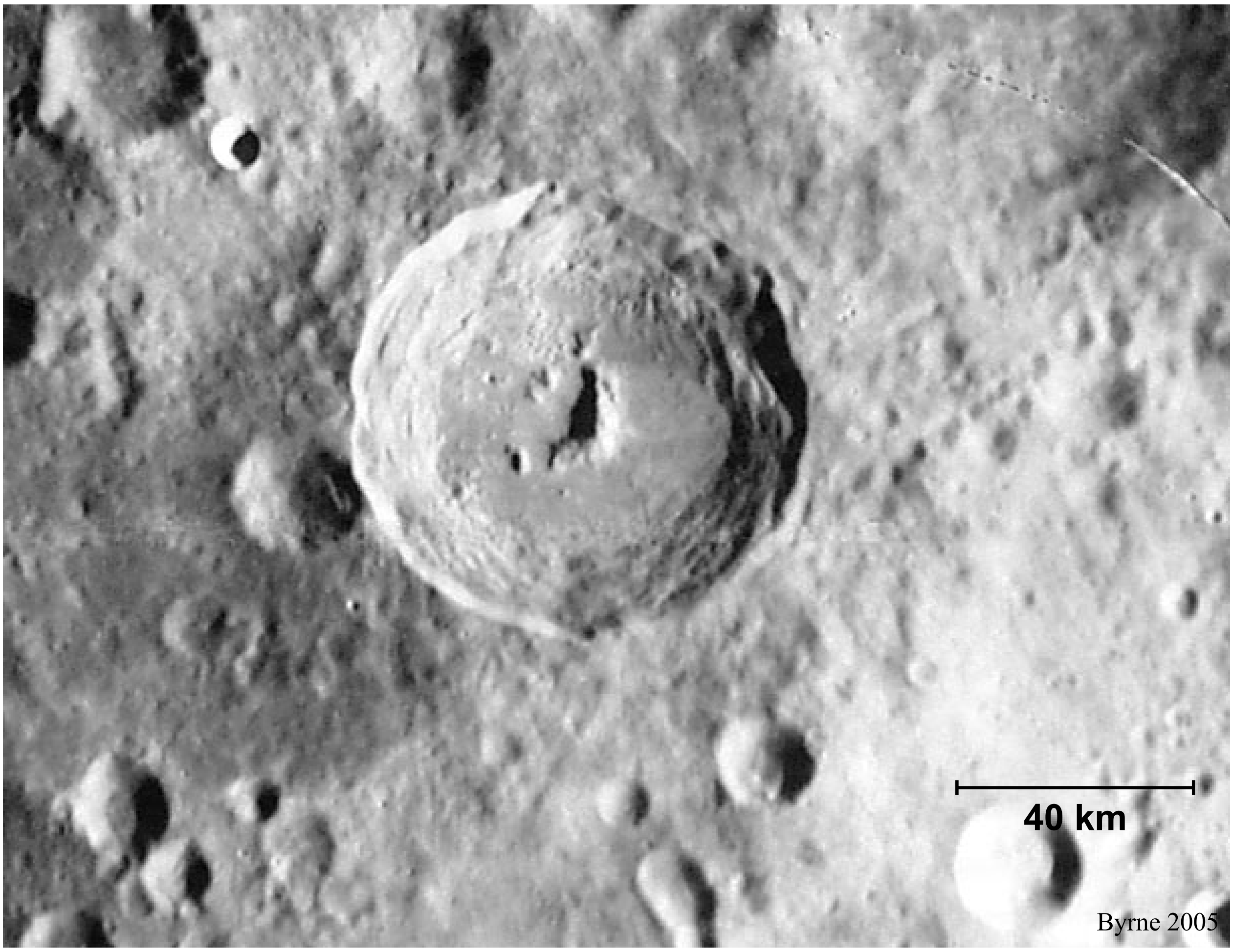
Appendix 1G. Eudoxus (~1.0 Ga)



