Plausibility of Earth Once Having a Thick Atmosphere – Examining the Rate of Impact Cratering

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Theories abound as to how dinosaurs and other prehistoric creatures could have grown to such immense sizes, inconsistent with the spectrum of sizes for today's creatures and Earth's living conditions. Some focus directly on changes in the governing physics of the universe, such as a different gravitational constant. Some postulate that, rather than this difference, the earlier Earth experienced lower gravity due to differences in its size and mass. The majority focus on biological and aerodynamical anomalies that may have prevailed to explain these gargantuan sizes. This paper focuses on the latter group, offering an independent means by which to test the hypothesis that a (much) thicker atmosphere provided the buoyancy needed by these creatures to exist on land. This means is astronomical, an examination of possible differences in the rate of impact cratering on Earth due to atmospheric differences. With the Earth's atmosphere allegedly experiencing eras of much greater thickness than current, and alternating between these "thick" and "thin" atmospheric eras, it is postulated that, in addition to the biological and aerodynamical anomalies, a difference in the cratering rate from meteor impacts on Earth should be evident. Thicker atmosphere would "burn up" more meteors, reducing the cratering rate when compared to that during thinner atmospheric eras. This paper explores this, using the cratering rate from meteor impacts on the Moon as a "control" since it has no atmosphere to attenuate meteors but also is in Earth's orbital vicinity and should have experienced a nearly equivalent rate of meteor influx per unit surface area.

1. Introduction

Some dinosaurs (and other prehistoric "leviathans") were inexplicably large, especially in light of today's spectrum of creature sizes. Various theories to "explain" how they could have functioned given such sizes have been postulated. Some focus on postulates that the gravitational constant was lower, such that Earth's gravity would have been lower, or a varying size of the Earth may explain the paradox. Others pursue biological arguments, with connections to aerodynamics, for an explanation. We will not consider the first set, but rather focus on the second as being the more plausible. After reviewing the arguments for the biological/aerodynamical postulates, we examine an independent means of ascertaining the plausibility of these, both of which contend that Earth had a much thicker atmosphere in the past. For that independent means, we select an astronomical approach, namely examination of possible differences in the cratering rates due to meteor impacts on the Earth during "thicker" and "thinner" atmosphere eras, representing eras of greater and lesser attenuation ("burn up") of incoming meteors, thereby affecting the cratering rate per unit surface area on Earth relative to what has been experienced on the geologically and climatologically dead Moon. Since the Moon is in the same orbital neighborhood as the Earth, it should have experienced the same meteor influx per unit surface area over the same eras.

2. Two Prominent Theories for Thick Earth Atmosphere

Two prominent theories supporting the proposition that Earth has previously experienced (much) thicker atmospheric conditions are examined. Both focus on biological and aerodynamic arguments regarding dinosaur and other prehistoric creatures having sizes incongruously large when viewed in terms of how they could possibly exist today.

2.1. Levenspiel, Fitzgerald and Pettit

In "Earth's Atmosphere before the Age of Dinosaurs," Levenspiel, Fitzgerald and Pettit state [1]:

… [I]f you believe that biology's mouse-to-elephant curve also applies to the flying creatures of the past, and if you also trust aerodynamic theory (which applies equally to flying insects, birds, and airplanes), then the giant flying creatures of the dinosaur age could only fly if the atmospheric pressure was much higher than it is now: at least 3.7–5.0 bar.

If this is so, it raises several interesting questions. For example, how did the atmosphere get to that pressure 100–65 million years ago (Mya)? What was the pressure before that? And how did it drop down to today's 1 bar? Although we have no definite answers to these questions, let us put forth reasonable possible explanations.

What was the air pressure for the 97% of Earth's life before the age of dinosaurs? We have three possible alternatives, as shown in Figure 1.

- *The pressure could have been at 1 bar throughout Earth's earlier life, risen to 4–5 bar ~100 Mya (just at the time when the giant fliers needed it), and then returned to 1 bar (curve A).*
- *The pressure could have been ~4–5 bar from Earth's beginning, 4600 Mya; and ~65 Mya, it could have begun to come down to today's 1 bar (curve B).*
- *The atmosphere could have started at higher pressure and then decreased continuously through Earth's life to ~4–5 bar ~100 Mya and down to 1 bar today (curve C).*

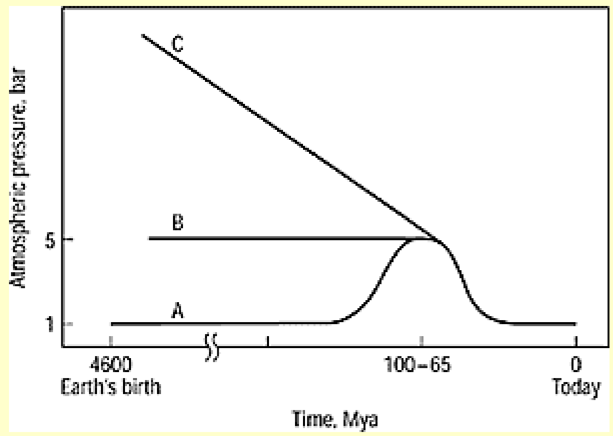

Figure 1. Three possible alternatives for the atmospheric pressure early in Earth's lifetime, *given that it was at ~5 bar, ~100 Mya.*

The third alternative seems to be the most reasonable …Geologists believe that most of the carbon on the young, hot Earth, >4000 Mya, was in the form of gaseous carbon dioxide, carbon monoxide, and methane. With time, the CO and CH_4 reacted with oxide minerals and were transformed into CO_2. These reactions did not change the total amount of carbon in the atmosphere.

Our sister planet and nearest neighbor, Venus, has an atmosphere of 90 bar pressure, consisting of 96% CO_2 (5). Why should Earth be so different? … [W]hy did Venus's atmosphere remain at 90 bar while Earth's decreased to a few bar during the age of dinosaurs and then declined to the 1 bar it is today? What happened to Earth's CO_2 and by what mechanism did it virtually disappear? ... Being thinner, Earth's crust was fragile and broke up under the action of the mantle's convective forces. In contrast, Venus's thicker crust remained rigid and did not permit the mechanisms that removed the CO_2 from its bound state. In addition, because Venus is closer to the Sun and hotter than Earth, free liquid water cannot exist on it, whereas Earth has giant oceans that cover two-thirds of the planet. The oceans played an important secondary role in removing CO_2 from the atmosphere …

Today, vast deposits of sedimentary carbonate rocks are found on land and on ocean bottoms, >1,000,000 km^3 throughout Earth's crust. Above the continents, the CO_2 was taken up by rainwater and by groundwater. This CO_2-rich water reacted with rocks to form bicarbonates, followed by transport to the ocean and precipitation as calcium and magnesium carbonates. In the ocean, dissolved CO_2 combined with the calcium hydroxide to form deposits of chalk, or it was taken up by coral, mollusks, and other living creatures to form giant reefs. A study of the distribution through time of these deposits gives us clues to the history of CO_2 in the atmosphere …

With time, the concentration of CO_2 steadily decreased, primarily because of the formation and deposition of limestone and other carbonaceous materials. CO_2 was also lost by photosynthesis followed by the deposition of carbonaceous substances such as coal, petroleum, peat, oil shale, and tar sands; however, this loss was quite minor. Calculations show that the deposit of what are now considered fuel reserves lowered the atmospheric CO_2 by $<<1$ bar. At the same time, the concentration of oxygen slowly rose. These two changes, the decrease in CO_2 and the rise in oxygen, thinned the forests and the dead material began to be oxidized more rapidly, so that dense layers of dead organics were no longer deposited. Evidence of this change in atmospheric conditions is that we cannot find any massive coal deposits younger than 65 million years. Animal life found this changed atmosphere to its liking, so mammals and dinosaurs flourished, first as very small creatures but then increasing in size as a result of evolutionary competition. This led to the giant flying creatures close to the end of the dinosaur age. It could be that these creatures died out as the total pressure of the atmosphere dropped below their sustainable level …

If we assume that Earth's early atmosphere was very different, both in composition (mainly CO_2) and total pressure, that would answer some puzzling questions from a variety of disciplines.

