POSSIBLE EXTINCTION RATES

OF CHONDRICHTHYES BASED ON

OCEAN ACIDIFICATION AND OCEAN ANOXIA

by

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ABSTRACT

Possible Extinction Rates of Chondrichthyes based on Ocean Acidification and Ocean Anoxia

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In order to understand how species will respond to future environmental stressors, paleontologists and other scientists look to the past for biological patterns. Chondrichthyes, or the class of sharks, rays, skates, and chimeras, are older than the dinosaurs but will they continue to stalk our environments? Based on their response to four mass extinctions, these species have endured ocean acidification, ocean anoxia, sea level rise and fall, climate change, volcanic eruption, and attacks from space. Through all this, chondrichthyes have come out stronger than ever now staking the oceans as one of the apex predators facing a new challenge against humans that puts their strength and numbers to the ultimate test.

Table of Contents

List of Figures

Acknowledgements

I would like to acknowledge my thesis reader, Kathleen Saul for all her help, suggestions, and support throughout this process. She helped take both pressure and anxiety off my chest while writing which made this all possible. I would also like to thank my parents for listening to me nonstop talk about research until I came across an “ah-ha!” moment then proceeding to run off to write it down.

Introduction

1.1. What if Dinosaurs Survived?[1]

Imagine yourself during the Cretaceous period, 65 million years ago. You stand as a great reptilian species, a powerful predator with a successful day of hunting and now you can bring your catch to your family. Perhaps you coexist as an herbivore instead, having spent the day grazing along the edge of the forests where you have a variety of leafy vegetation to choose from, or shelter should a pesky predator come within your sights. Either way, everything seems normal. That is, until a large object falling from the sky comes into view. It comes closer and closer, getting faster the closer it comes to the ground. You can do nothing but stand and gaze with wonder and possibly in fear with your prehistoric eyes. Unknown to you, this asteroid initiated the mass extinction of the Cretaceous-Tertiary period, wiping out between 57-83% of species on Earth; the most well-known species being the dinosaurs (Macleod, 2013).[2]

What if dinosaurs didn't go extinct? What if the asteroid missed? Several films have tackled the question, including include Michael Crichton's *Jurassic Park* and Pixar's *The Good Dinosaur*. Both of these use the common image of a dinosaur -- the *Tyrannosaurus Rex*, *Velociraptor, Brachiosaurus* -- and put them into the world as we know it among other mammals and humans.

[1] This introduction was adopted from the introduction of *Improbable Destinies* by Jonathan Losos but focuses on chondrichthyes and picturing them as dinosaurs rather than going into what would have happened to mammals had dinosaurs not gone extinct (Losos, 2017).
[2] For the rest of the thesis, I will refer to dinosaurs as a species as a whole, when in reality there were over 700 species who were lumped into the phrase dinosaur simply meaning that they were a prehistoric reptile or avian (Parker, 2009).

However, we don't need computer generated imagery (CGI) or animatronics to see dinosaurs. Some did survive the asteroid; some species exist today that predate the dinosaurs. Their ancestors live in the world among us. One of these ancient species we know as chondrichthyes (chon-drik-the-ezes), or the class of sharks, rays, skates, and chimeras (examples of these species are shown in the Figure 1 below). These classes of cartilaginous species survived four mass extinctions, enduring volcanic events, global warming, global cooling, lack of oxygen in water, and even more acidic waters. Now, chondrichthyes must prepare themselves for another round of cataclysmic events as natural and anthropogenic environmental stress impact their ocean habitats.

Two of the environmental stressors tied to many other stressors and having strong impacts on the marine biome are ocean acidification and ocean anoxia. Acidification has a strong impact on shelled or invertebrate species, robbing them of the calcium carbonate they require for building skeletons or shells, while ocean anoxia effects fish species that still require oxygen to breath. However, chondrichthyes rest in a unique position since they do require oxygen to breath, but have bones made entirely out of cartilage rather than calcium (Castro and Huber, 2016). Does this mean that both of these stressors will affect them rather than just one? Will these descendants of ancient dinosaurs see a higher extinction rate in the years to come from environmental stressors and human caused degradation? Or will they dodge the asteroid once again and continue stalking the oceans?

Figure 1. This collage of images represents the four types of chondrichthyes sharks (top left), rays (top right), chimeras (bottom left), and skates (bottom right). Sources of these images: New York Post, Wikipedia, New Scientist newsletter, and Pinterest.

In the pages that follow, we will travel through time starting back at the Devonian period where chondrichthyes went through their first mass extinctions. From that time, we will move on through the Permian-Triassic, Triassic-Jurassic, and Cretaceous-Tertiary mass extinctions before finally arriving at the modern day. Since each extinction started by a stressor(s) triggering other stressors amplifying negative environmental conditions for living species, we will dive into those causes and effects to understand why each extinction took place. Once we reach the present, we will examine the stressors now impacting the oceans. Additionally, we will examine how chondrichthyes stand as a base line before making a projection; after our journey through time, we will take the information we've learned from previous extinctions and project into the future of the species to determine whether dinosaurs in the ocean will continue to survive.

1.2. Clarifications

Before we start turning back the clocks and starting this journey, I should provide a few clarifications including the scale of time we will be considering, the level and severity of extinctions, and what makes a species a chondrichthyian. I will go more into the value of using chondrichthyes as a species of concern when we get closer to the modern day and looking to project into the future that's when humans put value of select species over another whether that value translates into monetary value or avoidance due to fear. Similarly, I will explain more about ocean acidification and ocean anoxia as they come up in our journey. That way we can make connections to causes and the effects they have on both wildlife and the environment.

First, as humans, it's easy for us to consider time based on our life span. Seconds and minutes go by in a blink of an eye, hours and days seem short, and we usually consider years and generations very long temporally. However, as the scenario from the first paragraph hinted at, this work covers a time span extending for more than a few hundred years. We will explore events over at geologic time. Events considered to have occurred over a short geologic time interval happened over one much longer than we would normally consider to be short. For example, paleontologists often describe mass extinctions as happening quite suddenly. By 'sudden', those paleontologists actually mean within a three to eight million years' time period (Macleod, 2013).

Distinct features in the layers of soils have allowed geologists to separate an amount of time into periods and eras in a way similar to distinctions of dynasties or empire reigns in political history (Pough, Janis, & Heiser, 2005). Figure 2 below shows a geologic timeline that shows all of the periods the earth has gone through. The red bolded lines represent each of the stops we will take in this review of the past, as each mass extinction has been named after the period it happened during or between.

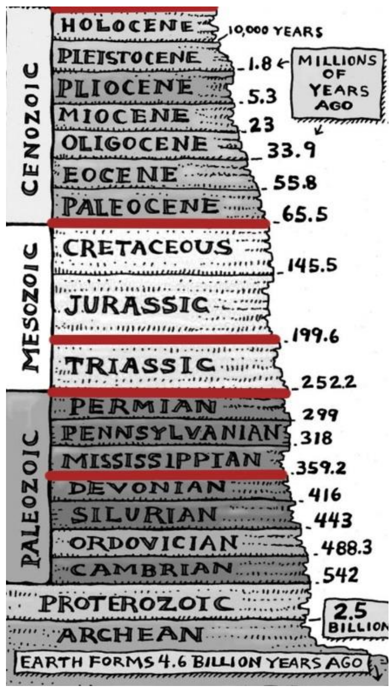

Figure 2. The earth has been around for nearly five billion years through which geologists have found patterns from geologic formations suggesting that a variety of periods and eras. This has enabled geologists to separate the earth's life into a geologic timeline such as the one presented here. This geologic timeline highlights the four mass extinctions that *chondrichthyes* have been through during the Devonian, Permian-Triassic, Triassic-Jurassic, and Cretaceous-Tertiary periods. Additionally, the modern day of the Holocene

was bolded to show the fifth period we will be evaluating (“Geologic Time - Ms. Ash’s Science Website,” n.d.). [3]

Up to this point, I’ve mentioned ‘mass extinction’ several times, but what does a mass extinction mean exactly? Scientists have not yet agreed upon parameters that characterize mass extinctions, but the five agreed upon mass extinctions have three common features (Darwin, 1859; Macleod, 2013). [4] First, each mass extinction happened within the sudden time frame of three to eight million years, a period during which species went extinct due to multiple stressors strengthening one another. Next, during each extinction, a steady rate of successful reproduction and survival started to balance out the rate of death. Finally, species and the environment started to recover. More than 70% of all living species on earth must go extinct during a given period for it to be considered a mass extinction (Macleod, 2013). Although this number doesn’t appear in many resources dealing with mass extinctions, this percentage reflects the fact that enough species have gone extinct to result in some kind of biotic downfall but life can still recover.

Finally, before we talk about chondrichthyes and their long battle for survival in the ocean, what exactly are chondrichthyes? As mentioned above, and shown in Figure 1, there are four types of chondrichthyes: sharks, rays, skates, and chimeras. All four of these species can come in all sorts of sizes, the whale shark can measure to around 18 to 32 feet while the dwarf lanternshark only stands at 6.3 to 7.9 inches long (Pough et al.,

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[3] This caption and the remainder of this thesis will refer to this mass extinction as the Cretaceous-Tertiary mass extinction, however, there are some resources that refer to the Tertiary period as the Paleocene period instead. Both geological period titles are correct, it merely depends on the author’s preference or their education. For the sake of repetition and clarity, I will only use the Tertiary period.