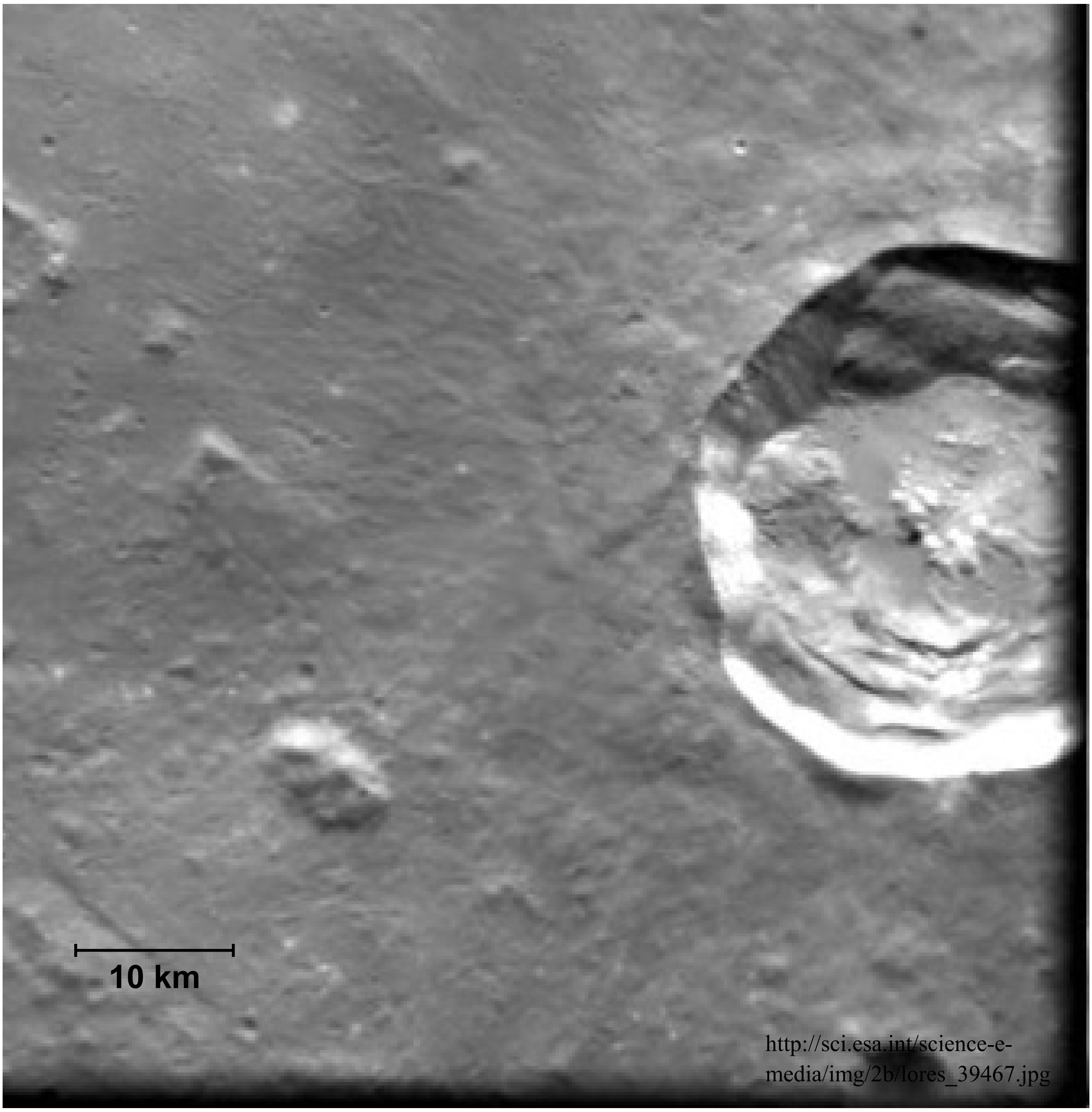
Appendix 1H. Copernicus (0.8 Ga)