- *How did the flying creatures from the age of dinosaurs have enough energy to fly when physiology, biology, and aeronautics say that this was impossible?*
- *How could life have developed on Earth when astronomy says that Earth was too cold to sustain life?*
- *If Earth's atmosphere had stayed at ~1 bar throughout its history, where did the equivalent of 50–70 bar of CO_2 in limestone and other carbonates on Earth's surface come from?*

This picture of high CO_2 concentration and high pressure in the past also explains why most massive coal seams are older than 65 million years and why most limestone caves are younger than 100 million years. Although we do not know the values for the atmospheric pressure in those early times, and although each of the arguments in this paper only leads to suggestions, when taken together, the evidence from these various sources leads to the same conclusion: The atmospheric pressure was higher in the past than it is today and consisted primarily of CO_2. This hypothesis presents a picture of our evolving planet that should be examined and that could have interesting consequences.

2.2. Esker

In a subsequent, more comprehensive look at this topic, "Scientific Theory Solving the Dinosaur Paradox and Numerous Other Paradoxes Regarding Earth's Evolution," Esker states [2]:

… [T]he large dinosaurs and pterosaurs of the Mesozoic era present a scientific paradox. Four areas of scientific incongruities regarding these animals' large size are identified: 1) insufficient muscle strength, 2) insufficient bone strength, 3) unacceptably high blood pressure within the tallest dinosaurs, and 4) the paradox of pterosaurs having grossly insufficient power to fly in atmospheric conditions similar to the present … [T]he development of airplanes has always been more of an art than a science. The absence of a theoretical understanding of flight becomes most apparent when the paleontologists make their foolish attempts trying to explain how the giant pterosaurs flew. Common sense tells everyone that a reptile the size of a horse should not be capable of flight, but until now there has not been a theoretical understanding of flight enabling us to scientifically clarify what is wrong with the paleontologists' claim that there is nothing odd about gigantic flying reptiles … The Thick Atmosphere Solution's ability to solve the dinosaur paradox qualifies it as being a strong hypothesis, but with additional evidence it can be shown that the Thick Atmosphere Solution is actually a new scientific theory … [T]he Thick Atmosphere Theory solves the long-standing paleoclimatologist puzzle of how the Mesozoic era Earth had the same pleasant climate over its entire surface …

Just as the largest animals have the lowest relative bone strength, it is also true that the largest animals have the lowest relative muscle strength. Absolute strength can be defined as how much weight an animal can lift regardless of the animal's own weight, and clearly the larger animals have greater absolute strength than the smaller animals. But when we look at relative strength, the lifting ability of an animal relative to its own weight, it is the smallest animals that have the greatest relative strength … For most physically fit human beings we have more than enough relative strength so that getting out of bed in the morning is not outside our physical capacity. But the larger animals that have lower relative strength lifting their body off the ground can be a serious issue. Large farm animals such as cattle or horses exert all the strength that they have when they pick themselves up off the ground. Likewise the large wild animals such as elephants and giraffes need all their strength to perform this task that is not challenging for the smaller animals. As a consequence of these difficulties, it is not surprising that many of these larger animals evolved the behavior of sleeping while standing up. Yet numerous dinosaurs were much larger than these animals. Their greater size would mean that their relative strength would be substantially less than that of the large animals of today. It is not realistic to imagine that the large dinosaurs never fell or otherwise found themselves on the ground throughout their entire lives. If a Jurassic Park was actually created, any sauropod or other large dinosaur would be stuck lying on the ground much like a helpless whale stranded on a beach.

Many researchers have questioned how it would be possible for a Brachiosaurus to supply blood to its head. Several unlikely hypotheses have been suggested ... Brachiosaurus had a massive heart to produce the needed pressure to lift the blood ... Brachiosaurus evolved a series of several evenly spaced hearts in the neck as a pumping system that would get the job done ... Brachiosaurus never lifted its head up but instead just moved it back and forth horizontally … At approximately six feet, or a little less than 2.0 meters, human beings stand tall among most terrestrial vertebrates, yet at 18 feet or 5.5 meters the giraffe is the much taller modern-day champion of height. Our occasional feeling of light headedness when standing up is hardly comparable to the 15 feet or 5.0 meters elevation change a giraffe goes through in obtaining a drink of water.

If not for valves in the veins and arteries of its neck, the extreme pressure would cause the blood vessels to break when the giraffe lowers its head, and conversely the giraffe would pass out from lack of blood when it later lifts its head … Yet the giraffe's greatest cardiovascular problem is having a strong enough heart to lift blood up to its brain. To produce the necessary blood pressure the giraffe's heart is a huge muscle with walls up to three inches (eight cm) thick and weighing 25 pounds (11 kg). But even more impressive is that the giraffe's resting heart rate is 65 beats per minute. This is about twice what is expected for an animal of its weight. The giraffe's massive 'revved up' heart produces the 300 / 180 mm Hg blood pressure needed for the blood to reach the giraffe's head. Giraffes have a relatively short lifespan of only 20 years and are prone to heart attacks as a consequence of their cardiovascular adaptations … The sauropod blood pressure paradox has been debated for several years ... Increasingly, paleontologists are coming to the belief that the Brachiosaurus could not have held its head up. Likewise Apatosaurus the other sauropods could not have reared up on their hind legs to reach the higher foliage. Yet remounting all the brachiosaur exhibits so as to lower the head is not the solution. This ad hoc solution does not explain why the Brachiosaurus has a posture for reaching up high. The Brachiosaurus, the 'arm lizard', and its cousins, are the only dinosaurs with longer forward legs than rear legs. The logical explanation for the longer forward legs is that the addition of longer legs and its long neck serve the purpose of extending the Brachiosaurus' reach up to the highest foliage. Thus we have the paradox of having an animal that is built for its head and mouth reaching the maximum height and yet at this great height its heart lacks the ability to pump blood up to its head …