[4] Geologists have debated whether or not there have been more or less than five, but generally the Ordovician-Silurian, Devonian, Permian-Triassic, Triassic-Jurassic, and Cretaceous-Tertiary mass extinctions have been agreed upon.

2005)! However, when we look at how their body structure, there are many similarities. These cartilaginous fishes have little to no bones, most of their bodies consist of a cartilage like bone rather than our calcium bones, muscles, and even more cartilage (Pough et al., 2005; Willson, 1984). If we move to the outside of the species, they all breath through five to seven gills that are located behind their heads (Willson, 1984). Speaking of their dangerous mouths, chondrichthyes, have a conveyor belt of teeth. As one tooth breaks, weakens, or simply falls out, another tooth moves up the belt and becomes the new active tooth.

2. Mechanics of the Journey

How will this journey work? How can we going to go back several million years ago into the past? I went on my own little adventure trying to make connections from other published research to build a picture of the past. To do this, I built a storyboard centered around a geological timeline, marking each of the mass extinctions. For each extinction, I collected an equal number of articles and wrote down on post-it notes all of the causes or effects mentioned. Each time a cause was mentioned, that post-it note received a tally mark. I would then take a step back and looked for the connections between stressors that amplified or caused one another and used yarn to display that connection. Figure 3 documents process for the Devonian and Permian-Triassic mass extinction. I continued this detective work up until the present day condition of chondrichthyes and marine environments.

Figure 3. This is a picture taken of the storyboard used to grasp the connections between causes and effects of the four mass extinctions. This particular image is that of the Devonian mass extinction. Regardless if the post-it notes are able to be read, this image demonstrates the tally system used for each mass extinction to understand what possibilities could have been more likely to have happened versus causes (or effects) that weren't. Likewise, this also shows for future reference the sheer complexity of the environment and how each stressor is connected in some way.

To project into the future, I looked for the causes of an extinction event, what other factors might have come into play, and the potential effects of those. The more common a certain cause was during an extinction event and the more frequent the connections between it and other factors, the higher the likelihood it will happen once again. I will go more into the specifics of this once we stop in future. For now, let's buckle up our seat belts as we head back nearly 360 million years ago to the Devonian mass extinction.

3. The Devonian Mass Extinction

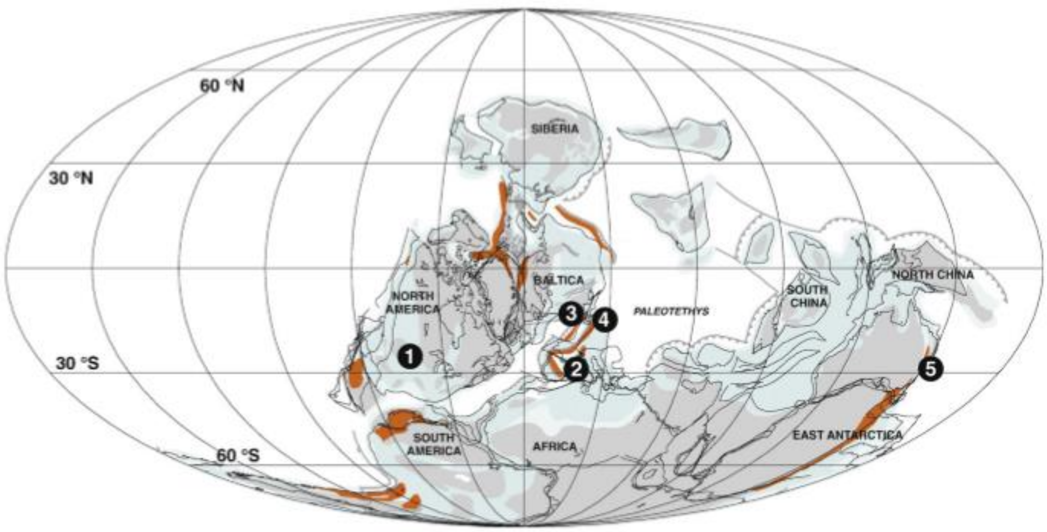

Figure 4. This globe is a representation of what the earth could have looked like during the Devonian period between 420 to 360 million years ago. The researchers who built this model in particular noted that the grey is to represent the land formations of the time, the light blue is the ice shelf, while the white is open ocean. Additionally, the numbers correlate to modern states to showcase familiar landmarks. These include number one being Iowa, two is France, three is Germany, four is the Czech Republic, and finally number five is Australia (Joachimski et al., 2009).

3.1. Introduction

The Devonian period took place nearly 420 to 360 million years ago. The world looked a lot different than it does today, demonstrated in Figure 4 above. All landmasses present rested together forming the super continent known today as Gondwana. The oceans opened and connected to one another, well suited for the primary species at the time. You see, the Devonian period stands as “the age of fishes” given that not only was the earth catering for their needs more than any other species, but there was an explosion in the numbers of boney fish for the first time in Earth’s history (Pough et al., 2005).

The differences between the Devonian period and the modern world don't stop there though. The climate of the Devonian period started out with relatively warm, almost tropical temperatures across the entire globe (Macleod, 2013). There was little variation in the spread of temperatures across the earth during this time. Even the northern and southern poles' climate resembled the equator's climate. The Devonian period had a limited amount of oxygen before the extinction began. MacLeod notes that there could have been less than 13% of oxygen in the atmosphere as compared to the about 20% oxygen in the current earth's atmosphere (Macleod, 2013). That 7% difference had a part to play in what species flourished and what species went extinct during the mass extinction.

3.2. Environmental Causes of the Devonian Mass Extinction

There wasn't a single event that was responsible for starting the Devonian mass extinction, nor for keeping it going for nearly three million years (Macleod, 2013). Instead, multiple stressors continued to build upon each other like pouring sugar into a spoon; the spoon can hold some sugar, but adding a grain or two to many, it all slides off. With that being said, we'll pause time and start at one of the causes, follow the path of influence through the web of environmental processes to understand how the extinction wiped out between 70 to 85% of all living families (Macleod, 2013).

Figure 4 above outlines how the landmasses were generally pushed together. Slowly a few landmasses begun to break apart and drift away from one another based on tectonic plate activity triggering volcanic eruptions (Pough et al., 2005). However, one volcano didn't respond. An entire episode of volcanic eruptions occurred. These large igneous provinces, also referred to as LIPs, impacted both the physical and chemical environment significantly. Each LIP episode was named after the cluster of volcanos that erupted during that period. For example, during the Devonian mass extinction, the Viluy Trap volcanos of Eastern Europe erupted. The Viluy Traps cluster was smaller than other as other LIP episodes that we see later on in both the Permian-Triassic and Triassic-Jurassic mass extinctions (Bond & Grasby, 2017; Mahoney & Coffin, 1997). Despite its size, the Viluy Traps still introduced enough carbon, phosphate, and ash to completely change the ecosystem.

Paleontologists of all specializations seem to agree that plants were the least impacted category of life forms during this mass extinction. Those results suggest that the volcanos would have been submerged in the ocean itself (Klapper, Sandberg, & Johnson, 2014). These volcanic eruptions released elements that were taken up into the atmosphere or were absorbed by the ocean’s chemical reactions. A few of these elements includes phosphorous, carbon, and ash; each had an important role to play in the extinction.

Ash from volcanic eruptions shot up into the atmosphere and created a blanket separating the sun from the earth’s surface. Well, not literally darkening the sky from ash, but enough elements lingered in the air preventing the earth to get enough sunlight by decreasing earth’s albedo, or the ability for a surface to either absorb or reflect a certain amount of sunlight. By decreasing albedo more sunlight is reflected back into the atmosphere resulting in less warmth being stored by the ocean (Bond & Grasby, 2017).

While we are down on the chemical level of the ocean, phosphorus introduced from the eruptions created a challenge for the ocean systems. Phosphorus naturally occurs within the ocean. Like oxygen, it is necessary for life. Unlike nitrogen or oxygen, phosphorus occurs in such small quantities that it becomes a limiting factor for any reactions that use it. Thankfully, organisms and natural reactions don't require much phosphorus. Now, what if there was more phosphorus? Like after the LIPs explosion? Then it can become deadly.

In the ocean, phosphorus takes the form of phosphate (PO_4^{3-}), residing in the deep water, usually from the ocean floor. As deep water rises to the ocean surface to fill in the 'missing' water that evaporates during the early stages of the water cycle, it brings with it nutrients such as nitrogen and phosphate (Garrison, 2007). Those organic nutrients slowly sink back to the deep. Phosphates react with oxygen to balance its charge. Due to the competing demand put on oxygen by natural systems, reactions that require it, and organisms, oxygen can be in short supply. Any additional phosphorus or phosphate added into the system could likely tip the scales into the ocean falling into an oxygen debt. After the eruptions, that happened. The additional phosphorus took oxygen away from other systems, resulting in the ocean becoming oxygen deficient, a stage also called ocean anoxia (Garrison, 2007). To make matters worse, anoxia acts as a self-reliant process: once it starts, it can keep itself going for years. Only once the excess phosphate and phosphorus settle into the ocean's sediments will the oxygen start to balance out again (Garrison, 2007). That can take thousands, if not a million, years.