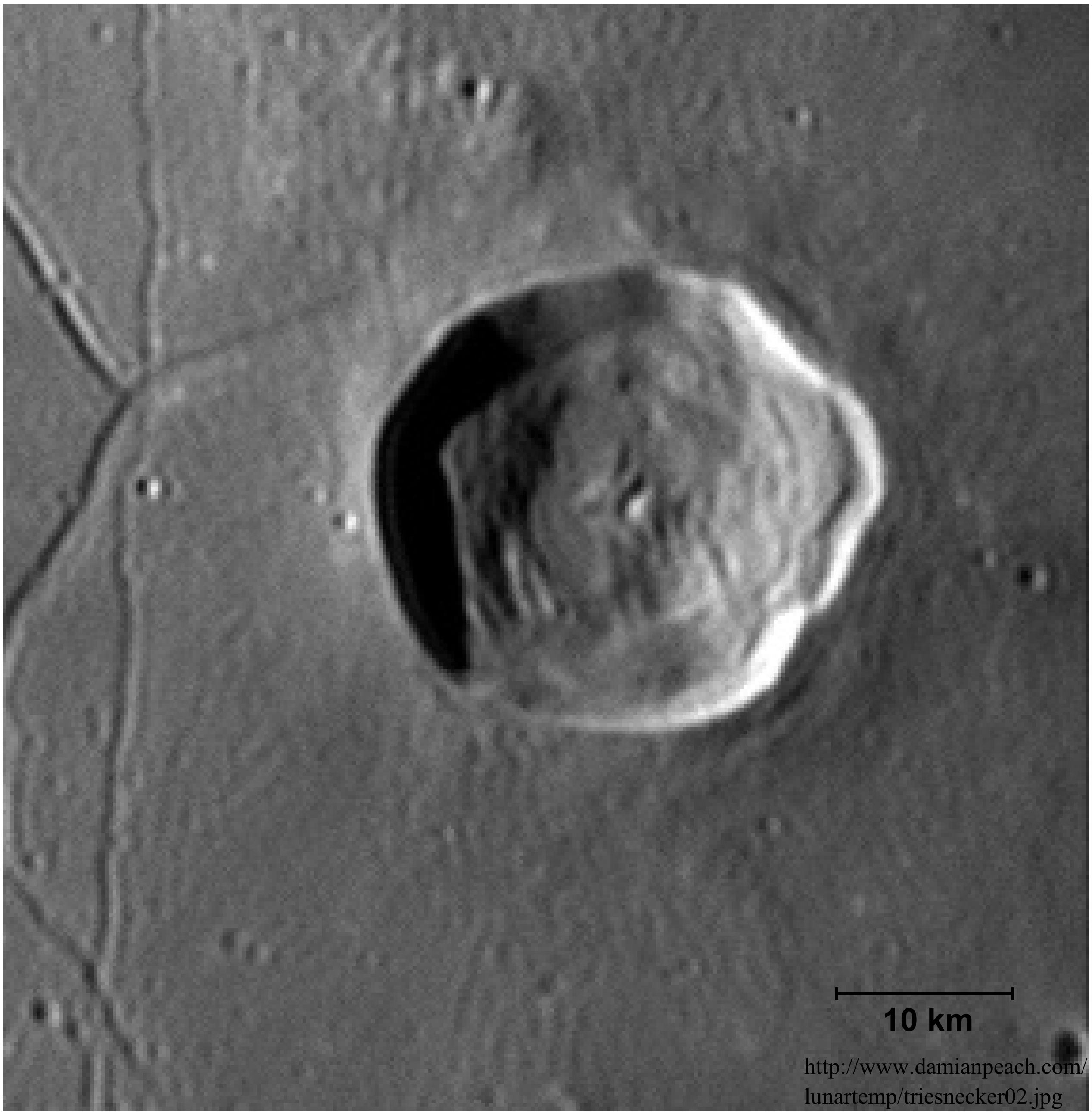
Appendix 1l. Stevinus (~0.5 Ga)