... [T]he largest flying animals today are birds because birds have evolved a hot blooded high metabolism that gives them the power needed for flight. Warm blooded flying mammals, or bats, are on the next notch down the power scale. The consequence of having a lower metabolism is that the largest flying bats are no more than one tenth the mass of the largest flying birds. Among vertebrates, cold blooded reptiles are on the lowest rung of the power scale ... Today there are no reptiles capable of generating the power needed to fly, and yet during the Mesozoic era reptiles grew to be the largest flying animals that ever existed. The largest of these pterosaurs was the Quetzalcoatlus. It had a chest size as large as a horse and stood as tall as a giraffe ... [Y]et some paleontologists continue to insist that there is no scientific paradox regarding how the pterosaurs could have flown ... [P]terosaurs could not have flown in today's atmospheric environment. The application of aerodynamic equations show pterosaurs falling far short of meeting the requirements for obtaining flight in today's atmosphere, and the experimental efforts using RC models provide physical evidence confirming these conclusions. It should be alarming to all scientists and science educators that some paleontologists continue to claim that they understand how pterosaurs flew when the evidence is so overwhelming in refuting their claim …

***Starling** – With a 6.6 power ratio flying is a not a challenge for these and other small and medium size birds. With such an abundance of relative power it is no wonder that small and medium size birds often appear playful as they fly. **Giant Bat** – Giant bats have a power ratio of only 1.6. This marginal power ratio explains why the largest bats are rarely ever seen flying in the rain. **California Condor** – This is another extremely marginal flyer that can only fly when the weather conditions are favorable. A 1.1 power ratio is barely enough to allow these large birds to lift off after feasting on a carcass. But once they lift off they glide themselves over the rising air thermals that act like a rising elevator to lift them higher. Once they are soaring, these large birds require only enough power to guide their flight over the rising air thermals. **Argentavis** – Six million years ago there existed an extremely large bird known as the Argentavis. It flew in South America like the modern large flyer the Andean condor. However the wingspan of the Argentavis was two and a half to three times that of the Andean condor. Its mass would be proportional of the wingspan cubed and so its mass would have been 16 to 27 times greater than the Andean condor. This places it far beyond the modern crowded field of bird species competing for the title of being the largest flying birds. Consequently many scientists investigating this matter are baffled in their attempts to explain how the Argentavis flew. **Quetzalcoatlus** – Unlike the Argentavis there are no living relatives of the Quetzalcoatlus and this makes it difficult to estimate the Quetzalcoatlus' mass. The author produce values that fell in a range between 500 kg to two tons; thus arriving at a rough estimate of 700 kg. With a 12 m wingspan and a chest cavity larger than that of a horse there is no getting around the fact that this was a huge animal. However some paleontologists tell a different story in estimating the Quetzalcoatlus mass to be between 90 and 250 kg. Thus they are claiming that the Quetzalcoatlus had a body density that was about seven times less than any animal presently flying. These paleontologists need to do some explaining as to how the muscle, bone and other bodily parts of a Quetzalcoatlus could have a density seven times less than what is found in present day birds. Some paleontologists have suggested that the pterosaurs may have been warm-blooded. While warm-bloodedness is unusual for reptiles this is nevertheless a feasible hypothesis and so the available power for the Quetzalcoatlus is calculated using the power-to-weight equation for a warm-blooded mammal. Even so, the power ratio of the Quetzalcoatlus is still only nine percent of the minimum requirement for flight ...*

The buoyancy force is best described by Archimedes' principle that states that when an object is partially or fully submerged in a fluid, an upward buoyancy force lifts up on the submerged object that exactly equals the weight of the fluid displaced. … [B]uoyancy … is what gives a lifting force to hot air balloons. The main difference in the buoyancy effect provided by these two fluids [air vs. water] *is the amount of fluid volume that needs to be displaced to achieve flotation. For terrestrial vertebrates, it is the net force produced by their weight that often limits their size. But this is not true for species that exist in the water. For the latter species it is not their weight but rather other factors, such as the availability of food that might limit the size of these species. Without the weight limitation some of these aquatic species grow to display gigantism. It is the buoyancy of water that allows the whales, the largest animals of today, to grow so large … Without this buoyancy to counteract gravity, the poor whale that finds itself stuck on a beach is soon having its bones broken from its own weight. To produce an effective buoyancy force on dinosaurs the Earth's atmosphere would have to be thick enough to have a density comparable to the density of water. By summing the forces acting on a typical dinosaur such as a Brachiosaurus the density of the necessary atmosphere is calculated … to be 670 kg/m*^{3}*. This says that to produce the necessary buoyancy so that the dinosaurs could grow to their exceptional size, the density of the Earth's air near the Earth's surface would need to be 2/3's of the density of water …*

It may be hard to imagine that the Earth's air could be so thick that its density would be comparable to water. Nevertheless, there is no reason why a gas cannot be compressed so much that it has properties similar to that of a liquid, and in fact compressing a gas into a liquid is a common industrial process … 150 million years ago the Earth's atmospheric pressure near the surface was about 370 atmospheres … 370 times thicker than what it is today …[C]onsider the pressure that currently exist at the deepest depths of the oceans. The average ocean depth is 3790 m and at this depth the pressure is 380 atmospheres. So for all practical purposes, the present day pressure at the average depth of the ocean is the same as the pressure at the bottom of the Mesozoic atmosphere. Yet there are numerous species that live at this depth and many more that live much deeper. Extremely high absolute pressure has no ill effect on our present creatures of the deep that have evolved in these environments; likewise, the extremely high pressure of the Mesozoic era had no ill effect on the terrestrial species of the Mesozoic era … If both the inside and outside of an enclosed container are at the same absolute pressure, no matter what the absolute pressure might be, there will be no net force on the sides of the container …

Within the Phanerozoic eon [current geologic eon … during which abundant animal and plant life has existed – 541 million years to the present] *we can identify two thick atmosphere eras and two thin atmosphere eras … Twice during the Carboniferous and the Cretaceous/Paleogene periods, the atmosphere transitioned from being extremely thick to being relatively thin … With a massive amount of* CO_2 *being removed from the atmosphere we would expect to see large carbon deposits during these times and indeed that is the case … [T]he only time that the atmosphere transitioned from being relatively thin to being extremely thick was when the earth was void of most life … around the time of the P-T* [Permian-Triassic] *mass extinctions and continuing into the Triassic period …*

Figure 2 is a linearized approximation of Esker's graph of "Atmospheric Levels during the Last 350 Million Years," on which I have arbitrarily drawn transition times between the two Thick and Thin Atmosphere Eras using an arbitrary transition atmosphere of 200 atm. Starting around 350 million years ago with an atmospheric thickness of nearly 500 atm, he presents alternating periods of decreasing and increasing atmospheric pressure up to today's present "Thin" atmosphere, which I have assumed to be "Thick" and "Thin" as shown in my approximation of Esker's figure. This results in two Thin and Thick Eras, as shown. They transition at approximately 340, 230 and 53 million years ago, with the Thick1 Era assumed to begin 2.4 billion years ago, since this is the reported age of the oldest recorded Earth crater, the 16-km Suavjärvi crater in Asia [3].