The final cause that occurred was sea level rise. The ocean at the time stood surprisingly shallow compared to the depth we know today (Macleod, 2013). Over time, water rose as tectonic plates moved. As the landmasses and glaciers moved, tearing up the earth, water levels continued to rise and fall based on tectonic plate movement allowing for species to grow larger (Klapper et al., 2014). Sea level rise also had an important effect on corals that I will go into more detail below when we resume time and watch the extinctions unfold.

3.3. Effects of the Mass Extinction

3.3.1. Global

Now let's continue the clocks and watch how these stressors impacted species such as corals, sponges, mollusks, marine invertebrates, young boney fish, chondrichthyes, and many other species living during the Devonian period.

We begin our journey at a tropical coral reef.[5] The corals stood proud as both living organisms and a habitat for new boney fish that found protection among them. This fragile forest found the perfect location to make its colony, basking in warm, shallow waters that any coral taking in as much sunlight as they liked. The bacteria that strengthened the corals loved here as well seeing as countless phytoplankton and zooplankton swam around free for snacking. The coral reef became a little paradise until that day.

The variety of corals struggled to hold their place while the ground beneath them shook violently. The bases held strong, but a few branches broke off. At least the young fish were okay, a few corals sighed in relief. The rest of the colony looked up to the surface seeing the sky above grow darker than usual as if something was blocking them from the light. It would pass and the sun would be shinning on them again, surely. It just had to.

[5] These 'short stories' are fictional stories that I produced in order to convey the effects of ocean anoxia, LIPs eruptions, sea level rise, and global cooling on a more personal level. Additionally, any stressor being described may not be the one that caused that species' extinction specifically. The stressors are being used one or two at a time for simplicity and the purpose of storytelling.

The corals held onto hope, waiting as time passed on. Days became months, months became years, and their reward for being patient became even crueler. The waters began to grow cold, killing a few fish that not only couldn't bear the cold but didn't flee in time. Even the corals found themselves 'shivering' and felt their branches growing weaker. Several clusters of the coral reef collapsed from the cold early on into the second phase of a mass extinction, the survival period. All hope seemed frozen, the sea level began to rise.

Any corals still standing reached for the light that grew further and further away leaving the stationary corals one of two choices; freeze or starve to death. For this coral reef, the corals suffered from both until the entire reef stood as a dead zone. No fish could bare to swim in the now oxygen deficient waters nor did they have the protection that they used to. All that remained was a field of coral corpses. If we followed the fish that managed to get away, their journey through the survival period of the mass extinction was just beginning.

Similar to other living species, early fish required oxygen to breathe. While their beloved corals couldn't go through photosynthesis anymore or produce oxygen, they had to leave to find waters with plenty of oxygen to sustain them. Although, it wasn't just coral reefs that were suffering from these anoxic conditions. Most of the ocean's waters had seen a decline in available oxygen after the eruptions. While some of those fish were able to push through with a lack of oxygen to support their organs and brain functions, enough early vertebrates suffered that put these young fish back in development by removing genes from the ocean's gene pool (Macleod, 2013). Development that likely enabled their survival in future mass extinctions.

3.3.2. Chondrichthyians

One group of chondrichthyes that dominated before the mass extinction began was the xenacanth shark (Pough et al., 2005; Turner, Shneider, & Hampe, 2008). These prehistoric sharks were formed more like large eels, as shown in Figure 5 below, and although they mainly swam the waters of rivers instead of open ocean, they still experienced the Devonian extinction effects. Xenacanths, like all chondrichthyes, have left behind only partial teeth and skeletons, making it difficult to tell what caused not only that individual's death but also the shift in development. Teeth only provide a snap shot of information on the individual—their diet, hunting styles, and feeding grounds, for example. Chondrichthyes also have a conveyer belt of teeth that replace each other should one break or fall out, even with early individuals like the xenacanth. Adding difficulty in determining whether the tooth was one that fell out during that individual's life or represents all of the solid remains of an individual (Pough et al., 2005).

In response to the mass extinction, these species along with other extant chondrichthyes and vertebrates started to decline in size (Sallan & Galimberti, 2015). The decline was gradual throughout the rest of the Devonian period and even into the next geologic period. Some fossils of xenacanths from the Devonian period ranged from a meter to two meters in length (Turner et al., 2008). That's a shark between three to six feet in length! Although, we're unsure if that they were that size before or after the mass extinction. By all other records the many xenacanth species endured this mass extinction along with many of their early chondrichthyian cousins. However, this was just the beginning for chondrichthyes as another mass extinction was just around the next corner.

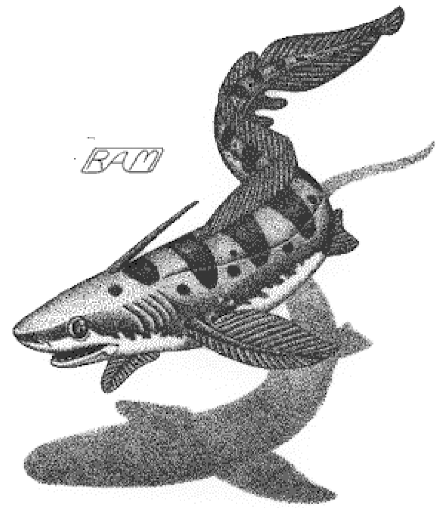

Figure 5. Based on fossil records, this image presents what one xenacanth species could have looked like during the Devonian period up until their extinction in the late Triassic period. Although they are classified as sharks, their bodies were more elongated like an eel (Martin, n.d.).

4. The Permian-Triassic Mass Extinction

4.1. Introduction

Despite nearly 70 to 85% of species going extinct during the Devonian mass extinction, it also has been referred as one of the smallest mass extinctions of the five affecting mainly the marine invertebrates (Bond & Grasby, 2017; Macleod, 2013). However, our next stop about 108 million years later during both the Permian and Triassic periods holds the record of being the largest mass extinction that occurred on earth. Just how many species went extinct during those periods if the Devonian's 70-85% extinction rate was considered small? Well, the extinction rate for the Permian-Triassic mass extinction stands between a staggering 95 to 97% extinction rate (Bond & Grasby, 2017; Macleod, 2013; Song, Wignall, & Yin, 2013). That's nearly all life on earth! If we were to break that down further, around 90% of marine species went extinct compared to the 70% of terrestrial species (Chen & Benton, 2012; Song et al., 2013). So, let's dive into the ocean of the Permian-Triassic periods to understand what happened this time.

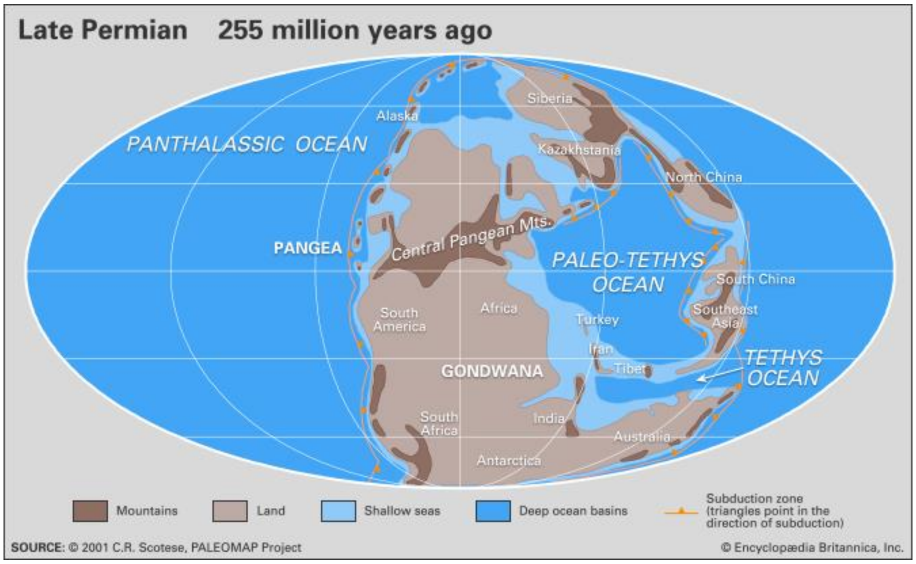

Figure 6. Similarly, to the Devonian period, the late Permian period still had wide open oceans with the landforms pushed together. However, now attached to the super-continent Gondwana is a second super-continent Pangea (Ross & Ross, 1999).

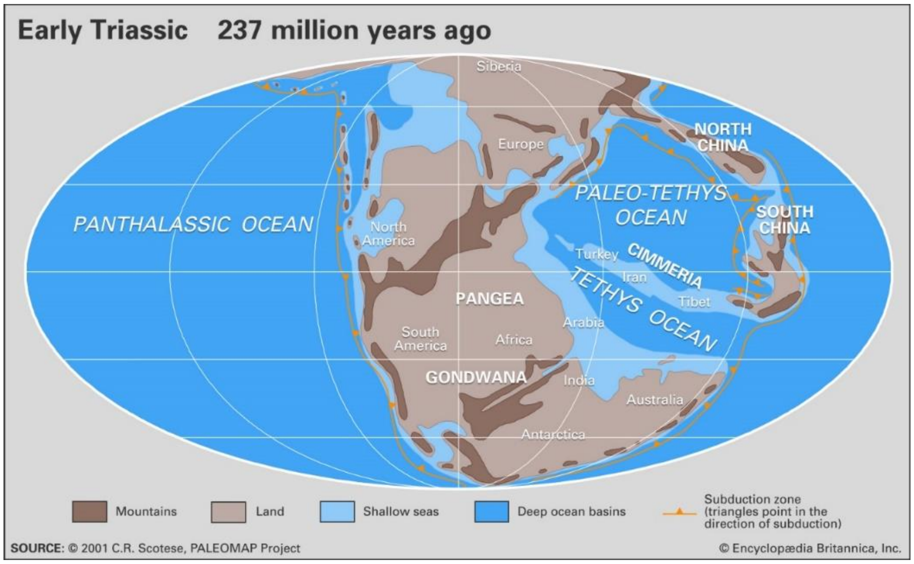

Figure 7. Likewise, to the Permian period, the early Triassic period shows the rise of Pangea, a super continent that started to push land forms apart from one another. However, the land forms are still somewhat close together during these early stages as shown above (Logan, 1999).