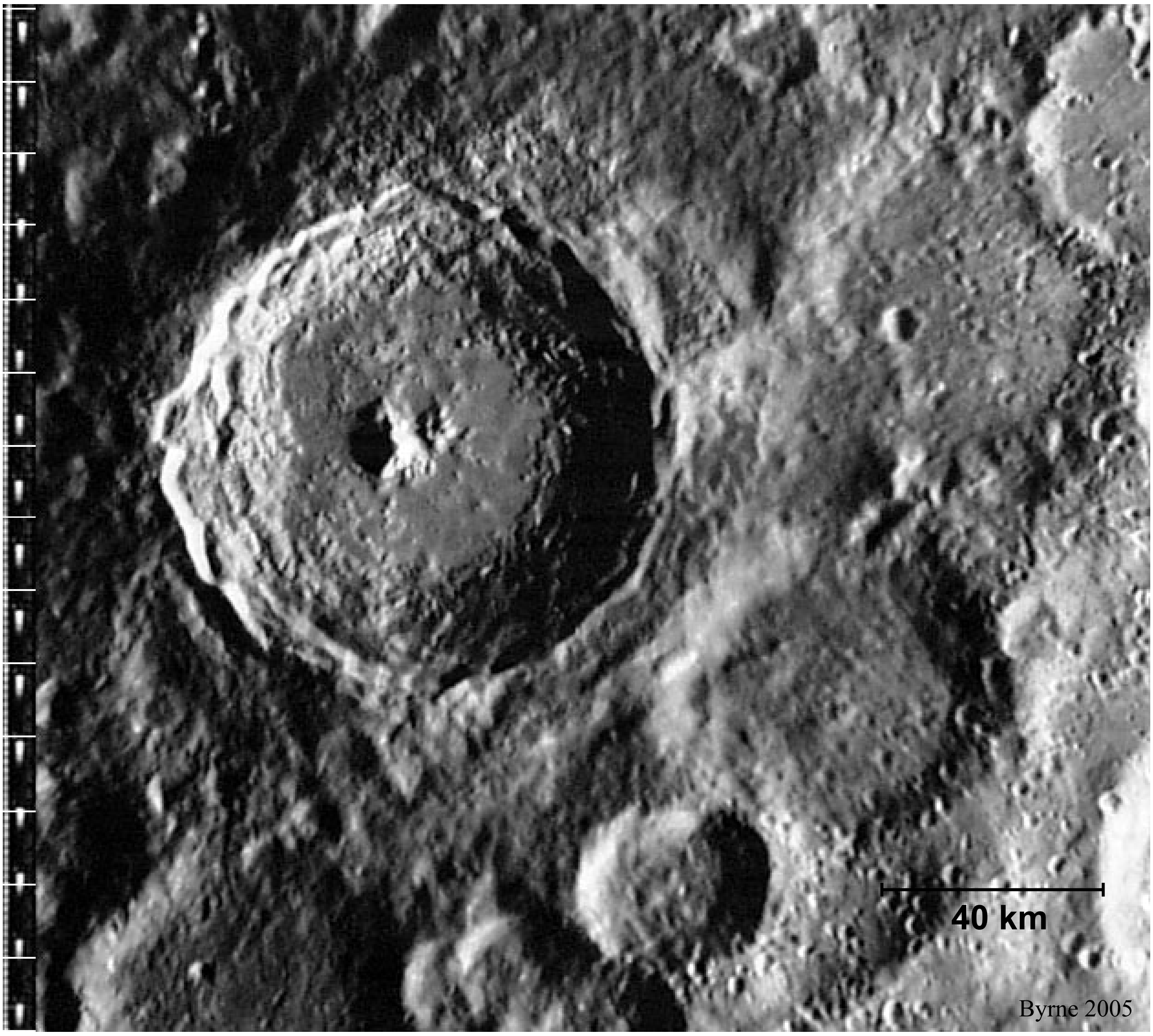
Appendix 1J. Kepler (~0.4 Ga)



Appendix 1K. Triesnecker (~0.4 Ga)



Appendix 1L. Tycho (0.1 Ga)



Appendix 2A

Endymion (Appendix 1A). Total counting area 12 271.85 km^2.				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
~2	~1.04	17	1385.28	1.39×10^{-3}
3	1.56	3	244.46	2.44×10^{-4}
4.5	2.34	2	162.97	1.63×10^{-4}
6	3.12	1	81.49	8.15×10^{-5}
7	3.64	3	244.46	2.44×10^{-4}