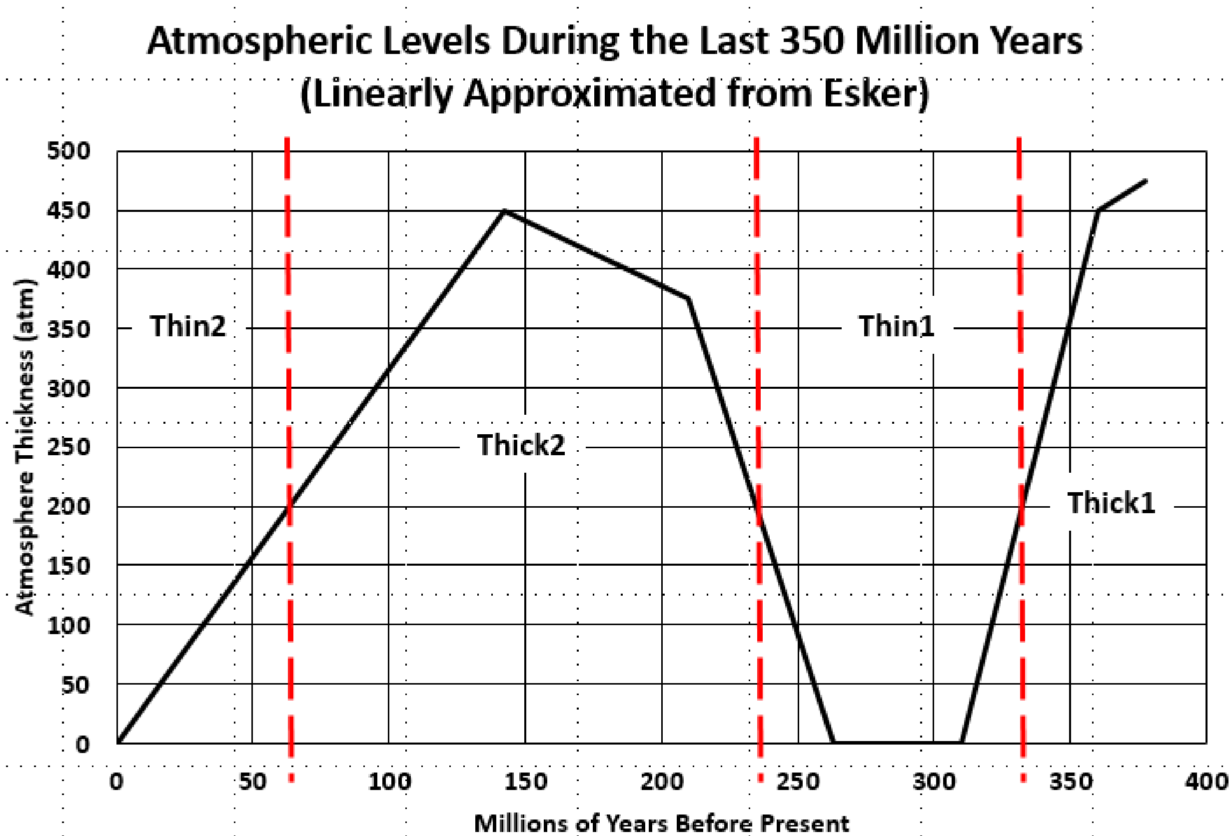

Figure 2. Atmospheric Levels during the Last 350 Million Years with Assumed Transition Times

3. Thick Atmosphere Theory and Earth Cratering Rates

The previous discussions by Levenspiel, et al., and Esker supporting a Thick Atmosphere Theory focus on mainly biological and aerodynamic arguments. After reading these discussions, I seek an independent means by which to examine this theory at least for plausibility, as anything definitive is currently beyond achieving. Reasoning that a thicker atmosphere should "burn up" more incoming meteors than a thinner one, I examine the cratering rate for impacting meteors on the Earth, based on the Earth Impact Database [3]. The list of all such craters is provided at the end of this article. From the Earth Impact Database I compile a list of all Earth craters from meteoric impacts that have been recorded (including some still cited as "unconfirmed"). For reasons that will become evident, only craters at least 4 km in size are counted. To the present 163 such craters have been identified, which reduces to 111 if only those at least 10,000 years old are counted (roughly up to the end of the last Ice Age). Note that this affects only the last Esker Era, labelled as Thin2. This somewhat arbitrary truncation results from the preponderance of North American craters of most recent age relative to similar craters worldwide. The intent is to remove possible bias from more extensive crater identification having been performed on our continent.

Before proceeding, it is important to ascertain the time history of what the cratering rate would have been for the Earth in the absence of an atmosphere, its geologic activity, etc. This may be possible by assuming the time history of the Moon's cratering rate would be closely representative, on a per unit area, given its proximity to the Earth. Figure 3 from Reference [4] presents an estimate of the lunar cratering rate over the assumed roughly five-billion-year lifespan of the Moon. Corresponding to the four Esker Atmospheric Eras is this figure showing the estimated rate of cratering on the Moon since its alleged birth in terms of the rate per unit surface area (km^2) for craters > 4 km in size. Table 1 shows the starting and finishing times for each of the Esker Eras, with the corresponding cratering rates at the start and finish of each based on the "constant production rate" curve (dashed). For each Era, the geometric mean (given the logarithmic plot) between the starting and finishing rates is assumed to be characteristic for that Era. For example, for Thick1, the geometric mean is just the square root of the cratering rates at the start and finish, i.e., $\sqrt{(8.5x10^{-5}km^{-2})(1.1x10^{-5}km^{-2})} = 3.06x10^{-5}km^{-2}$. Consistent with the curve, this decreases with time, from ~3E-5/km^2 during the earlier Thick1 Era down to ~2E-6/km^2 for the present Thin 2 Era, slightly over a factor of 10. When the time-weighted rates for both Thick and Thin Eras are calculated, we see that the weighted cratering rate for the Thin Eras is about one-quarter of that for the Thick ones.[1] This is expected given the Thick Eras always precede the Thin ones, such that their cratering rates are relatively higher, and the cumulative time periods for the Thick Eras (~2.2 billion years) is over 10 times longer than for the Thin ones (~160 million years).

