THE EXTINCTION OF THE LATE CRETACEOUS:FROM COLD CASE TO HOT TOPIC

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Abstract

Brachiopods are marine animals belonging to their own phylum, the Brachiopoda. Nowadays rare, they were of great diversity during the Paleozoic era. Previous studies have proven a decimation of the brachiopod species and a change in their major traits coinciding with the end-Cretaceous mass extinction, around 66 million years ago. This mass extinction, last of the five major extinctions in the history of the Earth, marked the end of the Cretaceous period and the start of the Paleogene period.

The cause of this mass extinction is still highly debated to this day. Scientists have set out a variety of theories such as an extraterrestrial bolide impact or intense volcanic activity being the causes of a drastic climate change that wiped out the vast majority of species. Faunal and microfossil assemblages around the Cretaceous-Paleogene (K-Pg) boundary in the southern region of Scandinavia have proven changes in the tropical and subtropical climate of the late Maastrichtian age, as well as the decrease of specific species in the Danian age. This paper examined the environmental changes that took place around the K-Pg boundary, and the impact on aquatic animal species in the Southern Zealand. Nannofossils, plankton foraminifera, and brachiopods morphology studies were compared and analyzed to better understand the nature of the mass extinction.

It was concluded that 40% of the brachiopod species survived, while the rest went extinct due to major changes in their ecological niche, because of climate change. After looking at the different theories explaining this mass extinction, the team settled on a series of events consisting of gradual warmings, cooling and warming again, along with recurrent ocean acidifications. Extensive literature findings found Deccan Traps to be the cause for the climate change around the K-Pg boundary; especially since more recent studies clarified some unanswered questions while proving that the Meteor theory required further evidence.

Table of Contents

Introduction

While many tend to look forward and study the future, we must not forget about the past. Studying past events is of utmost importance to understand the situations and environments of today, predict future outcomes and avoid catastrophic mistakes. Millions of years ago, the end-Cretaceous mass extinction took place, wiping out entire population and most famously the dinosaurs. This rare event has been increasingly studied by scientists with the purpose of finding its root cause. Tracking the changes in the biome and climatic conditions has helped to understand and analyze this massive event in history. It has become possible to predict the future by looking at the past, using the many natural geological landmarks present all around the world. This study compares many of them for their aquatic assemblage but will delve deeper into those located in Europe.

Stevns Klint is a white chalk cliff located on the southeast part of the isle of Zealand, Denmark. It is classified as a World Heritage Site by the UNESCO for its high geological importance as it is one of the best places to observe the exposed layers of rock showing the Cretaceous-Paleogene (K-Pg) boundary.

The K-Pg boundary is a geological signature, a thin recognizable layer of rock testifying of a particular geological event. This one signature is a layer of Fish Clay (also known as *Fiskeler*) and corresponds to the Cretaceous-Paleogene mass extinction that happened between 65.5 and 66 million years ago. In this paper, we will use the preferred absolute age of 66 (rounded from 66.043) million years, found by Renne *et al.* (2013).

The Cretaceous-Paleogene extinction is the fifth mass extinction in Earth's history (Raup, Spekoski, 1982), and it is estimated that around 70% of all species went extinct during this time (Jablonksi, 1994), among them the dinosaurs. Thus, this event is of high importance in the chronology of the Earth, and marks (see Fig.1):

- The end of the Mesozoic era and the start of the Cenozoic era,
- The end of the Cretaceous and the start of the Paleogene period,
- And the end of the Maastrichtian age and the start of the Danian age.

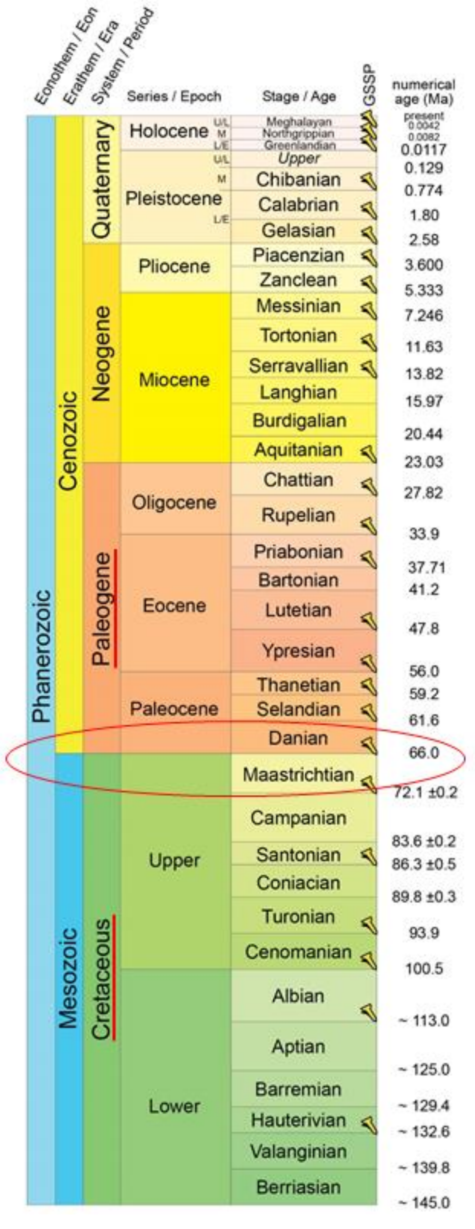

Figure 1: *International Chronostratigraphic Chart. Source: International Commission on Stratigraphy (2020). See Appendix for full chart.*

Nevertheless, the cause of this extinction event is still hotly debated. Amongst the many theories presented, the most famous ones include the impact of a meteor, and high volcanic and geological activity, which resulted in devastating climate changes. Those would have caused scarce food and nutrient resources, and the potential wiping out starting at the bottom of the food chain (Golovneva, 2000).

The implications of the K-Pg extinction deserve to be explored further, thus this paper aims to build on previous studies looking at the events and changes occurring around the K-Pg boundary. By elaborating a hypothetical chronological map of events, this study ambitions to explore the incidents of that time in greater depth, and answer the research question:

What environmental changes took place during the K-Pg extinction event in Southern Zealand, and how did it impact the brachiopods of the late Cretaceous period and following generations?

Due to the high literature content and the non-homogeneous opinions on the topic of the Cretaceous-Paleogene extinction, the following sub-questions were elaborated as guidelines:

Sub-questions:

I. What were the characteristics of the Southern Zealand biome in the late Cretaceous period and early Paleogene?
II. What were the climatic conditions before and after the K-Pg extinction event, and what were the effects of climate change on Southern Zealand?
III. What are the assumed chronology events around the K-Pg extinction?

The assemblages' variations in this study were focused on aquatic life around the Southern Zealand region (see squared area, Fig. 2), as it is where Stevns Klint is located. Brachiopods (Brachiopoda) have been chosen as the target phylum since they have prevalence as a geological indicator and existing research has used them to illustrate the effect of climate change on maritime species.

Firstly, this paper provides background information on the climatic conditions, the biome and aquatic biodiversity of Southern Zealand. Then, an overview of the different theories surrounding the extinction is made, along with a more detailed explanation of two of the main theories: the meteor impact and the Deccan Traps. Finally, those theories as well as the team’s conclusion of events are discussed.

It is important to note that the team had initially planned to collect rock samples from late Maastrichtian and early Danian, from the Omya quarry in Store Heddinge, next to Stevns Klint. These samples would have been treated to isolate brachiopods fossils, allowing the team to observe and compare them. The results would have illustrated the effects of the mass extinction on the aquatic biome. This experiment was not done because of technical difficulties with the quarry and the impossibility to obtain samples.

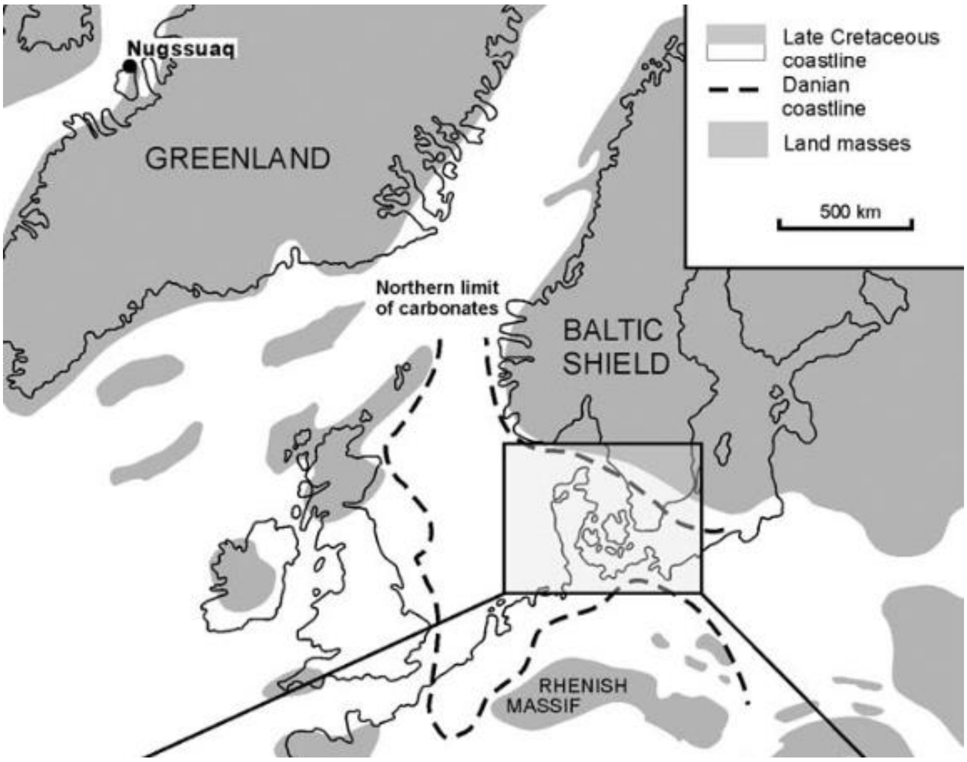

Figure 2: *Map of Northern Europe around 66 million years ago. Source: M. Bernecker, 2005.*

Methods

This study contemplated the series of happenings during the K-Pg extinction by gathering and analysis of existing hypotheses. These were chronologically gathered with a focus on the periods preceding and following the K-Pg event, with a location restraint to the Southern Zealand area.