Alphonsus (Appendix 1B). Total counting area 9 503.3 km^2.				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
~3	~1.23	46	4840.42	4.84×10^{-3}
4	1.64	13	1367.95	1.37×10^{-3}
6	2.46	4	420.91	4.21×10^{-4}
7	2.87	2	210.45	2.10×10^{-4}
8	3.28	3	315.68	3.16×10^{-4}
10	4.1	1	105.23	1.05×10^{-4}
11	4.51	1	105.23	1.05×10^{-4}

Mare Humorum (Appendix 1C). Total counting area 53 681.54 km^2.				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
1-1.5	1.19-1.785	83	1546.16	1.55×10^{-3}
2	2.38	19	353.94	3.54×10^{-4}
2.5	2.975	6	111.77	1.12×10^{-4}
3	3.57	9	167.66	1.68×10^{-4}
4	4.76	4	74.51	7.45×10^{-5}
4.5	5.36	3	55.89	5.59×10^{-5}

Plato (Appendix 1D). Total counting area 8 011.8 km^2.				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
1.5-2	0.795-1.06	~30	~3744.48	$\sim 3.74 \times 10^{-3}$
3	1.59	4	499.26	4.99×10^{-4}
3.5	1.855	2	249.63	2.5×10^{-4}
4	2.12	1	124.82	1.25×10^{-4}
4.5	2.385	1	124.82	1.25×10^{-4}
5	2.65	2	249.63	2.5×10^{-4}
6	3.18	1	124.82	1.25×10^{-4}

Appendix 2B

Hercules (Appendix 1E). Total counting area 3 739.3 km².				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km²)	Number of craters (km⁻²)
4.5	3.1	1	267.43	2.67×10^{-4}
10.5	7.25	1	267.43	2.67×10^{-4}
13	8.97	1	267.43	2.67×10^{-4}
21	14.49	1	267.43	2.67×10^{-4}

Aristoteles (Appendix 1F). Total counting area 5 944.68 km².				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km²)	Number of craters (km⁻²)
~2	~1.02	3	504.65	5.05×10^{-4}
3	1.53	1	168.22	1.68×10^{-4}
6	3.06	1	168.22	1.68×10^{-4}

Eudoxus (Appendix 1G). Total counting area 3 536.2 km².				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km²)	Number of craters (km⁻²)
~2.2-3	~0.528-0.72	12	3393.47	3.4×10^{-3}
6	1.44	1	282.79	2.83×10^{-4}
7	1.68	2	565.58	5.66×10^{-4}
8	1.92	1	282.79	2.83×10^{-4}
9	2.16	1	282.79	2.83×10^{-4}

Copernicus (Appendix 1H). Total counting area 6 720.06 km².				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km²)	Number of craters (km⁻²)
4-4.5	1.44-1.62	7	1041.66	1.04×10^{-3}
10	3.6	1	148.8	1.49×10^{-4}

Stevinus (Appendix 1I). Total counting area 3 992.72 km².				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km²)	Number of craters (km⁻²)
3	1.59	1	250.46	2.5×10^{-4}
3.5	1.86	2	500.91	5.0×10^{-4}

Appendix 2C

Kepler (Appendix 1J). Total counting area 794.2 km^2.				
Crater diameter (> 1 mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
0	0	0	0	0

Triesnecker (Appendix 1K). Total counting area 518.75 km^2.				
Crater diameter (> 1mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
0	0	0	0	0

Tycho (Appendix 1L). Total counting area 5 674.5 km^2.				
Crater diameter (mm)	Equivalent crater diameter (km)	Number of craters (photograph)	Number of craters (1,000,000 km^2)	Number of craters (km^{-2})
3	1.59	1	176.2	1.76×10^{-4}
4	2.12	1	176.2	1.76×10^{-4}

Tidigare skrifter i serien "Examensarbeten i Geologi vid Lunds Universitet":