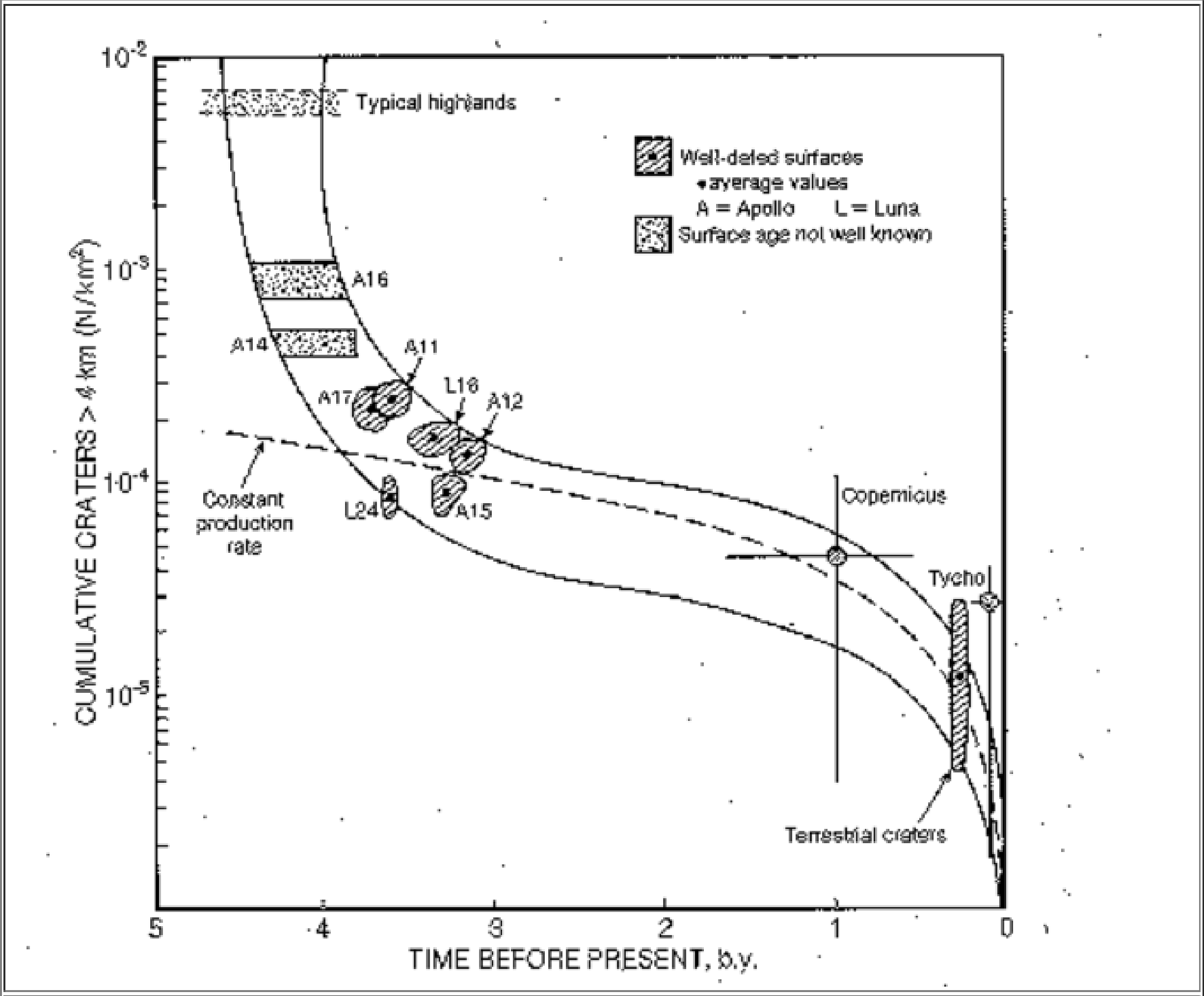

Figure 1. Lunar crater production rates through geologic time as reconstructed from the measurement of crater densities on the lunar surface and from absolute age dating of returned lunar rocks. Firm correlations can only be reconstructed for (1) the well-characterized basalt surfaces (3.8-3.2 Gyr) and (2) the contemporary meteorite flux based on current astronomical observations (t = 0). The ages of Tycho and Copernicus are inferred from indirect evidence. From F. Horz et al. p.84.

Figure 3. Lunar Crater Production Rates through Geologic Time

[1] Weighting over the two Thick and two Thin Atmospheric Eras is accomplished as follows (shown for the Thick Eras – it is analogous for the Thin Eras):

$$\frac{(3.06x10^{-5}km^{-2})(2.4x10^9y - 3.4x10^8y) + (5.05x10^{-6}km^{-2})(2.3x10^8y - 5.3x10^7y)}{(2.4x10^9y - 3.4x10^8y + 2.3x10^8y - 5.3x10^7y)} = 2.85x10^{-5}km^{-2}.$$

Table 1. Estimating the Rate of Lunar Cratering over the Corresponding Esker Atmospheric Eras for Craters at Least 4 km in Size

Atmospheric Eras (based on Esker [2])			Lunar Rate (/km^2)				
Name	**Start (y)**	**Finish (y)**	**At Start**	**At Finish**	**Geo Mean**	**Combined**	
Thick1	2.4E+09	3.4E+08	8.5E-05	1.1E-05	3.06E-05	Both Thick	2.85E-05
Thin1	3.4E+08	2.3E+08	1.1E-05	8.5E-06	9.67E-06	Both Thin	6.99E-06
Thick2	2.3E+08	5.3E+07	8.5E-06	3.0E-06	5.05E-06	Ratio	
Thin2	5.3E+07	0.0E+00	3.0E-06	1.0E-06	1.73E-06	Thin/Thick	*2.45E-01*

For each of the Esker Eras, I estimate the cratering rate on Earth (for craters at least 4 km in size, to place on an equivalent basis for comparison with the Moon) as the number of craters identified for that Era divided by the length of the Era and the ~29% of the surface area of the Earth that is land ($0.29x4\pi x6371km^2 = 1.5x10^8km^2$). This is evaluated on an annual basis, e.g., for Thick1 to the end of the Ice Age:

$$^{43}\!/_{(1.5x10^8km^2)(2.4x10^9y - 3.4x10^8y)} = 5.63x10^{-16}y^{-1}km^{-2}.$$

Then I weight over the two Thick and Thin Eras, as shown.[2] There are two sets of estimates, one where I truncate the counting of Earth craters at the end of the last Ice Age (10,000 years ago) and one without truncation (i.e., counting all craters to present time). This has no effect on the cratering rate for the Thick Eras (4.87E-7/km^2), which is a factor of 59 lower than the corresponding lunar cratering rate (2.85E-5/km^2), to be expected given Earth's active climate and geology. The cratering rates for the Thin Eras vary by about a factor of 2.5, being lower when truncated at the end of the Ice Age (2.64E-7/km^2 vs. 6.15E-7/km^2). Both are lower than the lunar cratering rate for the corresponding Thin Eras (6.99E-6/km^2), as would be expected, but notably not lower by as high a factor when compared to the Thick Eras (~59 for the Thick Eras, but around 26 and 11 for the Thin Eras).

Table 2. Estimating the Rate of Earth Cratering for the Esker Atmospheric Eras for Craters at Least 4 km in Size

Atmospheric Eras (based on Esker [2])			Earth Rate - to End of Ice Age				Earth Rate - To Present			
Name	Start (y)	Finish (y)	# of Craters	1/y-km^2	Combined	1/km^2	# of Craters	1/y-km^2	Combined	1/km^2
Thick1	2.4E+09	3.4E+08	43	1.41E-16	Both Thick	4.87E-07	43	1.41E-16	Both Thick	4.87E-07
Thin1	3.4E+08	2.3E+08	13	8.44E-16	Both Thin	2.64E-07	13	8.44E-16	Both Thin	6.15E-07
Thick2	2.3E+08	5.3E+07	29	1.10E-15	Ratio		29	1.10E-15	Ratio	
Thin2	5.3E+07	0.0E+00	26	3.31E-15	Thin/Thick	*5.42E-01*	78	9.94E-15	Thin/Thick	*1.26E+00*

What is of particular interest is the ratio of the weighted cratering rates (*red italics*). When truncated at the end of the Ice Age, the cratering rate during the Thin Eras is reduced by nearly a factor of two relative

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2 This weighting is slightly different from that used for the lunar rates, as follows, e.g., for the two Thick Eras:

$$(1.41x10^{-16}y^{-1}km^{-2})(2.4x10^9y - 3.4x10^8y) + (1.10x10^{-15}y^{-1}km^{-2})(2.3x10^8y - 5.3x10^7y) = 4.87x10^{-7}km^{-2}.$$