As Figures 6 and 7 show, the earth was still quite similar to the Devonian period up until the Triassic period. Landforms were starting to move up towards the poles before being to break apart from one another to the well-known super continent Pangea (Logan, 1999; Ross & Ross, 1999). There was plenty of open ocean that now had a higher sea level for not only more species, but also larger species as well (Carrier, Musick, & Heithaus, 2004). In fact, the sea level had raised from the Devonian mass extinction standing between 150 to 250 meters above the modern sea level (Macleod, 2013).

During the Devonian period bony fish were still evolving after what many paleontologists call origination, or coming into existence as a separate, new species (Darwin, 1859). These fish were making the transition from heavily armored to a special kind of hard, protective scales that chondrichthyes are known for (Macleod, 2013). Even though sharks had been around longer than bony fish, it was during the Permian period that shark diversity really exploded in both numbers and size (Carrier et al., 2004). Another feature within the marine ecosystem of the Permian period revolved around the invertebrates hit heavily by the Devonian mass extinction. That's right, those coral reefs that experienced extinction in several families or genus were *still* recovering. Some sponges were impacted as well but were able to recover faster and recolonized those reefs first (Macleod, 2013). Speaking of new species adaptations during these periods, wildlife species began to move out of the oceans onto land. This brought the introduction of amphibians, many of which lived in the emerging swampy biomes (Macleod, 2013). However, since this research focuses on chondrichthyes survival and evolution, we're going to stay beneath the waters while looking at causes and effects of this massive extinction crisis.

4.2. Environmental Causes of the Permian-Triassic Mass Extinction

Similar to the Devonian mass extinction, there wasn't a single event that caused the Permian-Triassic extinction. Multiple reinforcing events occurred over two periods. That's right, many paleontologists and geologists believe that this mass extinction happened in two phases; one occurring during the late Permian period and the second in the early Triassic (Bond & Grasby, 2017; Chen & Benton, 2012; Song et al., 2013). Perhaps it's these double phases that made this mass extinction so effective since most of the causes appeared to be same as the Devonian mass extinction (Bond & Grasby, 2017; Macleod, 2013; Song et al., 2013). Similar causes includes another LIPs episode, sea level shift, global climate change, and ocean anoxia. The new players to the field were ocean acidification and sediment overflow along with slight differences to a few mechanisms mentioned above (Bond & Grasby, 2017; Burgess, Muirhead, & Bowring, 2017; Clarkson et al., 2016; Isozaki, 1997; Macleod, 2013; Song et al., 2013).

During the first phase of the late Permian period, the Siberian Traps LIPs eruption plunged the environment into an unstable state which amplified the other causes (Figure 8) (Burgess et al., 2017; Macleod, 2013; Song et al., 2013). Just as we saw before, this led to number of chemical reactions in the atmosphere including leading to global warming, increased water temperatures and now, ocean acidification, after a large quantity of ash, carbon, sulfur, and phosphorus shot into the atmosphere, and descended into the ocean.

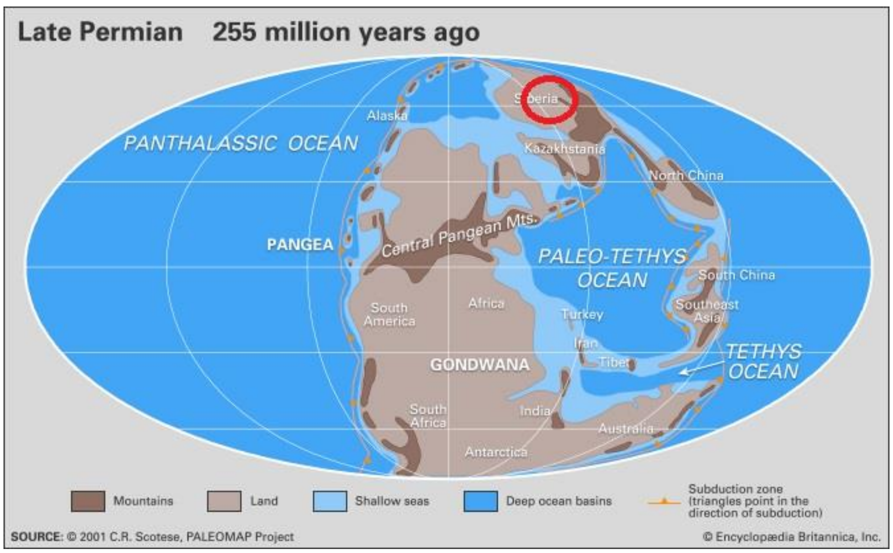

Figure 8. The Siberian Traps held a cluster of volcanos that all erupted during the same general period of time within the late Permian and early Triassic period, indicated by the red circle.

The Devonian Viluy Traps episode resulted in global cooling after a large amount of ash that erupted into the atmosphere acted as almost a blanket around the earth. However, this time, the Siberian Traps also released a large volume of greenhouse gases into the atmosphere (Burgess et al., 2017). These greenhouse gases trap warmth and the sun’s ultraviolet (UV) light until it continues to build up, increasing the temperature average over time.

Generally, the ocean tends to be slightly basic, with a pH of 8 out of 14 (Garrison, 2007). However, the sheer quantity of both sulfur and additional carbon released by the LIPs episode led to a drop in pH and oceans becoming more acidic--a process called acidification. In general, water and carbon dioxide constantly react with each other and trading oxygen to produce a compound called carbonic acid (H_2CO_3). That carbonic acid then breaks down into a bicarbonate ion (HCO_3^-) by removing a hydrogen to back into the water. When enough bicarbonate ions and extra hydrogens build up, the bicarbonate ions begin to bind together, releasing the hydrogen to produce a carbonate ion (CO_3^{2-}) and two positively charged hydrogens. These chemical reactions enable the ocean's pH to remain neutral while producing both acids, i.e. carbonic acid, and bases, i.e. carbonate ion. The eruptions, however, added in more carbon to the system, tipping the scales toward the first reaction of carbon dioxide plus water creating carbonic acid; the basic carbonate ion couldn't restore the neutral pH of water (Garrison, 2007).

In the early Triassic period, the effects of the LIPs eruption, global warming and ocean acidification continued; all building up to phase two. The second phase introduced sea level rise and ocean anoxia (Clarkson et al., 2016; Isozaki, 1997; Song et al., 2013). Some scientists have called the anoxic conditions during the Permian-Triassic extinction to be a part of superanoxia from not only the amount of species that anoxia killed, but also how much water went into anoxic conditions and the amount of oxygen dropped in the water primarily along warm shallow waters where corals were dying (Isozaki, 1997). With sea level rising in this phase, the corals and sponges' deaths, as well as phosphorus released from eruptions both contributed to how potent the superanoxia could become and amplify similar environmental stressors in the marine environment.

4.3. Effects of the Mass Extinction

4.3.1. Global

We now reach the first phase of the mass extinction shortly after the Siberian Traps erupted. However, before we continue I must warn you, ocean acidification had a horrific effect for some species and while I won't go into specific details, it was just harsh.

In the shallow waters along the coast of the Permian period, sponges have begun to recolonize the reefs, other species start to question if it was safe. While it seemed safe, that was before the Siberian Traps erupted. The eruptions threw excess carbon and sulfur into the ocean. As both elements built up, not only did the oceans start to become more acidic but the sponges, corals, and shell fish started to…feel a little funny. Almost like a tingle? This began the 'allergic reaction' these calcium rich species had to the acidic waters. The few corals coming back began bleaching, releasing the helpful bacteria that protected them as a last effort, before finally dying leaving behind small white corals that look like a pile of bones. Sponges and shell fish began to dissolve as the calcium in their shells pulled away to react with carbon and carbonic acid (Andersson & Gledhill, 2013). All the young vertebrates tempted to return to the reefs could do was watch and listen to the other species cry out for help, knowing help wouldn't come.

The horrific scene was just the beginning. With reefs dying once again, the second pulse of the Triassic period allowed for more effects on vertebrates. Marine plants and invertebrates' deaths helped push anoxia throughout the ocean from areas that were low in oxygen before to those that were rich with oxygen. While some fish species began to suffocate from the lack of oxygen levels in the water, some began to once again have their mental development hindered from the lack of oxygen. Some fish even began to feel that tingle from the high acidic levels in the ocean, what they didn't expect a second wave of ocean acidification to come from above. As the water cycle continued, soon acid rain began to fall adding more acidity to the ocean, dropping the pH to lethal levels for organisms.