Since geology is a widely debated subject with many possible explanations to the same topic, it was stated that all findings must be published and obtained from trustworthy sites who follow a proper scientific conduct. A limited array of keywords would be necessary to constrain the amount of information and keep the data relevant to the field of study. The table below references keywords and sites used in the gathering of research information during the first month of the study.

Keywords	
K-Pg extinction	K-T, C-T, K/T event
Climate Maastrichtian	Stevns Klint
Climate Early Danian	Late Cretaceous
Southern Zealand biome (Maastrichtian/Danian)	Mass extinction
Deccan Traps	Brachiopods

Established websites: Google Scholar, Google Books, PubMed (NCBI), science.gov, Educational Resources information Center, Worldwide Science, ScienceDirect, ResearchGate, Elsevier, Springer.

The K-Pg abbreviation refers to the Cretaceous (K) and the Paleogene (Pg) periods. It is often also written as KPB. In this case, the B is for "boundary" and the K refers to the word *Kreide*, meaning "Cretaceous" in German. It can also be found written as "C-T", "K/T" and "K-T" boundary, with the T standing for "Tertiary" which was the name of the period now composed of the Paleogene and the Neogene, up until 1989 (Surlyk *et al.*, 2006). This explains the different abbreviations used as keywords to find relevant data.

Theories regarding the K-Pg extinction are vast, and some contradict each other. Therefore, the team decided to focus on beliefs related to a meteor hit, volcanic activity and possible changes in climate by creating a timeline of occurrences around the event in question. For some hypotheses, such as the meteor hit, the components of the objects were researched and associated to recent findings for proof. Climatic activity and the biome of the southern Zealand region were investigated through published articles and maps. Changes in the flora, fauna, atmospheric oxygen, species survivorship and long-term environmental changes across high latitudes were analyzed for both Maastrichtian and Danian ages. Such data was collected previously by scientists like F. Surlyk, M. Jarrett, M. Bernecker and L. Golovneva which was later explored by the team in depth.

To assess how the brachiopod diversity changed between the two ages studied (late Maastrichtian and early Danian), the group compared survivorship and morphology of these species previously found in rocky samples from both ages. Brachiopod studies have been referenced in order to contemplate existing traits and those found below the Danian meter at the K-Pg boundary. Similarities in species dominance and changes were recorded for better understanding. Comprehending the diversity among brachiopods served as a guide to grasp the involvement, roles and extinction rates of other organisms, as well as build upon the biome changes knowledge.

Leaning on a study by F. Surlyk and M.B. Johansen (1984) on the brachiopods of Stevns Klint, this paper offers a brief comparison between assemblages of species within other sites in Denmark (Nye Klov) and in similarly high latitude regions around the globe, such as Texas (Brazos). Biodiversity above and below the Fish Clay layer has been observed not only in brachiopods, but in plankton foraminifera, calcareous nannofossils and other species as well.

Background

1. Climatic conditions throughout the Cretaceous-Tertiary boundary.

In order to fully comprehend the impact of climate change during the Cretaceous-Tertiary (K-Pg) boundary, if any; it is imperative to obtain a general knowledge of the climatic conditions of the time. This section explores the climatic characteristics pertaining to the boundary by exploring the ecological and taxonomic properties of floral assemblages and faunas in high latitudes (Golovneva, 2000, p.44).

Fossil floras	Latitue (°N)	Mean annual temperature (°C)	Cold-month mean temperature (°C)	Warm month mean temperature (°C)	Mean annual precipation (mm)	Mean monthly growing season precipation (mm)	Mean growing season precipation (mm)	Three consecutive driest months precipation (mm)	Length of the growing season (months)
Rarytkin	63	11	4	19	1722	129	1410	305	6.9
Kakanaut	63	10	3	19	1414	98	948	181	6.3
Edmonton	53	12	5	19	1804	141	1586	335	7.1
Sakhalin	49	14	8	20	1892	136	1214	293	8
Zaisan	48	11	4	19	1515	106	1065	230	7
Hell Creek	46	12	6	19	1899	131	1094	302	7
Lance	43	14	8	21	1574	119	1216	242	8
Medicine Bow	40	17	13	23	1933	172	1946	348	9.7
Ripley	35	17	11	23	1498	115	1126	204	9.2
SD		1.8	3.3	3.1	430	23	280	70	1.1

Table 1: *Climate data obtained from CLAMP studies for Maastrichtian time showing predictions for eight climate variables: Mean annual temperature, cold-month and warm months mean temperatures in ºC, mean annual precipitation, mean monthly growing season precipitation, mean growing season precipitation, three consecutive driest months precipitation in mm, and length of growing season in months. Source: Golovneva, 2000.*

In the geological signature, the Maastrichtian stage is considered the youngest stage of the Cretaceous period, and predecessor to the K-Pg boundary. An analytical procedure developed by Lena Golovneva called *climate leaf analysis multivariate program* (CLAMP) determined that the Maastrichtian climate was tropical in high latitudes and subtropical towards the south with high precipitations. CLAMP uses morphological leaf characters from several fossil floras to produce an estimate of climate variables such as precipitation during driest months, mean annual temperature, mean month growing precipitation, length of the growing season, mean temperature of the cold months as well as the warm months, and the mean growing precipitation (Golovneva, 2000, p. 44). Table 1 is an example of a CLAMP analysis to the Maastrichtian climate, where the climate variables are represented. The samples in this study were taken from a variety of high latitude locations, as, unfortunately, there are no Maastrichtian floral assemblages in the European regions that could have been used.

As mentioned, the climatic temperatures for the Maastrichtian time were warm, with mean annual temperatures at high altitudes ranging from 10º-14ºC, and 15º-17ºC in the south. Warm and cold months also had different temperatures depending on the latitude. In the more subtropical weather of the south, the temperatures for the cold months were similar to that of the mean annual temperatures in high latitudes, ranging from 10º-13ºC and going up to 20º-23ºC in the summer (warm months). As for the high to mid-latitudes, the temperature ranged from 3º-8ºC in the winter, and 19º-20ªC during the summertime. The annual range of temperatures was similar to that of modern maritime climate, about 12º-16ºC (Golovneva, 2000, p. 48). These digits paint a picture of mild winters where temperatures rarely went below

0ºC, and the frost periods were short. Additionally, CLAMP analysis estimated precipitation for Maastrichtian times to be relatively high in all the studied areas, with an average of 1500-1700 mm evenly distributed over the year (Golovneva, 2000, p.50).

In comparison with today's climate, temperatures of Maastrichtian time would be higher for the high to mid-latitudes, and lower in the southern regions. Differences in mean annual temperatures between the artic polar areas and the tropical/sub-tropical ones during the Maastrichtian time was about 10ºC, which is considerably less than the current mean annual difference (40º-50ºC) (Golovneva, 2000, p.51). Figure 3 offers a comparison for present and Maastrichtian temperatures.