Note that this is the same as combining the two Thick Eras initially:

$$^{(43+29)}\!/_{(1.5x10^8km^2)} = 4.87x10^{-7}km^{-2}.$$

to that for the Thick Era, somewhat to be expected given the lunar result which showed roughly a factor of four reduction. The fact that the Earth cratering rate during the Thin Eras is reduced by less compared to the Moon rate may be indicative of the effect of atmospheric thickness. That is, the thinner Earth atmosphere allowed more cratering during the Thin Eras than would be expected relative to the cratering rate during the Thick Eras when compared to the ratio for the Moon which is climatically and geologically dead (compare ratios of 0.542 to 0.245 [Table 1]). If the Earth crater counting is not truncated, i.e., counted to present time, this difference is much more pronounced. In fact, the cratering rate during the Thin Eras now is slightly higher than during the Thick Eras, by about one quarter (ratio = 1.26, in red italics). Figure 4 shows this graphically by the three different trend lines (solid red for the Moon; dashed green for the Earth to the Ice Age; and dotted blue for the Earth to Present). The lunar trend line is the steepest downward. That for the Earth to the Ice Age is also downward, but not as steep, while the trend line for the Earth to Present is slightly upward.

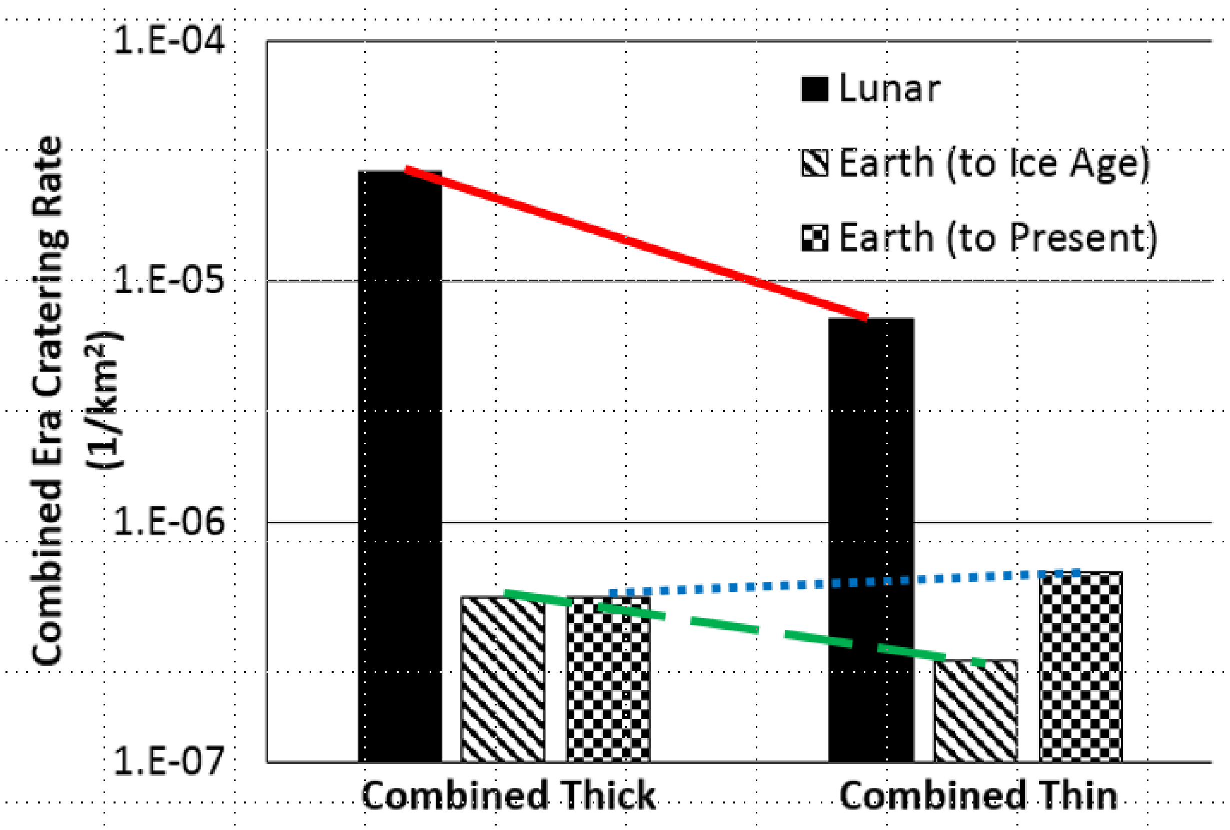

Figure 4. Comparing Trends in Cratering Rates for the Earth and Moon over the Combined Thick and Thin Atmosphere Eras

The Earth to Present trend is completely different from the lunar, which saw a <u>reduction</u> by about a factor of four rather than this increase by one quarter. This may be indicative even more so of the atmospheric thickness effect, although the caveat previously mentioned about the preponderance of the most recent craters having been identified in North America somewhat tempers it. Nonetheless, even the comparison for truncation at the end of the Ice Age shows a noticeable difference relative to what would be expected for a body without an atmosphere subjected to the same meteor influx, represented by the Moon.

4. <u>Summary</u>

Another factor, though likely not as dominant as the potential atmospheric effect, could be a decreasing geologic activity on Earth with time, since the Thick Eras each preceded the Thin Eras. However, given Earth is still quite geologically active, likely not much less so than around two billion years ago, this effect is expected to be dwarfed by the atmospheric thickness difference. Given all the assumptions and approximations employed, and the fidelity of cratering data for both the Earth and Moon, no definitive conclusion can be drawn. However, at least this cratering rate analysis does not contradict the postulate that Earth's atmosphere has varied substantially in thickness as per Esker and offers an independent means to test the hypothesis to supplement the more biological and aerodynamic ones that both he and Levenspiel, et al., provide. During the Thick Atmosphere Era, meteor impact on the Earth would be decreased by a relatively greater degree vs. the Thin Atmosphere Era when compared to what would be expected on a per unit surface area for the geologically and climatologically dead Moon. Given two meteors of comparable size, speed and entry angle, the one hitting the thick atmosphere would be less likely to survive to impact than the one hitting the thin atmosphere on Earth.