4.3.2. Chondrichthyians

Even chondrichthyian species may have gone extinct during this massive extinction period, though with the lack of evidence it's hard to know if it had an impact on them. At the end of the Permian period, however, the xenacanth shark that were dominant during the Devonian period now were extinct. The xenacanth's extinction gave rise to the hybodus shark during the early Triassic period (Pough et al., 2005). These hybodus sharks grew in both length and body size, their cartilage rich bodies looking more like armor as shown in Figure 9 below. After the massive extinction event of the Permian-Triassic periods, perhaps that proved to chondrichthyes that they needed tougher scales, sharper teeth to pierce their prey, and to swim faster in order to survive in the harsh environment of the ocean, or at least until the next mass extinction.

Figure 9. The hybodus shark rose into existence during the early Triassic period in response to environmental conditions to be better fit to survive after the xenacanth shark went extinct.

5. The Triassic-Jurassic Mass Extinction

5.1. Introduction

A mere 50 million years after the Permian-Triassic, the world found itself in yet another mass extinction and biotic crisis. Species didn't know how to handle these next two periods while still recovering from the largest mass extinction. While the causes were relatively simple in comparison to the last two mass extinction, because of the timing between 70 and 88% of living families of the time went extinct.

The environment of the time was just like the Permian-Triassic periods with respect to its climate. Both periods were warm, arid with a higher humidity along the tropics. As we move further away from the equator towards the poles, we see a slightly larger variation in climates than previous periods (Chen & Benton, 2012; Palfy, 2003; Percival et al., 2017). As we will explore later on, between the Triassic and Jurassic periods, the land forms start to move away from one another more than they had before. In Figure 10 below, we see what the late Jurassic period was like and how the landforms had pulled away from one another more into the multiple continents like we have today.

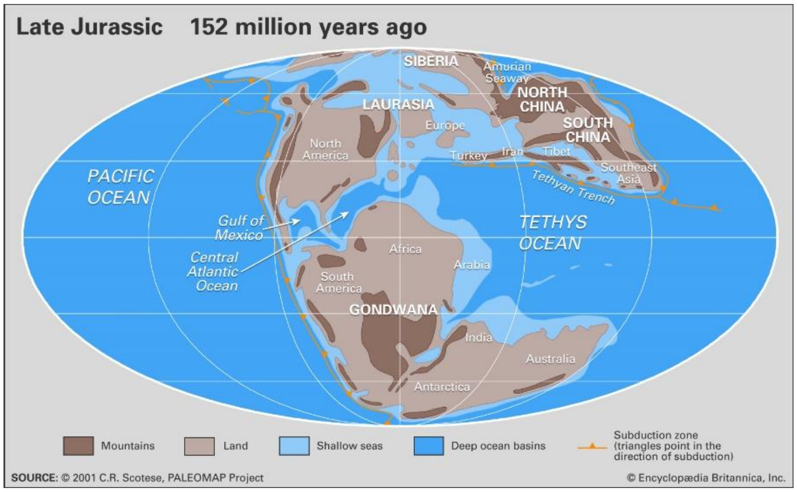

Figure 10. This map of the late Jurassic period shows the aftermath of the tectonic plate movement from the Triassic-Jurassic mass extinction. The world had finally begun to move away from one super continent, spreading apart from another (“Jurassic Period | Climate, Plants, Animals, & Facts | Britannica,” n.d.).

5.2. Environmental Causes of the Triassic-Jurassic Mass Extinction

Even during the late Triassic period, the ecosystem was recovering from the previous mass extinction that only ended earlier in the Triassic period. That also meant that conditions such as ocean anoxia, ocean acidification, and high sea levels would have been still present; although not as potent as they were during the mass extinction. What these stressors needed was another stressor. One stressor strong enough to push environmental conditions over the edge to unstable. One stressor that would enhance the leftover stressors from the previous mass extinction to increase in potency. This one stressor came in the form of volcanic eruption (Davies et al., 2017; Macleod, 2013).

Throughout the Triassic period, the tectonic plates became active, almost violently active, as the landforms were being ripped apart from one another separating Pangea. While the plates shifting or moving isn't uncommon, there was enough force from the activity to trigger a large cluster of volcanos to erupt in a geologically short period of time from one another. This particular cluster known as CAMP, or the Central Atlantic Magmatic Province, sat in what would become parts of North America, South America, western Africa, and northern Europe today as shown in Figure 11 below (Macleod, 2013). The area has been estimated to be around 6 million square miles! If we compare that massive cluster of volcanoes with the modern world, it would be slightly larger than Antarctica. Similar to previous LIP episodes we saw before, having a cluster of volcanoes that large erupting around the same time has prolonged effects for the surrounding areas which was enough to start another mass extinction period (Bond & Grasby, 2017).

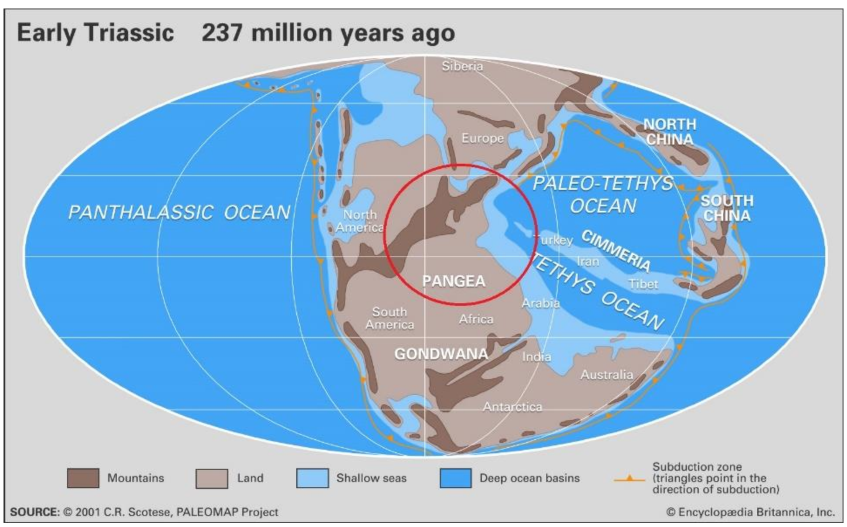

Figure 11. This figure of the Triassic period shows where exactly the CAMP location was. This large volcanic cluster was enough to push the world into a biotic crisis, spanning across four of the seven modern continents (Bond & Grasby, 2017; Logan, 1999; Macleod, 2013).

The initial response from the eruptions saw ash shooting out into the atmosphere before some fell to the oceans and land. The ash blanketed the sky similar to the Devonian period, increasing the earth's albedo leading to global cooling as a short term effect

(Macleod, 2013). Once the ash settled to the ground allowing for the earth's albedo to decrease again, the carbon released from the volcanoes led to a gradual global warming (Macleod, 2013; Palfy, 2003; Schoene, Guex, Bartolini, Schaltegger, & Blackburn, 2010). With that said, global warming didn't directly cause the mass extinction. Instead, because of the greenhouse gases large presence in the atmosphere, the soil in terms of nutrient supply, quality, and erosion rates lead to extinctions on land (Macleod, 2013).

In marine environments, the shifting tectonic plates caused the sea level to fall reducing the amount of available warm, shallow waters (Macleod, 2013; Palfy, 2003). Just how much shallow waters were lost? Macleod suggests a range between 160 to 330 feet of shallow waters was pulled back. With the water levels falling, marine species of all sizes and diets had to migrate to ensure that they would have enough space, proper conditions, and available food to survive, leading to more competition among species. Other chemicals released from CAMP, such as sulfur dioxide and heavy metals, mixed with carbon dioxide lead to ocean acidification, acidic precipitation, and likewise ocean anoxia (Davies et al., 2017).

5.3. Effects of the Mass Extinction

5.3.1. Global

This mass extinction was quite similar to the previous two mass extinctions, enough so that even the effects were the same. Species such as corals, sponges, mollusks, and other invertebrates who relied on these environments went extinction due to their inability to feed themselves. As the sea level fell, each of these organisms dried out and died. Furthermore, the rising temperature from the excess carbon in the atmosphere trapped heat in the atmosphere. The rising temperatures once it passed a certain threshold increased the water temperature to the point that some fish couldn't handle the warmth. For that reason, because it was so similar, I am not going to explore another narrative of an affected species.

5.3.2. Chondrichthyians

Similar to the Devonian mass extinction, little evidence has been discovered about chondrichthyes during this mass extinction. The hybodus still was the primary form of chondrichthyes during these periods, with no evidence to suggest that their size changed either. However, no evidence doesn't mean that no chondrichthyians went extinct, it simply means that we haven't found enough remains to know the truth.

6. The Cretaceous-Tertiary Mass Extinction

6.1. Introduction

The fifth extinction crisis has been perhaps the most famous mass extinction, the Cretaceous-Tertiary mass extinction happened nearly 65 million years ago and led to the end of the dominant species of the period; the dinosaurs. Although, because of this mass extinction, mammals were able to continue to evolve into what they are today (Losos, 2017).

After the tectonic plate's movement during the Triassic-Jurassic's mass extinction, the world looked a lot different than it did previously. The super continents were no more, as now all of the landforms have begun to drift away from one another. As Figure 12 shows, the world looks quite similar to what it does today. Just like the Triassic and Jurassic periods, the world had a warmer, almost tropical climate in some regions. There were also a few regions of the world that had arid climates (Macleod, 2013).