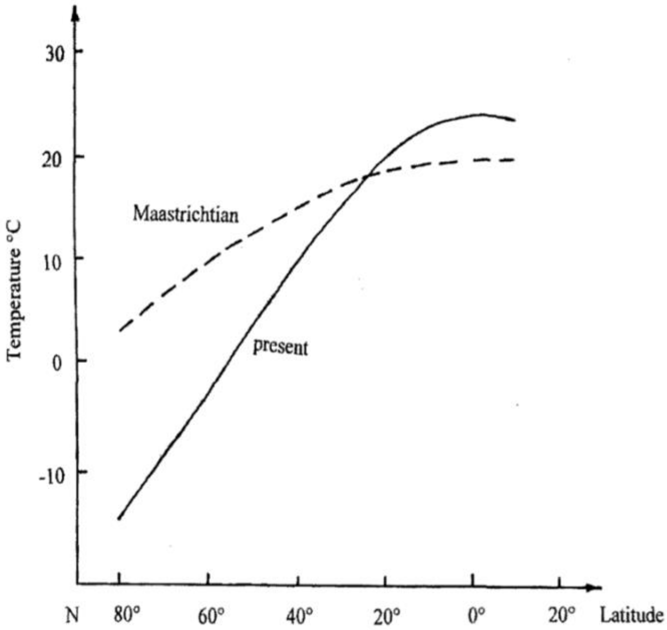

Figure 3: *Temperature comparison between Maastrichtian time (dotted line) and present time (continuous line). Latitude vs Temperature (ºC) plot. Sources: Barron, 1983, Golovneva, L. 2000.*

Figure 4: *Hesperornithoides miessleri during Cretaceous period. Image credit: Gabriel Ugueto.*

Another significant difference between the Maastrichtian climate and the modern one, is the temperatures of deep ocean waters. Currently, the temperature for deep ocean waters is 2ºC, significantly less than that of Maastrichtian Ocean waters that reached 10º-14ºC (Boersma, 1984). Such high temperatures might be the result of shallow epicontinental seas, and surface evaporation which causes an increase in salinity and density of the water that is then moved to the bottom of the ocean. Thus, the heat is transferred from the surface to the bottom of the ocean, raising the overall temperature. Since epicontinental seas were vast during the Maastrichtian time, and there's records of hesperornithoides fossils (Figure 4), dinosaur birds related to water masses of high productivity occurrences in the Cretaceous period; it is believed that these temperatures in the ocean not only raised the temperature of the surface but the atmosphere as well. Subsequently, explaining the elevated temperatures for the Maastrichtian time.

2. Biodiversity changes in the marine biome of Southern Zealand from Maastrichtian to Danian

When it comes to comprehending the chain of events that took place during the K-Pg event, a full understanding of its biome changes is necessary. The scale and origin of an extinction event is usually measured by the plotting of a sufficiently large and moderately well-preserved species, families and genera against time, as well as a complete analysis of their evolutionary units and taxonomic properties (Raup, 1988).

Within the north ocean biome of the late Cretaceous many organisms, both vertebrate and invertebrate, were found and are still present in our oceans today; these include corals (from the class azooxanthellate), sessile (meaning immobile) and tube-building annelid worms from the Serpulidae family, echinoids, mollusks, bryozoans, bony fishes, brachiopods, members from the Excavata group, solitary corals from genus *Caryophyllia*, and *Moltkia* genus (Bernecker, 1990; Surlyk, 2006; Klompmaker, 2016). In Faxe, Denmark and Limhanm, Sweden, remains of Danian animals among which: teeth from sharks, and skulls, jaws, vertebra, limb bone and isolated teeth from crocodilians (Adolfssen, 2017) have been found.

By analyzing the deposits concerning the Maastrichtian, K-Pg boundary and Danian periods, it is observed that layers preceding the Danian period contain larger organisms. Most of the fossils found in the Danian layers corresponded to bryozoans, echinoids, brachiopods and corals, which are relatively small entities (Surlyk, Damholt & Bjerager, 2006). Most of the corals were aphotic, meaning they were not symbiotic with photosynthetic organisms, like dinoflagellates, to obtain energy. Physiological similarities between current aphotic corals and the ones found in the deposits have been pointed out, which has led to the belief that ancient corals could also share similar preferences regarding their habitat, like depth. This means that the paleodepth would be equal to the one found nowadays in Denmark, i.e. between 100 and 300 meters (Bernecker & Weidlich, 1990).

When it comes to data recovered from the Danian period, interesting facts about their ecosystem stood out, such as the absence of algae but the occurrence of coccoliths and foraminifera. Additionally, diversity was remarkably low among the azooxanthellate coral community, which was believed to be aphotic and solitary corals, meaning they did not form colonial reefs (Bernecker, 1990). During the Cretaceous period, in the tropical reefs, many rudist bivalves appeared. They were mollusks that, together with the corals and sponges, acted as major reef builders. In addition, some species seemed to have been able to perform photo-symbiosis. This meant that throughout the middle Cretaceous a “rudistic bloom” existed, which continued until the late Cretaceous, matching the global warming situation of the time (due to high greenhouse gas emissions). However, during this time an increase in diversity among both rudists and corals was recorded, inconsistent with the supposed on-going mass extinction. Corals seemed to evolve further in deeper waters which fully matches the properties of fossil findings (Van Oppen, 2018).

At the K-Pg extinction, rudists disappeared completely due to high temperatures and ocean acidification. Coral reefs disappeared as well, except solitary corals (and corals living towards deep waters like azooxanthellate corals, non-photosymbiotic corals) who remained along the next age, the Danian. Once again, this pattern of extinction correlates with the aforementioned estimations about the biome. Researchers have argued that the major cause of reef depletion at the time was ocean acidification (Van Oppen, 2018).

3. Brachiopods of the late Cretaceous and early Paleogene

Brachiopods are marine animals belonging to their own phylum, the Brachiopoda. They can be found in all geological periods since the Cambrian. Though nowadays rare, they were of great diversity during the Paleozoic era. Their prevalence started to decline after the Permian-Triassic (Pe-Tr) extinction (see Fig. 5). There are only 5 orders of brachiopods living today: lingulida, craniida, rhynchonellida, terebratulida and discinida. Since certain orders and species of brachiopods went extinct at certain times, they can be used as markers in stratigraphical subdivisions. This makes brachiopods valuable in both paleontology and geology. It is possible to divide the Danish/Maastrichtian into 10 zones only using brachiopod species as markers. Figure 5 shows the time range specific orders in which brachiopods lived. (Surlyk, 1972)

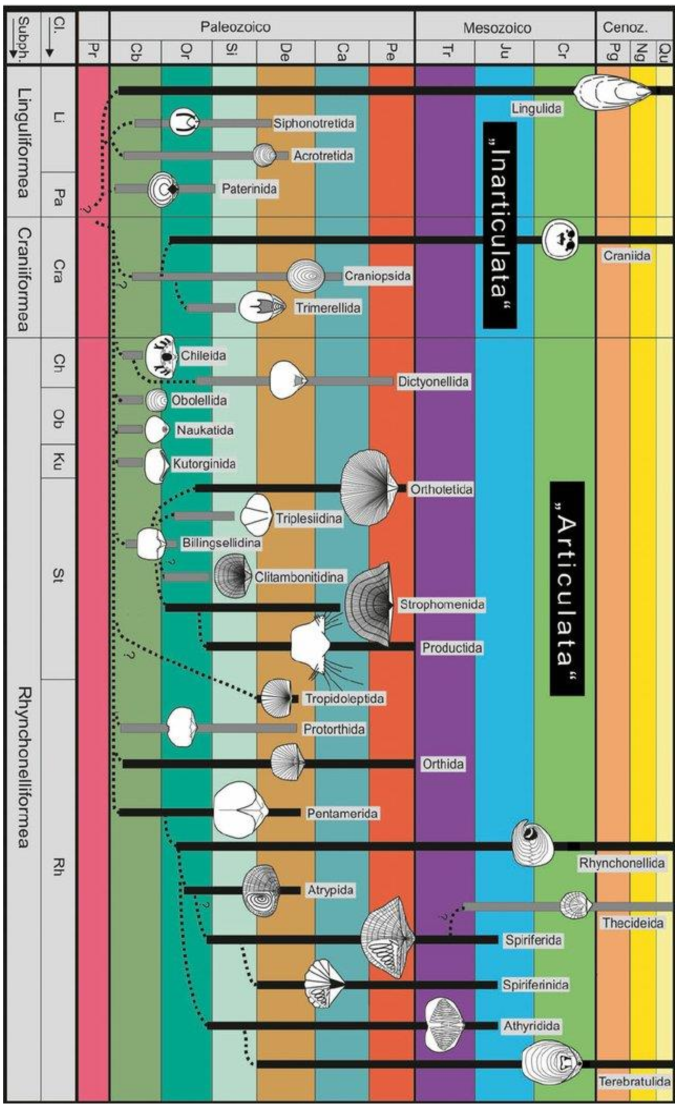

Figure 5: Brachiopods have been used as stratigraphical markers for multiple extinctions, Such as the Triassic -Jurassic, the Permian -Triassic and the late Devonian extinctions. (Schemm-Gregory, 2013)

At the time of the late Cretaceous there were over a 100 brachiopod species alive on the planet. Although no order of brachiopods seemly became extinct during the K-Pg event, there were multiple species and genera which did. Approximately 80 species of brachiopods went extinct during the K-Pg event, but that list continues to grow as there are constantly more species being discovered.

Only a few species survived the extinction: approximately 25 survived, with 7 still living today. After the K-Pg event more species of brachiopods started to emerge. During the aftermath of the K-Pg extinction more than 13 new species appeared (Paleontology database, 2021).

The area of southern Zealand had a rich brachiopod fauna in the late Maastrichtian, with 42 species living in that time and place, many fitting into very specific ecological niches. The sediment had a lot of coccolithic mud, which is favorable for borrowing and free-living brachiopods species. After the K-Pg extinction the sediment became dominated by coral and bryozoan mounds, which favored species of brachiopods attached by a pedicle or cemented to the sediment. This had a great impact on the brachiopods.