References

1. Levenspiel, O.; Fitzgerald, T.; and Pettit, D. "Earth's Atmosphere Before the Age of Dinosaurs," Chemical Innovation, Vol. 30, No. 12, pp. 50-55, December 2000 (available at *http://pubs.acs.org/subscribe/archive/ci/30/i12/html/12learn.html*).
2. Esker, D. "Scientific Theory Solving the Dinosaur Paradox and Numerous Other Paradoxes Regarding Earth's Evolution" (to be published; currently available at *http://www.dinosaurtheory.com/index.html*).
3. "List of Impact Craters on Earth," Earth Impact Database (available at *https://en.wikipedia.org/wiki/List_of_impact_craters_on_earth*).
4. "Lunar Crater Production Rates through Geologic Time" (available at *http://muller.lbl.gov/pages/crateringrates.htm).*

Complete List of Identified Earth Craters [3]

#	Name/Location	Continent	Size (km)	Age (yr)
1	Suavjärvi	Asia	16	2.4E+09
2	Vredefort	Africa	300	2.0E+09
3	Yarrabubba	Australia	30	2.0E+09
4	Dhala	Asia	11	1.9E+09
5	Keurusselkä	Europe	30	1.8E+09
6	Paasselkä	Europe	10	1.8E+09
7	Shoemaker (was Teague)	Australia	30	1.5E+09
8	Matt Wilson	Australia	7.5	1.4E+09
9	*Ullapool*	*Europe*	*50*	*1.2E+09*
10	Amelia Creek	Australia	20	1.1E+09
11	Lumparn	Europe	9	1.0E+09
12	Suvasvesi North	Europe	4	1.0E+09
13	Jänisjärvi	Asia	14	7.0E+08
14	Strangways	Australia	25	6.5E+08
15	Söderfjärden	Europe	6.6	6.0E+08
16	Acraman	Australia	90	5.9E+08
17	Luizi	Africa	17	5.8E+08
18	Spider	Australia	13	5.7E+08
19	Sääksjärvi	Europe	6	5.6E+08
20	Kelly West	Australia	10	5.5E+08
21	*Massive Australian Precambrian/ Cambrian Impact Structure, MAPCIS*	*Australia*	*1250*	*5.5E+08*
22	Foelsche	Australia	6	5.5E+08
23	Lawn Hill	Australia	18	5.2E+08
24	Glikson	Australia	19	5.1E+08
25	*Wilkes Land*	*Antarctica*	*485*	*5.0E+08*
26	Gardnos	Europe	5	5.0E+08
27	Mizarai	Europe	5	5.0E+08
28	Neugrund	Europe	8	4.7E+08
29	*Decorah crater*	*North America*	*5.6*	*4.7E+08*
30	Lockne	Europe	7.5	4.6E+08
31	Kärdla	Europe	4	4.6E+08
32	*Ishim*	*Asia*	*350*	*4.5E+08*
33	*Tokrauskaya*	*Asia*	*220*	*4.5E+08*
34	*Jeptha Knob*	*North America*	*4.3*	*4.3E+08*
35	Kaluga	Asia	15	3.8E+08
36	Ilvinets	Europe	8.5	3.8E+08
37	Siljan	Europe	52	3.8E+08
38	*Panther Mountain*	*North America*	*10*	*3.8E+08*
39	*Alamo bolide impact*	*North America*	*assumed > 4 km given age*	*3.7E+08*
40	Woodleigh	Australia	90	3.6E+08
41	Piccaninny	Australia	7	3.6E+08
42	Gweni-Fada	Africa	14	3.5E+08
43	Aorounga	Africa	12.6	3.5E+08
44	*East Warburton Basin*	*Australia*	*200*	*3.3E+08*
45	*West Warburton Basin*	*Australia*	*200*	*3.3E+08*
46	*Weaubleau-Osceola*	*North America*	*17.5*	*3.3E+08*
47	*Unnamed impact*	*Australia*	*130*	*3.0E+08*
48	*Unnamed impact*	*Australia*	*120*	*3.0E+08*
49	Serra da Cangalha	South America	12	3.0E+08
50	Dobele	Europe	4.5	2.9E+08
51	Ternovka	Europe	11	2.8E+08
52	Kursk	Asia	6	2.5E+08
53	Bedout	Australia	200	2.5E+08
54	Araguainha	South America	40	2.4E+08
55	Saqqar	Asia	34	2.4E+08
56	*Saqqar**	*Asia*	*34*	*2.4E+08*
57	Rochechouart	Europe	23	2.1E+08
58	*Guarda*	*Europe*	*30*	*2.0E+08*
59	Riachão Ring	South America	4.5	2.0E+08
60	Obolon	Europe	20	1.7E+08
61	Puchezh-Katunki	Asia	80	1.7E+08
62	Vepriai	Europe	8	1.6E+08
63	Morokweng	Africa	70	1.5E+08
64	Gosses Bluff	Australia	22	1.4E+08
65	Mjølnir	Europe	40	1.4E+08
66	Tookoonooka	Australia	55	1.3E+08
67	Mien	Europe	9	1.2E+08
68	Oasis	Africa	18	1.2E+08
69	Mount Toondina	Australia	4	1.1E+08
70	*Kebira*	*Africa*	*31*	*1.0E+08*
71	Dellen	Europe	19	8.9E+07
72	*Praia Grande*	*South America*	*20*	*8.4E+07*
73	Lappajärvi	Europe	23	7.3E+07
74	Kara	Asia	65	7.0E+07
75	Tin Bider	Africa	6	7.0E+07
76	Chukcha	Asia	6	7.0E+07
77	*Bow City*	*North America*	*8*	*7.0E+07*
78	Vargeão Dome	South America	12	7.0E+07
79	Boltysh	Europe	24	6.5E+07
80	*Shiva*	*Asia*	*600*	*6.5E+07*
81	Vista Alegre	South America	9.5	6.5E+07
82	Chicxulub	North America	170	6.5E+07
83	*Wembo-Nyama ring structure*	*Africa*	*41*	*6.0E+07*
84	Connolly Basin	Australia	9	6.0E+07
85	*Silverpit*	*Europe*	*20*	*6.0E+07*
86	Goat Paddock	Australia	5	5.0E+07
87	Kamensk	Asia	25	4.9E+07
88	Jabal Waqf es Swwan	Asia	5.5	4.7E+07
89	Ragozinka	Asia	9	4.6E+07
90	Chiyli	Asia	5.5	4.6E+07
91	*Victoria Island structure*	*North America*	*5.5*	*4.3E+07*
92	Logoisk	Europe	15	4.2E+07
93	Logancha	Asia	20	4.0E+07
94	Beyenchime-Salaatin	Asia	8	4.0E+07
95	Popigai	Asia	100	3.6E+07
96	Flaxman	Australia	10	3.5E+07
97	Crawford	Australia	8.5	3.5E+07
98	*Toms Canyon*	*North America*	*22*	*3.5E+07*
99	*Vichada Structure*	*South America*	*50*	*3.0E+07*
100	*Ross*	*Antarctica*	*550*	*2.8E+07*
101	Nördlinger Ries	Europe	25	1.5E+07
102	Karakul	Asia	52	5.0E+06
103	Karla	Asia	10	5.0E+06
104	Bigach	Asia	8	5.0E+06
105	El'gygytgyn	Asia	18	3.5E+06
106	*Corossol*	*North America*	*4*	*2.6E+06*
107	Bosumtwi	Africa	10.5	1.1E+06
108	*Pantasma*	*North America*	*10*	*1.0E+06*
109	Zhamanshin	Asia	14	9.0E+05
110	Rio Cuarto	South America	4.5	1.0E+05
111	*Iturralde*	*South America*	*8*	*2.1E+04*
112	*Zerelia West*	*Europe*	*250*	*7.0E+03*
113	*Zerelia East*	*Europe*	*150*	*7.0E+03*
114	Sudbury	North America	250	1.9E+03
115	*Strente*	*Europe*	*127.5*	*1.7E+03*
116	Santa Fe	North America	9.5	1.2E+03
117	Beaverhead	North America	60	6.0E+02
118	Rock Elm	North America	6	5.1E+02
119	Presqu'ile	North America	24	5.0E+02