176. Oster, Jessica, 2004: A stratigraphic study of a coastal section through a Late Weichselian kettle hole basin at Ålabodarna, western Skåne, Sweden.
177. Einarsson, Elisabeth, 2004: Morphological and functional differences between rhamphorhynchoid and pterodactyloid pterosaurs with emphasis on flight.
178. Anell, Ingrid, 2004: Subsidence in rift zones; Analyzing results from repeated precision leveling of the Vogar Profile on the Reykjanes Peninsula, Southwest Iceland.
179. Wall, Torbjörn, 2004: Magnetic grain-size analyses of Holocene sediments in the North Atlantic and Norwegian Sea – palaeoceano-graphic applications.
180. Mellgren, Johanna, S., 2005: A model of reconstruction for the oral apparatus of the Ordovician conodont genus *Protopanderodus* Lindström, 1971.
181. Jansson, Cecilia, 2005: Krossbergskvalitet och petrografi i den kambriska Hardebergasandstenen i Skåne.
182. Öst, Jan-Olof, 2005: En övergripande beskrivning av malmbildande processer med detaljstudier av en bandad järnmalm från södra Dalarna, Bergslagen.
183. Bragée, Petra, 2005: A palaeoecological study of Holocene lake sediments above the highest shoreline in the province of Västerbotten, northeast Sweden.
184. Larsson, Peter, 2005: Palynofacies och mineralogi över krita-paleogengränsen vid Stevns Klint och Kjølby Gaard, Danmark.
185. Åberg, Lina, 2005: Metamorphic study of metasediment from the Kangilinaaq Peninsula, West Greenland.
186. Sidgren, Ann-Sofie, 2005: $^{40}Ar/^{39}Ar$-geokronologi i det Rinkiska bältet, västra Grönland.
187. Gustavsson, Lena, 2005: The Late Silurian Lau Event and brachiopods from Gotland, Sweden.
188. Nilsson, Eva K., 2005: Extinctions and faunal turnovers of early vertebrates during the Late Silurian Lau Event, Gotland, Sweden.
189. Czarniecka, Ursula, 2005: Investigations of infiltration basins at the Vomb Water Plant – a study of possible causes of reduced infiltration capacity.
190. G³owacka, Ma³gorzata, 2005: Soil and groundwater contamination with gasoline and diesel oil. Assessment of subsurface hydrocarbon contamination resulting from a fuel release from an underground storage tank in Vanstad, Skåne, Sweden.
191. Wennerberg, Hans, 2005: A study of early Holocene climate changes in Småland, Sweden, with focus on the '8.2 kyr event'.
192. Nolvi, Maria & Thorelli, Gunilla, 2006: Extraterrestrisk och terrestrisk kromrik spinell i fanerozoiska kondenserade sediment.
193. Nilsson, Andreas, 2006: Palaeomagnetic secular variations in the varved sediments of Lake Goœci¹¿, Poland: testing the stability of the natural remanent magnetization and validity of relative palaeointensity estimates.
194. Nilsson, Anders, 2006: Limnological responses to late Holocene permafrost dynamics at the Stordalen mire, Abisko, northern Sweden.
195. Nilsson, Susanne, 2006: Sedimentary facies and fauna of the Late Silurian Bjärsjölagård Limestone Member (Klinta Formation), Skåne, Sweden.
196. Sköld, Eva, 2006: Kulturlandskapets förändringar inom röjningsröseområdet Yttra Berg, Halland - en pollenanalytisk undersökning av de senaste 5000 åren.
197. Göransson, Ammy, 2006: Lokala miljöförändringar i samband med en plötslig havsyteförändring ca 8200 år före nutid vid Kalvöviken i centrala Blekinge.
198. Brunzell, Anna, 2006: Geofysiska mätningar och visualisering för bedömning av heterogeniteters utbredning i en isälvsavlagring med betydelse för grundvattenflöde.
199. Erlfeldt, Åsa, 2006: Brachiopod faunal dynamics during the Silurian Ireviken Event, Gotland, Sweden.
200. Vollert, Victoria, 2006: Petrografisk och geokemisk karaktärisering av metabasiter i Herrestadsområdet, Småland.
201. Rasmussen, Karin, 2006: En provenansstudie av Kågerödformationen i NV Skåne – tungmineral och petrografi.
202. Karlsson, Jonnina, P., 2006: An

investigation of the Felsic Ramiane Pluton, in the Monapo Structure, Northern Moçambique.