In the early Danian there were 17 living species of brachiopods in the area of southern Zealand, representing a biodiversity drop of 60%. With 24% of the brachiopod species of southern Zealand in the late Maastrichtian being free living brachiopods, they hardly occurred in early Danian period. This is the major difference between the brachiopod fauna of the late Maastrichtian. (Schrøder, 2019)

Appearance of the Lilliput Effect can also be observed between the brachiopods of the Maastrichtian and Danian. The Lilliput Effect designates the reduction in the size of surviving species following a mass extinction (Harries, 2009). Indeed, most of the brachiopod species found in the early Danian were micromorphic. Along with this, most fossils from that period were from organisms that had not reached sexual maturity. This implied a low survival rate of the offspring, and thus less chance of survival for the entire species.

Because of the change in their environment, brachiopod species of the late cretaceous were forced to adapt. The change from coccolithic mud to small bryozoan mounds favored smaller species. Because of their small size, (some were in the millimeter range) they fitted well into the new environment. This is observable on Figure 6 with a shift to the left of the size of brachiopods. The brachiopod species which were able to attach themselves to hard substrates were even more likely to survive.

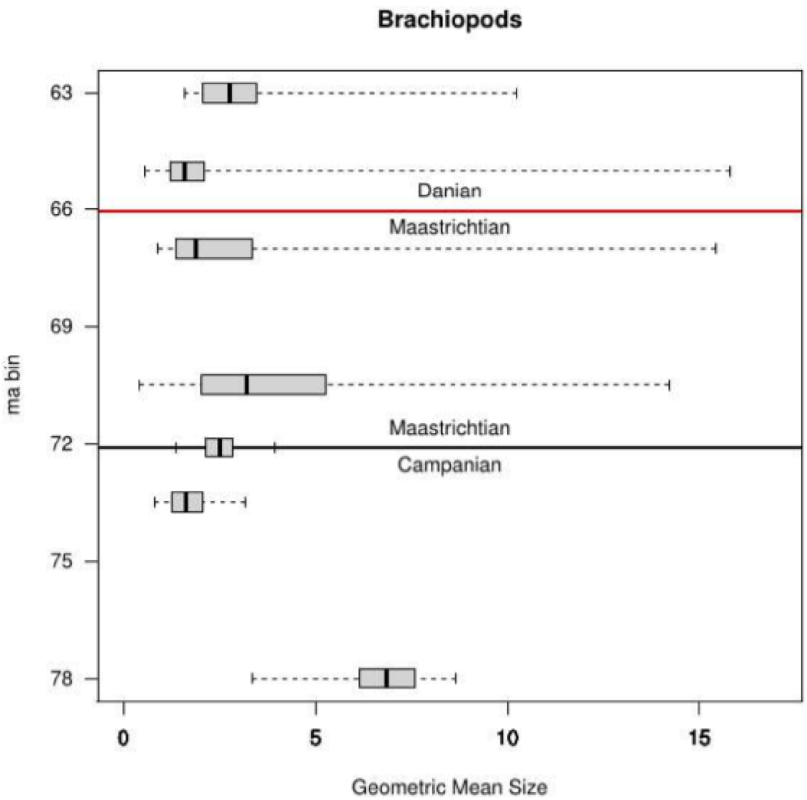

Figure 6: *Change in size of brachiopods from the Campanian to the Danian. Source: Jarrett, 2016)*

Generalists like Lingulata remained unchanged throughout the period. A generalist is defined by National Geographic as:" [a] species which can feed on a wide variety of things and thrive in various environments" while a specialist is the opposite (National Geographic Society, 2020). Lingulata have been described as living fossils because their morphology has barely changed since their inception. This shows that the brachiopods of this order have a very versatile form, proving to be suitable for a huge range of environmental conditions. This also explains that the maximum size of brachiopods found during the period was unchanged by the K-Pg extinction (see Fig. 6, Jarrett, 2016).

Results – Theories for the K-Pg extinction

Seeing such changes in the biome and climate after the Cretaceous period, scientists began to wonder about the reason for such transformations. The following elaboration provides an overview of the research on the Cretaceous extinction, as well as a description of two main opposing theories, the meteor impact theory and the Deccan Traps theory.

1. Overview of the state of the research on the Cretaceous extinction

Despite having knowledge about the substantial change in Earth's fauna and flora happening between the Mesozoic and Cenozoic era since the 1820s, it was not until 1970s that researchers began investigating the events around this drastic mass extinction, which wiped out around 70%

of all species on Earth. Three phases have been designated to describe the history of the research on the dinosaur extinction (Benton, 1989):

- The non-question phase (up until the 1920s)
- The dilettante phase (1920-1970)
- The professional phase (1970 and on).

During the dilettante phase, over 60 different theories were put forward, mostly focusing on the dinosaur extinction. Starting from the 1970s and 1980s, the process shifted, leading to theories encompassing the entire K-Pg event. Benton classified them into two major categories: gradualists (the event that caused the extinction was gradual and on a long-term) and catastrophist theories (advocating for a sudden event). Among these catastrophist theories, the meteor impact is one widely known by the public. It was first proposed by Luiz Alvarez, American physicist, and his son Walter in 1980 after they discovered anomalously high concentrations of iridium at multiple K-Pg boundaries. These findings created great debates among the scientific community and are still a controversial discovery to this day.

Gerta Keller, a Swiss American paleontologist, is one of the principal contesters of Alvarez's theory. She advocates for the Deccan Traps volcanism theory, a series of large-scale eruptions that released volcanic gases into the atmosphere, which might have contributed to climate changes leading to mass extinction. The thought of volcanic eruptions taking place at the time was and still is a mainly agreed upon idea within both theories. However, geologists who agreed with Alvarez's theory hypothesized that the volcanic eruptions were not sufficient to cause a mass extinction (Chiarenza, 2020). Meanwhile, Dr. Keller saw volcanism as the original cause of climate change and the mass extinction, and the meteor as a mere coincidence with almost no relationship to the event.

4. Meteor impact theory

In 1980 Luis and his son Walter, along with their scientific team, found anomalously high concentrations of iridium at the K-Pg boundary in different countries. Iridium is a rare metal usually only found in the inner earth or as an extra-terrestrial element on meteors and comets (Encyclopedia, 2021), mostly found in low concentrations in sedimentary rocks. After analyzing samples from Italy and Denmark, Alvarez's team concluded that the only explanation compatible with such a high increase in iridium (and no other element) was not a crustal or a marine source, but an extraterrestrial one (Alvarez *et al.*, 1980).

Looking at iridium isotope ratios, they ruled out the hypothesis of supernova radiations as the cause for extinction, which led them to come up with the asteroid impact hypothesis. Alvarez and his team suggested that an asteroid hit the Earth, projecting heavy dust up into the stratosphere and causing it to spread all over the planet. This massive cloud of dust would also have prevented sunlight from hitting the Earth's surface, inhibiting photosynthesis over several years after the impact and destroying the food chains (Alvarez *et al.* 1980). The impact of the asteroid would have created tektites, which are bodies composed of natural glass formed from terrestrial debris that are ejected during meteorite impacts.

In 1991, the discovery of the Chicxulub crater in the Yucatán peninsula (see Fig. 7) by Hildebrand *et al.* seemed to confirm Alvarez' hypothesis. The crater, first mentioned 10 years prior and estimated to be 180km wide, showed igneous rocks presenting evidence of shock metamorphism. Moreover, they had a chemical and isotopic composition similar to those of the tektites found in the K-Pg boundary ejecta (Hildebrand *et al.*, 1991).

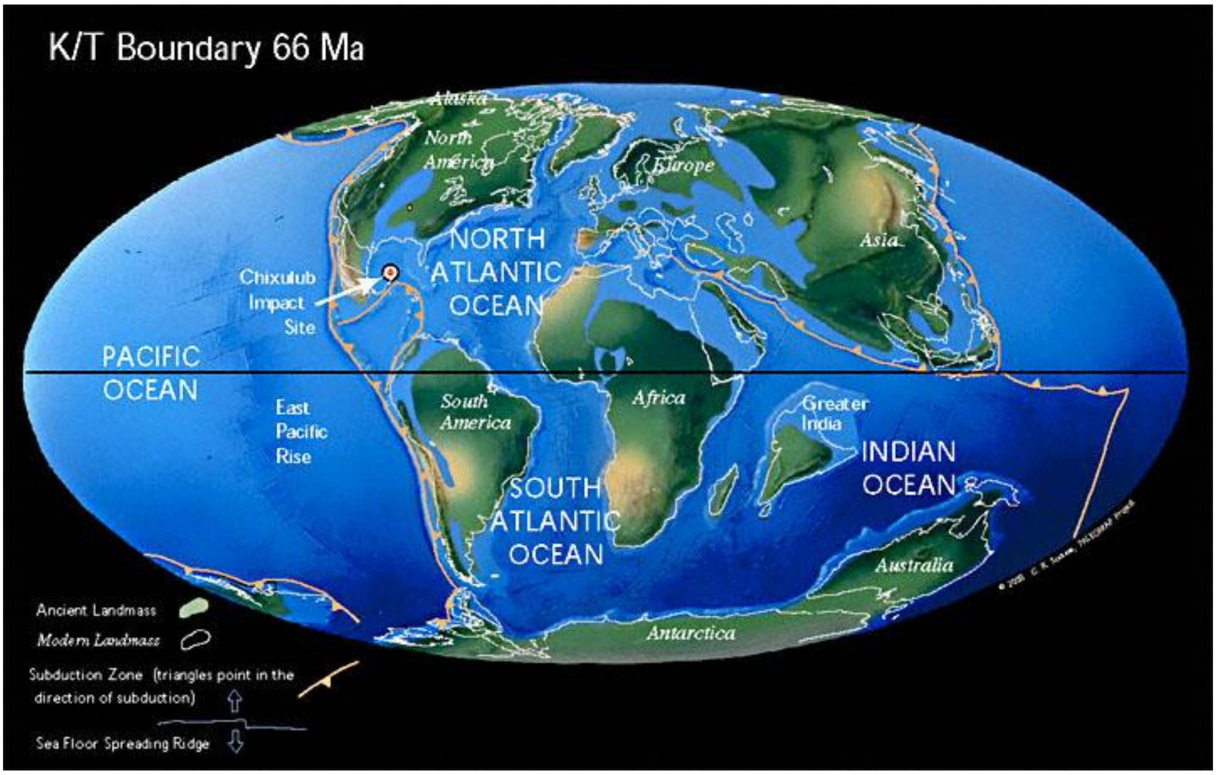

Figure 7: *Map of the Earth showing where the continents were 66 million year ago. Source:* http://www.scotese.com/K/t.htm