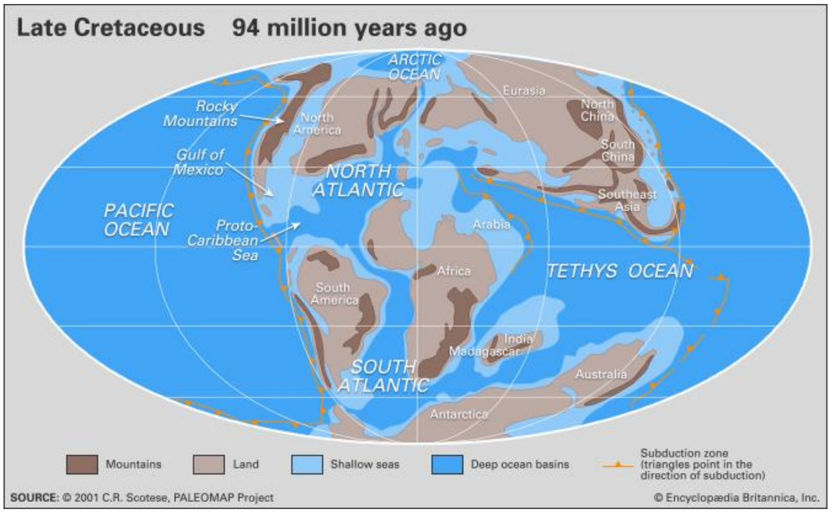

Figure 12. During the Triassic-Jurassic mass extinction the tectonic plate movement led to the landforms separating from one another. The results of their activity showed during the Cretaceous period 134 million years later. This map shows what the Cretaceous period looked like towards the end of the period as the land forms are still in the process of separating, drifting in the oceans, and forming new continents (Koch & Hansen, 1999).

6.2. Environmental Causes of the Cretaceous-Tertiary Mass Extinction

The dinosaurs along with between 75% of families living at the time, extinction was the source of debate among geologists for years (Bond & Grasby, 2017; Macleod, 2013). However, the final push for the environment to become instable didn’t come entirely from a LIP episode like the previous mass extinction. Instead, it also came from the sky.

During the Cretaceous period, an asteroid impacted the earth in Chicxulub, Mexico (Bond & Grasby, 2017; Macleod, 2013; Schulte et al., 2010; Smit & Smit, 1990). When it entered earth’s atmosphere and impacted the ground, this asteroid was estimated to be around 2.5 miles to 7 miles in diameter, most likely being larger before parts were burnt off upon entering our atmosphere (Macleod, 2013). When the asteroid hit the ground it shook the earth, resulting in earthquakes, tsunamis, wildfires, sediments being ejected into the atmosphere, and introduced both heavy metals and toxic heavy metals into the environment (Kring, 2007; Macleod, 2013; Schulte et al., 2010). The sediments and dust shot into the atmosphere made a light blanket just like volcanoes did, increasing the earth's albedo and for a short period of time lead to global cooling.

By the end of the Cretaceous period, another cluster of volcanoes known as the Deccan traps went off (Bond & Grasby, 2017; Macleod, 2013). The Deccan traps were a lot smaller than the Triassic-Jurassic's CAMP, but it enhanced the asteroid's long term effects (Bond & Grasby, 2017; Kring, 2007). With the combination of the asteroid and LIP episode, the environment's primary production began to slow down as the once warm climate grew colder, both on land and in the ocean. As the mass extinction continued, this lead to ocean anoxia (Kring, 2007; Macleod, 2013). All of the sediments released from the Deccan traps and the asteroid lead to ocean acidification, acidic precipitation, and eventually long term global warming to keep species adapting to the cooler environment on their toes.

6.3. Effects of the Mass Extinction

6.3.1. Global

Unlike the other mass extinctions, the fifth one saw more extinctions among families on land than those in the ocean (Bond & Grasby, 2017; Kriwet & Benton, 2004; Macleod, 2013). Most recorded marine species who did feel impact of the Deccan LIP or the Chicxulub asteroid were stationary species such as corals, invertebrates, and mollusks. These species felt ocean acidification and ocean anoxia the most, but it was nothing compared to the amount of species that went on extinct on land (Kriwet & Benton, 2004). For that reason, we find ourselves in what would become North America on the day that the asteroid hit Chicxulub, Mexico.

It was just like a normal day, nothing too different; well perhaps from maybe being a little too cloudy. Everyone went about their business as usual. The tyrannosaurus rex proudly protected her kill while she dragged a large chunk of an edmontosaurus back for her young. The surviving edmontosaurus now carried on grazing along a lake's edge as their afternoon stalker was satisfied. They didn't mind the struthiomimus herd that mixed in with their own, at least they could alert the rest if another predator came along. Not to mention if they were lucky the predator would find the struthiomimus an easier catch and leave them alone.

That's when they all noticed something was off. Looking up to the sky with their prehistoric eyes seeing a bright light falling towards the earth. It wasn't like anything they had ever seen before. Sure volcanos erupted before, but they shot upward. This *thing* was falling from the sky! While some of the species watched cautiously, if not a bit skeptical if this would be a new threat they would have to deal with, there were some organisms who were more curious. Swimming closer or walking forward, the species of the Cretaceous period watched as the asteroid fell closer until it slammed into the ground.

The asteroid was massive, crushing any individuals who were in its way. Sediments flew into the sky and into the ocean from the impact. It would have been like a volcano erupted, instead of blanket of ash though a blanket of sediments darkened the sky briefly. That was just the beginning for the dinosaurs. Wildfires spread across the land afterward, destroying forests and grasslands, releasing more carbon into the atmosphere. The earth trembled and shook with large earthquakes, during the impact and for the years to come in the unstable environment.

6.3.2. Chondrichthyians

The chondrichthyes of both the Cretaceous and Tertiary period continued to grow, adapt, and evolve becoming into the species that we know them as today (Kriwet & Benton, 2004). While most fish species weren't affected by this mass extinction, the same could not be said for these predators. In these times of environmental uncertainty, species along both the bottom and top of the food web would feel high amount of stress. Sharks in particular were considered as one of the medium and large top predators. Along with other top predators of the time who stalked their prey near the surface, open ocean, and shores, especially those in areas around the equator, went extinct (Kriwet & Benton, 2004). If there were sharks who lived along the ocean floor or deep ocean that felt the impacts from the environmental stressors, their remains haven't been be found. However, the exact cause that lead to chondrichthyian extinctions are still unknown.

In the midst of the extinctions, stingrays began to diversify into multiple groups. These new families of stingrays not only separated stingrays away from skates, chimeras, and sharks with their morphology, but they were better equipped for this mass extinction than other chondrichthyes (Bertozzi, Lee, & Donnellan, 2016). Unlike sharks, stingrays have a flatter body shape allowing them to easily glide along the bottom of the ocean floor and deep ocean; the two places that the environmental stressors could barely reach allowing them to thrive through the periods up until the modern day (Bertozzi et al., 2016; Pough et al., 2005).

7. Modern Day

7.1. Introduction

Now we have reached the present day of the modern world. The world has been divided into seven continents and many islands separated by the oceans. There hasn't been a new type of vertebrate species since the Cretaceous-Tertiary mass extinction. Although, now the land has become dominated by mammals; humans being the most successful mammal. Some mammal species have specialized to move into the ocean only needing to come to the surface or shores either for air or breeding.

How about chondrichthyes? How have this class of species evolved over the past 63 million years? In the present day, the International Union for Conservation of Nature (IUCN) noted over 1,116 species in our oceans (IUCN, 2019). This includes the great white shark, giant manta ray, whale shark, and the hammerhead shark to name a few. These species occupy most of the oceans except the Arctic and Antarctic oceans due to the cold temperatures. Additionally, these species mostly live anywhere from the open oceans to the ocean floor, with a few exceptions of species that live in large rivers (IUCN, 2019). Finally, it's important to know that a number of chondrichthyes are now known as apex predators. That means that there are no predators above those species in the food chain, they are the top predator that only has to worry about competition for resources with themselves and other apex predators.

7.2. Causes of Marine Species Decline

7.2.1. Human Induced Causes

Although this research focused on environmentally caused stressors, during modern day that cannot be talked about without also mentioning human actions. The climate has naturally changed throughout history – both in our histories and geologic time. However, our actions have also impacted the severity. A few environmental stressors that we have indirectly caused or influenced the severity in the ocean includes ocean acidification, increased nutrient imbalance which could lead to anoxia, nonpoint source pollution, climate change, and sea level rise. Humans have also directly impacted the ocean by point source pollution, coastal development, habitat destruction, introducing invasive species, overfishing, and poaching or bycatch (Miller, 2000; Nye, 2015; Raven, Hassenzahl, & Berg, 2012).

We've talked before about a few of these causes forming naturally, but how have humans effected these? Human populations have been increasing at an incredible rate compared to other species, the population reaching 7.3 *billion* people as of 2015 (Nye, 2015). With so many individuals with no predators to keep the species in check of a carrying capacity, intuitive humans have found a way to make sure there's enough food, water, and space to survive. Although, as we find unique ways to solve those basic needs, unforeseen consequences are around the corner that find their way to the oceans (Miller, 2000; Nye, 2015; Raven et al., 2012).