203. Jansson, Ida-Maria, 2006: An Early Jurassic conifer-dominated assemblage of the Clarence-Moreton Basin, eastern Australia.

204. Striberger, Johan, 2006: En lito- och biostratigrafisk studie av senglaciala sediment från Skuremåla, Blekinge.

205. Bergelin, Ingemar, 2006: ^{40}Ar/^{39}Ar geochronology of basalts in Scania, S Sweden: evidence for two pulses at 191-178 Ma and 110 Ma, and their relation to the breakup of Pangea.

206. Edvarsssson, Johannes, 2006: Dendrokronologisk undersökning av tallbestånds etablering, tillväxtdynamik och degenerering orsakat av klimatrelaterade hydrologiska variationer på Viss mosse och Åbuamossen, Skåne, södra Sverige, 7300-3200 cal. BP.

207. Stenfeldt, Fredrik, 2006: Litostratigrafiska studier av en platåformad sand- och grusavlagring i Skuremåla, Blekinge.

208. Dahlenborg, Lars, 2007: A Rock Magnetic Study of the Åkerberg Gold Deposit, Northern Sweden.

209. Olsson, Johan, 2007: Två svekofenniska graniter i Bottniska bassängen; utbredning, U-Pb zirkondatering och test av olika abrasionstekniker.

210. Erlandsson, Maria, 2007: Den geologiska utvecklingen av västra Hamrångesynklinalens suprakrustalbergarter, centrala Sverige.

211. Nilsson, Pernilla, 2007: Kvidingedeltat – bildningsprocesser och arkitektonisk uppbyggnadsmodell av ett glacifluvialt Gilbertdelta.

212. Ellingsgaard, Óluva, 2007: Evaluation of wireline well logs from the borehole Kyrkheddinge-4 by comparsion to measured core data.

213. Åkerman, Jonas, 2007. Borrkärnekartering av en Zn-Ag-Pb-mineralisering vid Stenbrånet, Västerbotten.

214. Kurlovich, Dzmitry, 2007: The Polotsk-Kurzeme and the Småland-Blekinge Deformation Zones of the East European Craton: geomorphology, architecture of the sedimentary cover and the crystalline basement.

215. Mikkelsen, Angelica, 2007: Relationer mellan grundvattenmagasin och geologiska strukturer i samband med tunnelborrning genom Hallandsås, Skåne.

216. Trondman, Anna-Kari, 2007: Stratigraphic studies of a Holocene sequence from Taniente Palet bog, Isla de los Estados, South America.

217. Månsson, Carl-Henrik & Siikanen, Jonas, 2007: Measuring techniques of Induced Polarization regarding data quality with an application on a test-site in Aarhus, Denmark and the tunnel construction at the Hallandsås Horst, Sweden.

218. Ohlsson, Erika, 2007: Classification of stony meteorites from north-west Africa and the Dhofar desert region in Oman.

219. Åkesson, Maria, 2008: Mud volcanoes - a review.

220. Randsalu, Linda, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta1 and Ta3 basins.

221. Fredh, Daniel, 2008: Holocene relative sea-level changes in the Tasiusaq area, southern Greenland, with focus on the Ta4 basin.

222. Anjar, Johanna, 2008: A sedimentological and stratigraphical study of Weichselian sediments in the Tvärkroken gravel pit, Idre, west-Central Sweden.

223. Stefanowicz, Sissa, 2008: Palynostratigraphy and palaeoclimatic analysis of the Lower - Middle Jurassic (Pliensbachian - Bathonian) of the Inner Hebrides, NW Scotland.

224. Holm, Sanna, 2008: Variations in impactor flux to the Moon and Earth after 3.85 Ga.

LUNDS UNIVERSITET

Geologiska institutionen
Gentrum för GeoBiosfärsvetenskap
Sölvegatan 12, 223 62 Lund