The asteroid was attributed to the family of asteroids called carbonaceous chondrites. American and Czech researchers Bottke and Vokrouhlický (2007) believed it to be born from the fragmenting of an asteroid 160 million years ago that created the asteroid family called Baptistina. Chondrites are space elements containing less than 35% of metals and are usually found in the most primitive meteorites. They are called chondrites because they contain chondrules, which are microscopic marbles of silicates embedded in a matrix formed during the condensation of the solar nebula (which is the formation of the solar system).

The type of rocks hit by the asteroid occupied around 13% of the surface of the Earth at the time: they were hydrocarbon and sulphur-rich rocks. Those rocks were heated by the impact and formed stratospheric soot and sulphate aerosols (Kaiho, 2017), making the massive cloud of dust mentioned earlier by Alvarez even more dramatic and susceptible to cause extreme cooling and drought worldwide.

In 2010, a paper called "The Chicxulub asteroid impact and Mass extinction at the Cretaceous-Paleogene boundary" was published in the journal *Science*, featuring 41 authors led by Perter Schulte. It was an important publication, as it acknowledged internationally Alvarez' impact theory as the most probable one and had a big impact among the scientific community; it was cited over a thousand times and received letters from fellow scientists (Geological Society, 2010).

Studies have been conducted to determine the age of the asteroid impact using the tektites it yielded. Those tektites were dated from 66.038 million years ago (Renne *et al.,* 2013), coinciding within a margin of error to the K-Pg extinction. However, that same study also showed that the climate change predated the K-Pg extinction, suggesting that the meteor hitting the Earth acted more as a tipping point than an origin for the mass extinction.

5. The theory of the Deccan-traps

Deccan-traps are a large igneous (of magmatic origin) province (LIP) in West India. They are the largest volcanic feature on Earth, covering 512,000 km^2. The size of the Deccan-traps prior to erosion and weathering mechanisms might have spanned across 1,500,000 km^2 (Adatte *et al.*, 2011). It is estimated that the eruptions which formed this large area occurred around 66 million years ago and lasted approximately 350,000 years (Keller, 2020). The magmatic streams following the eruptions have a span width of 1500 km across India, as shown in figure 8.

Figure 8: *Location of the Deccan Traps. Source: Sanders, 2019 UC Berkeley.*

The Deccan traps are also known as one of the largest LIP in the world. LIPs are described as: "intraplate magmatic events, involving volumes of mainly mafic magma upwards of 100,000 km^3, and often above 1 million km^3" (Ernst, 2014). Mafic describes rocks which are rich in magnesium and iron.

In India, the volcanic activities can be dated closely around the Maastrichtian and Danian border. Three phases can be described. An early one, rather small at 67.5 Ma, the main and strongest one exactly at the late Maastrichtian border and the last phase already lasting into the early Paleogene (Keller, 2012).

In four of the five major extinctions, volcanic eruptions were considered as trigger, the ejections of vast amounts of volcanic gas (CO_2 and SO_2) into the atmosphere causing the biotic extinction catastrophes (Bond *et al.*, 2014). Thus, Keller argues that since the four other mass extinction were caused by LIPs, it is highly probable that the K-Pg would be too (Keller 2020).

A link between the climate change, the biotic crisis and the Deccan volcanism 66 million years ago could be made through mercury anomalies in marine and terrestrial sediments (Keller, 2020). This was proven by the application of biostratigraphy and cyclostratigraphy to examine benthic foraminifera mercury. To further prove the standing of the Deccan traps as turning point in extinction studies interdependent approaches were evaluated with a focus on seven topics, each one providing evidence (Keller, 2020). Those studies were especially interesting, because they were done at a location similar to Stevns Klint, part of the Tethys Sea and geographically closer than similar sites in North and Central America.

The results yielded by the marine sediment studied led to the conclusion that the Deccan Traps eruption started 335 000 +/- 35 000 years prior to the K-Pg boundary (Keller, 2020). The Deccan Traps theory implies that the Chicxulub impact does not differ from other meteor impacts like the Alamo, Chesapeake and Popigai impacts, where other meteors of a similar size collided with the Earth without causing a mass extinction.

Discussion

1. Climatic situation and looks of the biome

a. Questioning Alvarez's theory

Despite the Alvarez theory being internationally acknowledged, the subject remains hotly debated. This impact is believed to have been the cause for a more dramatic climate change within the Late Cretaceous period. It is assumed that a dust clouds which blocked sunlight caused a nuclear winter, therefore limiting, or complete termination of the growth of fauna and thus the base of the food chain. Consequently, this directly affected the growth and lifespan of many organisms such as dinosaurs and vertebrates (Alvarez, 1980; Smit 1982). However, the evidence of such events is lacking due to the poor record of macrofossils found.

To examine the coherence of the events, it is important to consider error factors when calculating dates. An admitted error source for earlier studies might be the sediment movement by tectonic dynamics, and later human disturbances. Sedimentation is not linear but disturbed by erosions and hiatus patterns. That should be considered when calculating ages. Hiatus patterns correspond in this context to prolonged pause periods in deep sea sedimentation processes (Dutton, 2013). Those sedimentation stops are correlated to drastic long-term changes in current and/or past climate (Smilie *et al.*, 2019).

Taking erosion and breaks into account when analyzing sedimentation, the evidence pro-Chicxulub impact based on predating the Deccan Traps volcanism could contradict the meteor hit theory (Keller, 2012). Thus, the discovery of a preserved and untouched site would be a crucial factor in obtaining accurate data. The current oldest and best-preserved Chicxulub spherule impact layers are found in Texas and NE Mexico (Keller, 2020). They are situated in a zone called CF1. This zone is defined after the species found in it. It is also called the *lummerita hantkeninoides* zone and its estimated age is between 65.3 – 65.0 million years old (Farouk, 2014). The placement of the spherule in the CF1 layer led to the predating of the meteor hit by 300,000 years (+/- 30,000 years) before the K-Pg boundary (Keller, 2009).

However, this result was unsupported by a study conducted using argon datation (Renne *et al.*, 2013). While still supporting the idea that the Deccan Traps caused a drastic climate change, they suggested that the meteor impact had more importance than Keller gave it. They dated it to be around the same time as the K-Pg extinction, and deducted that it had acted as a tipping point, triggering a "planetary state shift" (Renne *et al.*, 2013).

Another important factor regarding the evaluation of dating the hit is the former nature and composition of the site. Those are decisive when it comes to layering and sedimentation.
The velocity of the sedimentation (and with it the sedimentation of the spherules) might vary drastically among the different sites. While a deep ocean (1000 – 4000 m) sedimentation proceeds with less than 1 cm in 1000 years, the sedimentation in shallower seas like the Tethys Sea (100 – 140 m) takes place at a higher rate of around 4.7 cm in 1000 years. Additionally, the sites in a shallow sea are usually better protected against strong currents and other disturbances (Keller, 2012). A slower sedimentation thus makes the sediments more prone to disturbance (like a hiatus or a current), increasing the possibility of errors regarding the dating of the meteor hit.

In a 2020 study, researchers modelled climatic conditions of the end-Cretaceous and their evolution during two case scenario: Deccan volcanism and meteor impact. It has been concluded that Deccan Traps volcanism wouldn't have caused dramatic enough climate changes to alone explain the mass extinction. It was even suggested that this volcanic activity could have had a mitigating effect, counter-balancing the global cooling brought by the impact. However, this study did not focus on biotic factors such as acid rains or wildfires and looked more specifically at the dinosaur extinction over other species. (Chiarenza, 2020)

b. A change of climate through the years

Many of the theories studied until now support a wide array of reasons justifying a sudden K-Pg extinction. However, it is possible than the event which took place many years ago was not due to a massive bolide impact, nor volcanic activity but the results of a long-term climatic change throughout many years. It can be hypothesized that the climatic conditions had been slowly changing by themselves ultimately causing the extinction of nearly an entire fauna.