Having 7.3 billion people living in different time zones, different ways of living, and unique cultures, a high demand has been put on industries such as agriculture. In order to produce enough food in a timely manner to be available, farmers developed innovative ways to genetically modify crops to grow quicker, be more resistant to diseases, and grow larger. Furthermore, to eliminate other stressors that would affect crops, farmers use pesticides and herbicides to remove harmful insects that put crops at risk or weeds that would compete against resources. Additionally, farmers apply fertilizers to add more nutrients to the soil that boost crop development.

What does this have to do with stressors impacting the ocean? During rainfall or too much irrigation, these fertilizers can either fall into groundwater supply or runoff into a nearby pond or river. Whichever way the fertilizers go; it follows the water flow until it ends in the ocean. A little fertilizer doesn't hurt the waters, adding in extra nitrogen that normally would be in small amounts. However, not only is agriculture a large industry, but also some gardeners and landscapers use fertilizers to add nutrients into the soil to make it better suited for their desired vegetation. These extra nutrients create an imbalance in chemical ratios where fertilizers break down in the ocean, adding in more nitrogen, phosphorus, and potassium than it would have usually gotten on its own.

We have seen how too much phosphorus shifts the oxygen level in waters over a long period of time. This time, another player takes the field - nitrogen. Nitrogen acts as the limited resource of the ocean meaning that all chemical reactions that use nitrogen can only go so long as nitrogen is available. Once it's gone, all reactions stop. However, too much of something can be a terrible thing. When too much nitrogen is present, harmful algae blooms across the ocean's surface preventing enough oxygen from reaching vital depths in the water. If left unchecked, these harmful algal blooms can create a dead zone, an area that doesn't have enough oxygen level for species, both plant or animal, to reside there anymore.

Not all the food we eat come from farms; humans enjoy eating a variety of meats from salmon and beef to goat and deer. Similar to fruits and vegetables we harvest, we have also found multiple ways to maximize the amount of meat we can gather with less effort. One such technique that fishermen use to collect enough tuna for the world sees them lowering a large net into the ocean and waiting until a large school of tuna are within the net's boundary before pulling up. However, as movies such as Disney's *Oceans* and *Finding Nemo* point out that other species can get caught within the net (Perrin & Clazaud, 2010; Stanton, 2003). Bycatch has resulted in other unwanted fish to not only get caught within the nets lines, but for most, it will be too late before their presence is noticed. Species such as whales, turtles, and sharks are generally those caught by the nets, with their bodies tossed aside marked merely as "Bycatch, throwbacks, travelers who will never reach their destination" (Perrin & Clazaud, 2010; Queiroz et al., 2019). These large haul fishing nets along with poaching has pushed over harvesting onto our marine environments.

These two examples are just a few of the many ways humans have either effected our marine ecosystems directly or pushed the severity of natural environmental stressors that has depleted fish populations.

7.3. Current Effects

7.3.1. Chondrichthyians

Before I mentioned that chondrichthyes are known as apex predators who only have to worry about competition among themselves and other apex predators. However, even apex predators have concerns that they can't control, such as environmental stressors. Currently there hasn't been any reports of ocean acidification or sea level rise affecting chondrichthyian species. Instead, the class of species have been facing population decline due to wasteful resource overharvesting for either vengeance or a cultural dish that represents power in some countries (Castro & Huber, 2016; Garrison, 2007). Over 90% of an individual shark, as shown in Figure 13, will be thrown back into the water since the meat from the body generally is deemed inedible. Similar to some of the other stories mentioned throughout this paper, the story following a great white shark to show the effects, may be disturbing for some.

The powerful great white shark swam through the ocean's open waters, searching for his next meal. While he would prefer seals, he also wouldn't complain if he found either a dead whale or school of fish first. Normally this great white doesn't mind waiting for what he wants, or what attracts him to come closer, but when he sees a lone seal swimming nearby, well, he couldn't resist the opportunity. The great white swam closer, making sure to stay under the seal's line of sight not to frighten his prey. The shark also noticed the ship nearby but didn't think anything of it while his mind was on the thrill of the hunt. That was the shark's mistake.

When he finally made his move, the shark rushed the seal from below and began to pull it below the surface. However, this seal didn't bleed like all of the other seals that he had hunted before. In fact, now it started to move to the surface erratically. The great white, though, still was in the predator frame of mind and didn't notice this difference.

The humans on the ship watched the predator as he played with his food, grabbing it and pulling it underwater before letting go, but time was of the essence. They began to pull up the net that waited in the water, pulling the great white up onboard their ship. The shark thrashed and flopped desperate to get out of the strange net and back into the water. It was a dangerous manner, having a fifteen-foot shark throwing its' tail fins seeing you as the thing standing between it and freedom. One of the men on the ship grabbed a sharp knife as the other men worked on holding down the shark. The one with the knife worked quickly to relieve his accomplices whilst he sawed off all of the sharks' fins one by one.

The king of the ocean, the great white shark now dethroned was thrown back into the water while he was still alive and still bleeding. Now, still hungry, the shark floated in the waters aimlessly as he could no longer swim. As horrible as dying of starvation sounded, the shark had many more horrible fates that laid before him; bleeding to death, drowning since he could no longer swim, starvation, or having another, healthier shark or apex predator killing him. For his sake, he hoped that another predator would find him and end his suffering quickly since the humans did not do it for him.[6]

[6] While this ending may seem cruel for the sake of emotional storytelling, this fate actually happens with shark finning. Most of the sharks are still alive when they are caught and have their fins cut off. Likewise, those sharks who survive the process are still alive when they are thrown back in the ocean in favor of saving room on the ships for more shark fins.

Figure 13. Shark finning is a form of poaching that not only is harming the chondrichthyian population but is a waste of our predators. Around 90% of a shark is unused and is thrown back into the oceans. This figure demonstrates the sheer amount thrown back, and a visual representation of the effects on the sharks themselves. Image source: http://www.unleashed.org.au/blog/shark+fin+soup

8. Projections for the Future?

In our modern age, scientists of multiple fields have been concerned with climate change and how it will impact our future depending on actions we take. If we enact more renewable energy within the next decade, can we reduce our consumption? What actions need to be taken in order to reduce our carbon emissions; a carbon tax, better technology, reusing carbon? How can we save species from our actions? These are just a few questions that scientists ask when discussing the current and future health of the air, water, soil, life, and cultures.

To get an idea of what could happen, scientists such as paleontologists look into the past for patterns within the environment or how species respond to stressors. A play off of the old saying, history repeats itself, one of the founding fathers of paleontology states, "There is no way of assessing cause and effect [in historical data] except to look for patterns of coincidence and this requires multiple examinations of each cause and effect pair. If all extinction events are different, the deciphering of any one of them will be next to impossible," (Raup, 1981).

8.1. Historical Pattern Connections

Reflecting back on our journey through the past four mass extinctions, were there any similarities in what caused a biotic crisis? The answer, is yes! Each mass extinction had volcanic eruptions, ocean anoxia, climate change, sea level rise or fall, with a few also including ocean acidification. While in most cases, not one of these acts as the defining cause for a mass extinction, it was the combination of factors that pushed ecosystems into instability. Ash blocking sunlight from earth's surface, too much carbon creating a greenhouse effect, carbon or sulfur increasing the acidity levels, more nitrogen or phosphate that hoards oxygen from other systems in oceans.

Likewise, there are also similarities among the species which were impacted from the mass extinctions. Species which laid at the bottom of the ocean floor along shores or shallow, warm waters such as corals, sponges, mollusks, and invertebrates who relied on these ecosystems. Bony fish were impacted primarily from ocean anoxia, acid rain, and climate change if water temperatures changed out of the usual thresholds.

Chondrichthyes on the other hand, experienced an entirely different impact. Based on the available data for chondrichthyes, we can tell that after the first mass extinction they simply grew smaller in size mostly likely along with their prey so they would have to consume less. The second and fourth mass extinctions had the dominant form of chondrichthyes extinction and led way to a new form, one that had wider teeth better equipped for piercing and shredding flesh and leveling out their buoyancy to enable them to swim faster (Pough et al., 2005). By time the Cretaceous period came, chondrichthyes had become more or less what we know them as today.

8.2. Current Survivability?

In the modern world, chondrichthyes are just as elusive as they were in the past. According to the IUCN, of the 1,116 types of chondrichthyes 900 species are listed for more research for population trends, size, and distributions, with 801 officially listed with unknown population trends (IUCN, 2019). That's about 81% of the entire chondrichthyian class that doesn't have enough research! For those that we do know about, only 10 species are increasing and 110 are stable. The other 200 species are decreasing due to overharvesting (IUCN, 2019). Other than that, chondrichthyes have found their place in the food web as apex predators where they intend to hold their place.

8.3. Will Chondrichthyians go Extinct?

It's important to note that we know the most about chondrichthyes during the Cretaceous mass extinction, the last one to occur. A result of having no true bones or exoskeletons, chondrichthyian remains don't fossilize. Cartilage decomposes into the sediments only leaving behind an individual's teeth. These teeth, while useful to know of an individual's presence, make it difficult to tell what caused its death. Not to mention, these teeth are quite small when compared to both the sheer size and depth of the ocean. We know the most about chondrichthyes from the Cretaceous period because any remains haven't fully finished decomposing or their teeth are easier to spot; unless those individuals lived along the ocean floor and their remains haven't been discovered yet. With all of that, it's not clear how chondrichthyes reacted to other stressors meaning this won't have all information for a completely accurate prediction.