#	Name/Location	Continent	Size (km)	Age (yr)
120	Glover Bluff	North America	8	5.0E+02
121	Ames	North America	16	4.7E+02
122	Slate Islands	North America	30	4.5E+02
123	Calvin	North America	8.5	4.5E+02
124	Pilot	North America	6	4.5E+02
125	Couture	North America	8	4.3E+02
126	Glasford	North America	4	4.3E+02
127	Nicholson	North America	12.5	4.0E+02
128	La Moinerie	North America	8	4.0E+02
129	Elbow	North America	8	4.0E+02
130	Charlevoix	North America	54	3.4E+02
131	Serpent Mound	North America	8	3.2E+02
132	Crooked Creek	North America	7	3.2E+02
133	Decaturville	North America	6	3.0E+02
134	Middlesboro	North America	6	3.0E+02
135	Île Rouleau	North America	4	3.0E+02
136	Lac à l'Eau Claire Ouest	North America	36	2.9E+02
137	Lac à l'Eau Claire Est	North America	26	2.9E+02
138	Des Plaines	North America	8	2.8E+02
139	Gow	North America	4	2.5E+02
140	Tunnunik	North America	25	2.4E+02
141	Saint Martin	North America	40	2.2E+02
142	Manicouagan	North America	100	2.1E+02
143	Wells Creek	North America	12	2.0E+02
144	Red Wing	North America	9	2.0E+02
145	Cloud Creek	North America	7	1.9E+02
146	Upheaval Dome	North America	10	1.7E+02
147	Carswell	North America	39	1.2E+02
148	Sierra Madera	North America	13	1.0E+02
149	Deep Bay	North America	13	9.9E+01
150	Kentland	North America	13	9.7E+01
151	Avak	North America	12	9.5E+01
152	Steen River	North America	25	9.1E+01
153	Wetumpka	North America	7.6	8.3E+01
154	Santa Marta	South America	10	8.3E+01
155	Maple Creek	North America	6	7.5E+01
156	Manson	North America	35	7.4E+01
157	Eagle Butte	North America	10	6.5E+01
158	Marquez	North America	12.7	5.8E+01
159	Montagnais	North America	45	5.1E+01
160	Haughton	North America	23	3.9E+01
161	Wanapitei	North America	7.5	3.7E+01
162	Mistastin	North America	28	3.6E+01
163	Chesapeake Bay	North America	90	3.6E+01
164	*Bowers*	*Antarctica*	*100*	*Unknown*
165	*Snows Island*	*North America*	*11*	*Unknown*
166	*Cerro Jarau*	*South America*	*10*	*Unknown*
167	Brent	North America	3.8	3.1E+08
168	Suvasvesi South	Europe	3.8	2.5E+08
169	Steinheim	Europe	3.8	1.5E+07
170	Flynn Creek	North America	3.8	3.6E+02
171	Colônia	South America	3.6	2.1E+01
172	Kgagodi	Africa	3.5	1.8E+08
173	Zeleny Gai	Europe	3.5	8.0E+07
174	Ouarkziz	Africa	3.5	7.0E+07
175	Pingualuit	North America	3.44	1.4E+00
176	Zapadnaya	Europe	3.2	1.7E+08
177	Newporte	North America	3.2	5.0E+02
178	Goyder	Australia	3	1.4E+09
179	Iso-Naakkima	Europe	3	1.0E+09
180	Granby	Europe	3	4.7E+08
181	Gusev	Asia	3	4.9E+07
182	Agoudal	Africa	3	1.1E+05
183	*Ramgarh*	*Asia*	*3*	*Unknown*
184	*Gatun structure*	*North America*	*2.85*	*2.0E+07*
185	*Mahas*	*Africa*	*2.85*	*Unknown*
186	Shunak	Asia	2.8	4.5E+07
187	Rotmistrovka	Europe	2.7	1.2E+08
188	Ritland crater	Europe	2.7	5.2E+02
189	Mishina Gora	Asia	2.5	3.0E+08
190	Roter Kamm	Africa	2.5	3.7E+06
191	Viewfield	North America	2.5	1.9E+02
192	West Hawk	North America	2.44	3.5E+02
193	Holleford	North America	2.35	5.5E+02
194	Tvären	Europe	2	4.6E+08
195	BP Structure	Africa	2	1.2E+08
196	*Brushy Creek Feature*	*North America*	*2*	*2.1E+04*
197	Tenoumer	Africa	1.9	2.1E+04
198	Lonar	Asia	1.83	5.2E+04
199	Xiuyan crater	Asia	1.8	5.0E+04
200	Talemzane	Africa	1.75	3.0E+06
201	Liverpool	Australia	1.6	7.7E+08
202	Saarijärvi	Europe	1.5	6.0E+08
203	Karikkoselkä	Europe	1.4	2.3E+08
204	Tabun-Khara-Obo	Asia	1.3	1.5E+08
205	Hummeln structure	Europe	1.2	4.6E+08
206	*Darwin Crater*	*Australia*	*1.2*	*8.0E+05*
207	Barringer	North America	1.19	4.9E-02
208	Tswaing (was Pretoria Saltpan)	Africa	1.13	2.2E+05
209	Malingen	Europe	1	4.6E+08
210	Wolfe Creek	Australia	0.87	3.0E+05
211	*Temimichat*	*Africa*	*0.75*	*Unknown*
212	Kalkkop	Africa	0.64	2.5E+05
213	*Cheko*	*Asia*	*0.5*	*1.0E+02*
214	Monturaqui	South America	0.46	1.0E+06
215	Amguid	Africa	0.45	1.0E+05
216	Aouelloul	Africa	0.39	3.0E+06
217	Macha	Asia	0.3	7.0E+03
218	*Hickman Crater*	*Australia*	*0.27*	*3.2E+04*
219	Boxhole	Australia	0.17	5.4E+03
220	Odessa	North America	0.168	5.0E-02
221	Henbury	Australia	0.16	4.2E+03
222	*Patomskiy*	*Asia*	*0.16*	*3.0E+02*
223	Wabar	Asia	0.116	1.5E+02
224	Kaali	Europe	0.11	4.0E+03
225	Morasko	Europe	0.1	1.0E+04
226	Veevers	Australia	0.08	2.0E+04
227	Ilumetsa	Europe	0.08	6.6E+03
228	Sobolev	Asia	0.053	1.0E+03
229	Campo del Cielo	South America	0.05	4.0E+03
230	Kamil	Africa	0.045	2.0E+03
231	Whitecourt	North America	0.04	1.1E-03
232	Sikhote-Alin	Asia	0.026	7.0E+01
233	Dalgaranga	Australia	0.02	3.0E+03
234	Haviland	North America	0.015	1.0E-03
235	Carancas	South America	0.0135	7.0E-06

Italicized entries (*red*) indicate "unconfirmed" craters. For size and age, if listing indicates finite range, midpoint value is assumed (geometric if range is order of magnitude or more); if open-ended range (i.e., > x or < x), minimum or maximum cited value (x) is assumed. Unknown entries excluded except for Alamo Bolide Impact which, given age, is assumed originally > 4km in size to be detectable today.