Skeletal remains of these microfossils, and nanoplanktons have occupied the oceans for more than 100 million years and compose most of the calcareous marine biogenic environment above the carbonate compensation depth; making them ideal for studying the origins of the K-Pg extinction, and any of the events that led to the termination of species (Smit & Romein, 1985). Figure 9 shows a map of the K-Pg boundary in Denmark, including two of the richest assemblages for the entirety of the European region, Nye Klov and Stevns Klint sections.

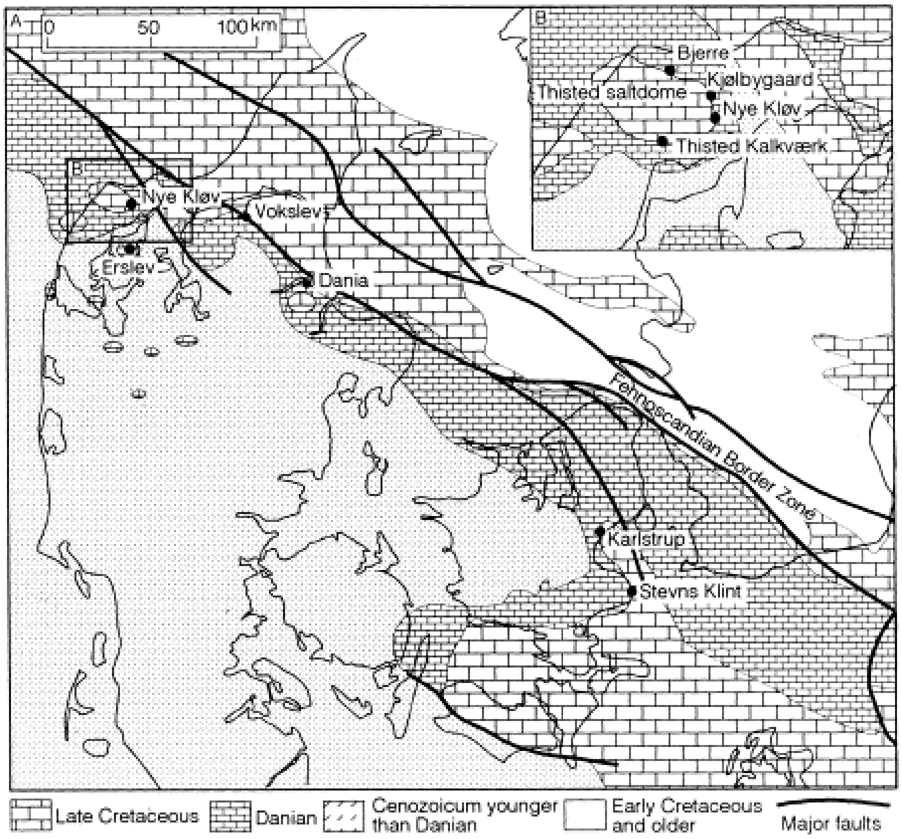

Figure 9*: K-Pg boundary map of Denmark, showing the Cretaceous, Danian periods along the Nye Klov and Stevns Klint sites. Source: Geological Society of America, 2002*

It has been argued that the extinction has not been sudden, but the result of a more progressive pattern with the disappearance of larger, ornamented and complex species followed by those small, less ornamented ones. Those species accustomed to stressed environment like in Stevns Klint and Nye Klov (with high salinity and high fluctuations in density) were more tolerant to climate changes and thus had a higher probability of survival. On the other hand, tropical and sub-tropical taxa seemed to have been disappearing more gradually over 100 000 to 300 000 years before the K-Pg boundary (Keller, 1993). These behaviors are more indicative of unstable climatic and oceanic conditions than that of a sudden impact.

Scientific research around the Danish areas of Nye Klov and Stevens Klint have demonstrated the faunal turnover of planktic foraminifera all throughout the late Cretaceous period and the K-Pg boundary. These are illustrated in figure 10, for which we notice a decline in the most prominent and dominant species, *Heterohelix globulosa*. These dominant species averaged from 50% to 60% of all faunal assemblages in for the Cretaceous period yet there is an imminent decrease after the K-Pg boundary, completely disappearing in some areas along with other species. However, other less dominant species such as *Guembelitria* have been reported to be most abundant in the meter below the K-Pg boundary, right into the early Danian period. Cases such as these are also common in other areas of the world, like Brazos, Texas where a variety of species thriving in the late Maastrichtian era seem to disappear after the K-Pg boundary giving way to a different kind of dominant species in the Danian period (Keller, 1993).

Though the decline of species through the K-Pg seems to affirm the belief of a sudden catastrophe wiping out entire colonies, there are other signs which might lead to a slower turn of events sharing the same outcome. One of the most striking similarities between these testing sites is the lack of species whose extinction was directly correlated to the K-Pg boundary. There have been other notorious similarities between testing sites when it comes to species patterns, indicating a surviving taxonomy. Thus, this means that whatever event occurring at the time had to be more beneficial for some species than others. Isotopic measurements help determining the era in which a species belongs to. Measurements for *Heterohelix globulosa*, and another Cretaceous species called *Cibicidoides succeedens* in Tertiary sediments show results for Tertiary isotopic signals, therefore they are believed to be Cretaceous survivors.

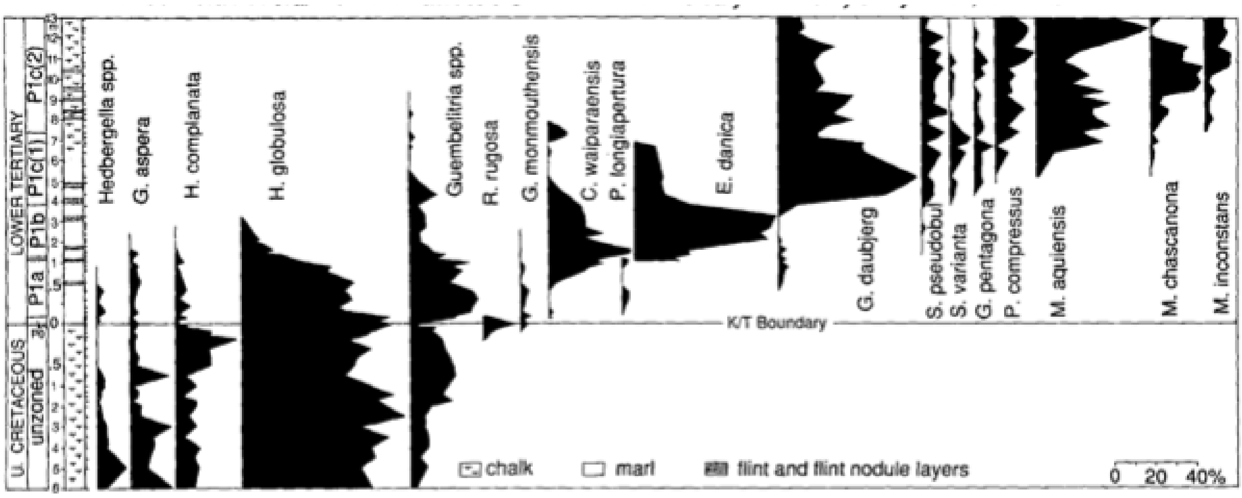

Figure 10: *Planktonic foraminiferal turnover across the K-PG boundary at Nye Klov, Denmark. Source: Geological Society of America Bulleting, 1993.*

Just like this, there are many other dominant species which are believed to have survived, that are found abundantly into the early Tertiary. At the Danish site, Nye Klov, 41% of dominant species (7 species) survived onto the Tertiary Zone Pb1 or for approximately 300,000 years. *H. holmdelensis, R. rugosa, and H. monmouthensis* species are believed to have survived as well, but in less amount of time (50,000 – 100,000 years). Other assemblages of the Cretaceous have been found well into the Tertiary zone, about 6 meters below the K-Pg boundary, such as *G. subcarinatus, P. brazoensis, G. petaloidea, H. navarmensis,* P. *Carseyae, G. arca and H. glabrans.* At Nye Klov, only one of the aforementioned species completely disappeared, *P. Carseyae.* Similar survivorship patterns have been seen at Stevns Klint, and in lower latitudes with planktonic foraminifera, invertebrate fossils and palynomorphs.

In the Brazos site in Texas, similar survivorship patterns had been identified, except 46% of the Cretaceous species had disappeared below the K-Pg boundary in a short hiatus which coincide with a sea-level low-stand at a tsunami bed (Keller, 1989). This occurrence can be correlated to Dr. Keller's hypothesis of volcanic activity causing climatic changes in the atmosphere and eventually leading up to the mass extinction of these species. In occasions, violent volcanic eruptions can cause a ripple effect of natural disasters. Although it is infrequent, it is possible that a raging volcanic activity in the late Cretaceous could have displaced big volumes of water and generate tsunami waves which wiped out the 46% of species residing near the Brazos site.

These discoveries suggest that many of the dominant and prevalent species in the Maastrichtian period were able to survive in the K-Pg extinction event, and those smaller, more specialized ones had started to disappear slowly throughout the late Cretaceous. This could have been due to some existing resistance within the taxa, which had been developed by the conditions of their environment. Thus, when climatic conditions worsened, these species were able to withstand the changes. The high abundance of Cretaceous species in Brazos, Texas reveals how the environmental conditions of the marginal sea, and shallow water were strained at the time. With that said, survivorship patterns and isotopic measurements have confirmed that only a small, refined taxon was able to endure, while most large and complex forms disappeared before or soon after the K-Pg boundary event (Keller, 1993).

2. Chronology of the extinction event

Series of events:

1. Gradual warming period for 170,000 years, two ocean acidifications
2. Gradual cooling period for 120,000 years
3. Drastic cooling of ~4°C for 30,000 years
4. Hyperthermal warming for 2-3°C, major ocean acidification, for 5,000 - 10,000 years

Taking into account the aforementioned possibilities as to the nature of the extinction, some facts point towards Deccan Traps as the major driving force of the K-Pg extinction 66 million years ago. The main reason being the lack of extinction of a single species of planktic foraminifera, due to the Chicxulub impact, given that these species suffered the most severe mass extinction around the K-Pg boundary (Keller, 2009, 2020). Moreover, none of the other four major mass extinctions were related to an extraterrestrial impact (Keller, 2020). The probability that the K-Pg, like three of the other mass extinctions, was driven by LIP volcanism is thus higher (Keller, 2012; Bond *et al.*, 2014; Scoville, 2020).

The likelihood of a meteor impact remains an open question as the methods proofing this theory should be further investigated and debated upon. If iridium were to be the most prominent evidence of a meteor impact, then the lack of iridium around and in the Chicxulub crater is one of the major concerns for the feasibility of this theory. Furthermore, the iridium anomaly found at the K-Pg boundary could be from more than a single origin, thus this is not yet fully clarified and understood (Keller, 2020).

The biggest argument in the use of iridium as evidence is that terrestrial iridium concentrations are very low while extraterrestrial objects usually are enriched with this element, so sharp peaks in iridium are instinctively connected to a meteor impact. However, given that iridium is also present in the Earth’s crust through up and down movements and condensed sedimentation this element can accumulate, leading to similar peaks for terrestrial iridium (Keller, 2020). Subsequently, the inner earth processes leading to iridium enrichment are still poorly understood, which makes further research necessary for the validation of iridium as evident proof of either theories crucial.

On the other hand, the use of mercury is a more advanced and promising tool for dating the series of events around the K-Pg mass extinction. Mercury analysis establishes a link between higher concentrations in sedimentation layers and volcanic activities even within longer distances. Though sedimentations and hiatus errors can be debated in this theory as well, in a 2012 study by Keller it was possible to connect volcanic events in India with the site in Tunisia (Keller 2012). Certainly, the linkage to global developments was difficult, although at locations near the Deccan Traps in India the mass extinction was easily linked to the eruptions lasting 350,000 years (Keller, 2020).

Based on the new findings by Keller, the group accepted that the impacts being valid in Tunisia are also valid further north at the Stevns Klint. This decision was supported by the diversity of evidence found and proven by various means of technics and disciplines (Keller, 2020). The extinction proceeding processes can be seen in the following graphic (see Fig. 11). The graphs are depicting trends in the climate during the late Maastrichtian period (Keller, 2020).

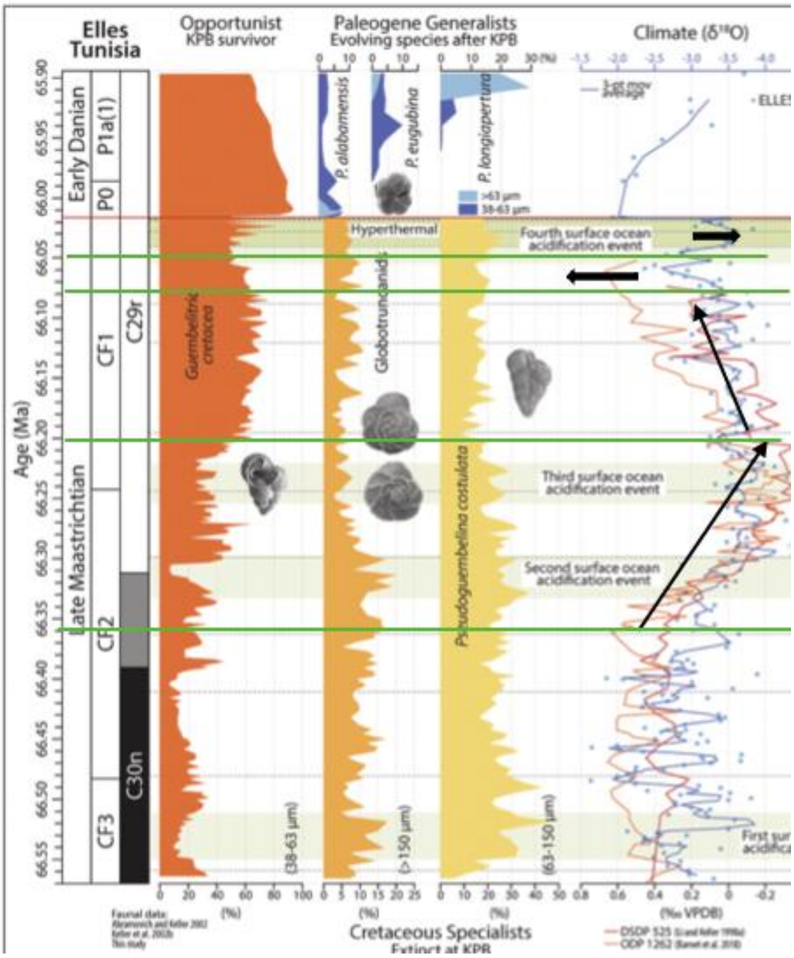

__Figure 11__: Overview on the eruptions over the timeline of the Late Maastrichtian to the Early Danian. In contrast to climatic trends and the acidification of the oceans. Source: Keller, 2020.

Deccan Traps volcanism started roughly 350,000 years before the K-Pg boundary which led to a long-term climate change. Due to the gradual changes in the climate most species were able to adapt to new and changing conditions. Therefore, nothing like a mass extinction can be observed during this first period of global warming in the late Cretaceous; some species who got extinct, but others survived. During this period, if the meteor hit happened, it had no effect on the climate change that led to a mass extinction (Keller, 2012; Bond *et al.*, 2014).

The gradual change is based on the increased levels of CO_2 and CO, whose removal through natural breakdown and weathering is too slow to counterbalance the increase. During this time pulsed eruptions in 40,000 – 50,000-year intervals can be described at the Deccan Traps. The perturbation of the climate cycle due to one eruption lasts around for 10,000 – 100,000 years due the slowness of the processes. The proceeding of the constant eruptions is a process which takes place over a long time-span (Adatte *et al.*, 2011; Keller, 2020).

During this warming period two acidification events of the oceans took place, which can be associated with volcanic eruptions and the ejection of vast amounts of SO_2 into the atmosphere. Sulfuric compounds are released into the atmosphere and then combined with H_2O vapor forming the acid, which then returns through precipitation as acidic rain back to the earth. This supports the thesis of ongoing volcanic activities in the Late Maastrichtian period (Self *et al.*, 2008; Adatte *et al.*, 2011; Keller, 2012; 2020).

The amount of sulfur ejected by volcanic activity and the amount released by a meteor hit have been analyzed. The volcanic activities are producing for each eruption around 150 GT per eruption, with the examination of the volcanic pulses towards the end of the Maastrichtian period it can be calculated with around 30 eruptions in a few decades (Self *et al.*, 2008). The total amount exceeds the estimated amount of sulfur released by the meteor hit (50 – 500 GT) easily (Keller, 2020).

The cooling effect of oxides, small hydrocarbons and for example hydrogen sulfide is only a short-term factor in the climatic change. Its residence time is with less than a year short compared to the temporal long nature of these events (Keller, 2012; 2020). Moreover, the intervals and the repeated emission of sulfur magnifies the effect of the volcanic activity compared to the Chicxulub impact through prevention of recovery (Keller, 2020). Nevertheless, the estimations around the concentrations of emissions during the late Cretaceous and early Paleocene are prone to large error margins, but they serve as tool for the first comparison.

After the first linear increase in temperature, peaking around 250,000 years before the K-Pg boundary, there has been a gradual decrease of temperature lasting around 140,000 years. It can be correlated to the decomposition of carbon oxides in the atmosphere. A rapid cooling ends this trend with a temperature drop of 3 – 4 °C for around 20,000 years. Successively, a sudden hyperthermal warming, with temperatures increasing for over 2°C followed. The hyperthermal warming is correlated to the strongest eruption pulse of the Deccan Traps happening 10,000 years prior to the mass extinction. The cause for those eruptions still needs to be analyzed and it is likely that Siberian trap eruptions took place as well.

During this time span, strong acidification of the oceans and other marine environments takes place; it is the strongest one during the observed series of events. The duration of the pulses lasted for around 10,000 years. They took place right before the K-Pg boundary and fit into the period of the mass extinctions. The phases of volcanic eruptions in India at the end of the Maastrichtian period account for around 80% of the Deccan Trap's size (Keller, 2009), while the eruptions at the early beginning of the Danian period are responsible for roughly 14% of its size (Adatte *et al.*, 2011). The Early Danian period started then with another temperature drop and the coldest temperatures in 500,000 years.

Considering the other possibility of a meteor impact, it is important to take into account the difficulties of dating the hit. Keeping eventual perturbations in sedimentation in mind, the meteor hit can be dated to around 66.043 million years ago, preceded by the global climate change (Renne *et al*., 2013). It is important to remember that the constant stress on individuals and organisms induced over the warming and cooling period and the final temperature drop followed by the hyperthermal warming might have led to an earlier extinction of a species. Furthermore, the years of ongoing environmental stress can have endangered many species, which were finally extinct by smaller events at the K-Pg boundary.

Finally, it must be stated that the group as non-professionals in geology do not claim to have insights which go beyond those of scientist in this area. The group is aware that the research in the field of the K-Pg mass extinction is not finalized, and that the complexity and the vast number of details go beyond this paper. Further research needs to be conducted and the views presented in this study are offered as an advice given by most researchers in this field (Schoene *et al.*, 2020).

Conclusion on the fate of the brachiopods and its relation to the K-Pg mass extinction

This study was carried out to answer the question **"What environmental changes took place during the K-Pg extinction event in Southern Zealand, and how did it impact the brachiopods of the late Cretaceous period and following generations?"**

Regarding the environmental changes: it has been shown in all the treated scientific papers that a gradual warming of the planet occurred during the last part of the Cretaceous period, increasing both drastically the atmospheric and ocean temperature. A high presence of greenhouse gases in the atmosphere contributed to keeping these temperatures high, and due to the reaction of these gases with water, the oceans became more acidic. What caused this climate change, and whether it was sudden, or gradual is something that must be investigated further. Still, all the theories point out to the volcano activity, in some way, as a trigger of this massive extinction.

The already mentioned climate change also affected to the region of the study, Southern Zealand. Fossil records in this area show that there was a change among the biodiversity of the planet, where some of the species that survived the extinction suffered morphological changes to adapt to the new climatic situation. Some of these species belonged to the Brachiopoda phylum, the target phylum for this research, which decreased both in size and in the survival rate of the offspring. The brachiopod species that went extinct did so gradually and approximately 40 % of them survived. The survivors, however, quickly adapted to their new environment. This most likely happened due to adaptive radiation.

Most of the brachiopods that didn't make it were living in a very specific niches, which were left completely changed after the K-Pg extinction. The survival of the other species was probably due to their ability get attached to the new irregular and harder substrate through a fixed corporal element such a pedicle. Size also played a role in survival of the brachiopods. Because of their micromorphic size, the new brachiopods were able to fit in to new niches, created by the extinction event. Up to 7 of the brachiopod species that survived the extinction are still present nowadays.

Outlook to the current mass extinction of the Capitalocene

In conclusion, the climate change at the end of the Cretaceous period had a tremendous effect on the climate and the biome of Southern Zealand. To push the discussion further, the team tried to look at the similarities and differences between the end-Cretaceous climate change and today's climate change.

The Capitalocene, also referred to as Anthropocene, is a term used to describe today's epoch and on-going mass extinction. The K-Pg extinction can only be analyzed in the frame of fossils, geology and models because of its temporal distance; while today's climate change is on-going, therefore the modelling its consequences and the outcome are only a way to assess today's impacts on the future.

The trigger of both climate changes is no way similar. Most scientists agree that humans and their actions are responsible for the global increase of temperatures, extreme weather events and the acidification of the oceans today, while back in the Cretaceous period it was believed to be due to natural catastrophic events and meteor impacts as discussed briefly in this paper. However, when it comes to the proceeding events, symptoms and outcomes there are some similitudes worth looking into.

Firstly, an increase of greenhouse gases in the atmosphere can be observed for both time periods of interest. Though, the release of sulfur oxides during the late Maastrichtian exceeded greatly that of the Capitalocene (Keller, 2012) the rate of at which these gases are produced in the Capitalocene is outrageous. Other symptoms include the acidification of the oceans, the increase of air and ocean temperatures and the extreme weather events. Finally and most importantly, both time periods show a severe extinction of species alive on Earth (see Appendix 2). A comparative table was elaborated in order to illustrate the comparison made here (see Appendix 3).

However, the overview leaves one part unmentioned: the possibility to act. Since the human species is responsible for the ongoing extinction of other species, increase in temperatures the raise of sea levels, the acidification of the oceans and with actions like deforestation and intensified land use; they also prevent the natural recovery of the environment. The climate change of the Capitalocene is happening now and human actions are leading to its acceleration.

The climate change is a global process, it does not stop with borders. Therefore, solutions must be found globally, and actions have to be taken together in order to prevent the Capitalocene from seeing a sixth mass extinction.

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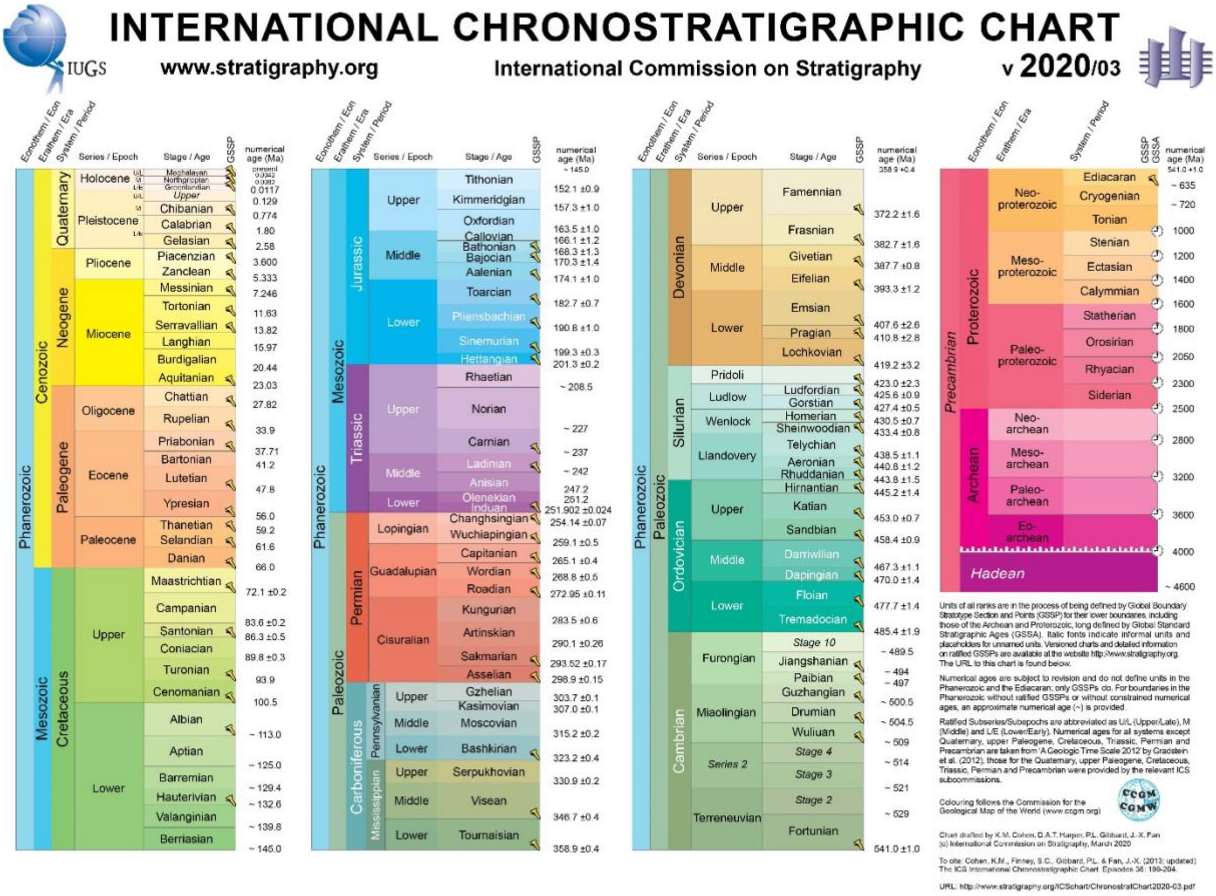
List of figures

List of tables

Appendices

Appendix 1: International Chronostratigraphic Chart. Source: International Commission on Stratigraphy (2020)



Appendix 2: The extent of today's on-going extinction. Source IUCN Red List of Threatened Species (2021).

Appendix 3: Comparative table of the main parameters of the K-Pg climate change and the current climate change. Source: made by the team.

	Maastrichtian-Danian Climate change	*Capitalocene-Climate change*	*Similarities*
Cause	Volcanic eruptions	Human actions	No
Symptoms	Increase in greenhouse gas emissions.	Increase in greenhouse gas emissions.	Yes
	Acidification of the oceans	Acidification of the oceans	Yes
	Increase in air temperature. (Extreme temperature changes over short periods)	Increase in air temperature. (Extreme temperature changes over short periods)	Yes
	Raise in ocean temperatures.	Raise in ocean temperatures.	Yes
	(Probably extreme weather events)	Extreme weather events	Yes
Consequences	The 5th of the major mass extinction	Ongoing increased extinction	Yes