Chondrichthyes showed signs of both resistance and resilience throughout time. Each mass extinction seemed to strengthen them for the next as they adapted their size, body, and internal systems to make them into the predator we know them as. No data on prehistoric chondrichthyes diets has been discovered, but those who survived mass extinctions were most likely those who had no preference or specialization for prey (Kriwet & Benton, 2004).

The chondrichthyes of the modern world range in multiple different ways from body size, range, diet, hunting behaviors, aggression, and more (IUCN, 2019). Based on past mass extinctions and responses to the current environment, larger chondrichthyes who hunt similar to whales, also known as filter feeders, will most likely experience extinction. Larger species need to use more energy to survive, such as energy that comes from eating prey. However, these filter feeders consume invertebrates like krill. Should another extinction crisis occur, these invertebrates are likely to be impacted heavily meaning chondrichthyian filter feeders, such as whale sharks and basking sharks, will have a dramatic decrease in prey and eventually will decline as well. Chondrichthyes who live along the ocean floor such as giant manta rays, have a better chance of survival where the ecosystem tends to be more stable based on historical patterns.

Overharvesting, however, could change that prediction model as it doesn't have a selection of species based on size, diet or range. Instead, individuals are chosen based purely on availability and timing. The stress upon chondrichthyes could lead to species who would normally survive an extinction crisis to go extinct. The danger in this, is that those species who are selected for finning could have been ones with strong genes that would continue the survivability of this class would be remove from the ocean; leaving behind those who aren't equipped for future stressors.

9. Conclusion

Despite all of that, however, it is impossible to know what the future may hold. In the words of Ian Malcolm from *Jurassic Park*, "Because the history of evolution is that life escapes all barriers. Life breaks free. Life expands to new territories. Painfully, perhaps even dangerously. But life finds a way" (Crichton, 1990). Life itself find ways to solve obstacles with the power of evolution and adaption. As trees grew larger, so did giraffe's necks. As the world moved to calcium rich bones, chondrichthyes kept their cartilage rich bones which saved their lives multiple times from environmental stressors such as ocean acidification and climate change that claimed the lives of other fish.

The prediction that large chondrichthyian filter feeders will go extinct and bottom dwelling generalist chondrichthyes will survive, could change in a moment's notice. The uncertainty of the future means that when the next mass extinction occurs, an entirely new and unforeseen stressor could come into the ecosystem and wipe out chondrichthyians or all of their prey. An example of this happened to the dinosaurs and the Chicxulub asteroid, the unforeseen meteor from space.

Not to mention, unlike other mass extinctions, humans and mammals have become the dominant species with an ability to modify their environments. We have impacted the environment from our actions towards industrialism and creating new technologies to expand on our way of life, increasing the amount of carbon emissions more than the natural emission rate (Nye, 2015). While we have made certain predictions about climate change's impacts, there are other effects that are unforeseen, such as potential effects that could impact chondrichthyes and their prey. Unless we do something to act against pushing stress and instability onto the environment, other species, and ourselves, all species on earth will experience impacts that will threaten all aspects of life (Nye, 2015).

Bibliography

Andersson, A. J., & Gledhill, D. (2013). Ocean Acidification and Coral Reefs: Effects on Breakdown, Dissolution, and Net Ecosystem Calcification. *Annual Review of Marine Science*, (5), 321–348. Retrieved from https://www.annualreviews.org/doi/pdf/10.1146/annurev-marine-121211-172241

Bertozzi, T., Lee, M. S. Y., & Donnellan, S. C. (2016). Stingray diversification across the end-Cretaceous extinctions. *Memoirs of Museum Victoria*, *74*. https://doi.org/10.24199/j.mmv.2016.74.26

Bond, D. P. G., & Grasby, S. E. (2017). On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *478*, 3–29. https://doi.org/10.1016/j.palaeo.2016.11.005

Burgess, S. D., Muirhead, J. D., & Bowring, S. A. (2017). Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nature Communications*, *8*(1), 1–6. https://doi.org/10.1038/s41467-017-00083-9

Carrier, J. C., Musick, J. A., & Heithaus, M. R. (Eds.). (2004). *Biology of Sharks and Their Relatives*.

Castro, P., & Huber, M. (2016). *Marine Biology* (10th ed.). McGraw Hill Education.

Chen, Z.-Q., & Benton, M. J. (2012). The timing and pattern of biotic recovery following the end-Permian mass extinction The end-Permian mass extinction. *Nature Geoscience*, *5*. https://doi.org/10.1038/NGEO1475

Clarkson, M. O., Kasemann, S. ., Wood, R., Lenton, T. M., Daines, S. J., Richoz, S., … Tipper, E. T. (2016). Ocean Acidification and the Permo-Triassic Mass Extinction. *Science*.

Crichton, M. (1990). *Jurassic Park* (1991st ed.). Ballantine Books.

Darwin, C. (1859). Origin of Species. In *The Havard Classics* (11th ed.). P.F. Collier.

Davies, J. H. F. L., Marzoli, A., Bertrand, H., Youbi, N., Ernesto, M., & Schaltegger, U. (2017). End-Triassic mass extinction started by intrusive CAMP activity. *Nature Communications*, *8*. https://doi.org/10.1038/ncomms15596

Garrison, T. (2007). *Oceanography: an invitation to marine science* (6th ed.; P. Adams, M. Arbogast, A. Brady, A. Marinkovich, R. Broyer, & C. Lindloff, Eds.). Thomson Brooks/Cole.

Geologic Time - Ms. Ash's Science Website. (n.d.). Retrieved February 29, 2020, from http://aashscience.weebly.com/geologic-time.html

Isozaki, Y. (1997). Permo-Triassic Boundary Superanoxia and Stratified Superocean: Records from Lost Deep Sea. *Science*, *276*(5310), 235–238. Retrieved from http://science.sciencemag.org/

IUCN. (2019). IUCN Red List of Threatened Species. Retrieved November 22, 2019, from https://www.iucnredlist.org/search?taxonomies=100043&searchType=species

Joachimski, M. M., Breisig, S., Buggisch, W., Talent, J. A., Mawson, R., Gereke, M., … Weddige, K. (2009). Devonian climate and reef evolution: Insights from oxygen isotopes in apatite. *Earth and Planetary Science Letters*, *284*(3–4), 599–609. https://doi.org/10.1016/j.epsl.2009.05.028

Jurassic Period | Climate, Plants, Animals, & Facts | Britannica. (n.d.). Retrieved May 29, 2020, from https://www.britannica.com/science/Jurassic-Period

Klapper, G., Sandberg, C., & Johnson, J. G. (2014). Devonian eustatic fluctuations in Euramerica. *Geol Soc Am Bull*, *96*, 567–587. https://doi.org/10.1130/0016-7606(1985)96<567:DEFIE>2.0.CO;2

Koch, C. F., & Hansen, T. A. (1999, June 26). Cretaceous Period . Retrieved May 26, 2020, from Britannica website: https://www.britannica.com/science/Cretaceous-Period

Kring, D. A. (2007). The Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *255*(1–2), 4–21. https://doi.org/10.1016/j.palaeo.2007.02.037

Kriwet, J., & Benton, M. J. (2004). Neoselachian (Chondrichthyes, Elasmobranchii) diversity across the Cretaceous-Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *214*(3). https://doi.org/10.1016/S0031-0182(04)00420-1

Logan, A. (1999, July 26). Triassic Period | geochronology. Retrieved March 25, 2020, from Britannica website: https://www.britannica.com/science/Triassic-Period

Losos, J. B. (2017). *Improbable Destinies: fate, chance, and the future of evolution* (1st ed.). New York: Pennguin Random House.

Macleod, N. (2013). *The Great Extinctions: what causes them and how they shape life* (1st ed.). London: Firefly Books.

Mahoney, J. J., & Coffin, M. F. (1997). *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism* (J. J. Mahoney & M. F. Coffin, Eds.). https://doi.org/10.1029/GM100

Martin, A. (n.d.). Earliest Sharks. Retrieved March 24, 2020, from ReefQuest Centre for Shark Research website: http://www.elasmo-research.org/education/evolution/earliest.htm

Miller, T. G. (2000). *Living in the Environment* (11th ed.). Brooks/Cole Publishing Company.

Nye, B. (2015). *Unstoppable: Harbessing Science to Change the World* (C. S. Powell, Ed.). St. Martin's Press.

Palfy, J. (2003). Volcanism of the Central Atlantic Magmatic Province as a Potential Driving Force in the end Triassic Mass Extinction. *Geophysical Monograph*, *136*, 255–267.

Parker, S. (2009). *Dinosaurus: The Complete Guide to Dinosaurs* (1st ed.). Firefly Books.

Percival, L. M. E., Ruhl, M., Hesselbo, S. P., Jenkyns, H. C., Mather, T. A., & Whiteside, J. H. (2017). Mercury evidence for pulsed volcanism during the end-Triassic mass extinction. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(30). https://doi.org/10.1073/pnas.1705378114

Perrin, J., & Clazaud, J. (2010). *DisneyNature Oceans*. United States: Disney.

Pough, F. H., Janis, C. M., & Heiser, J. B. (2005). *Vertebrate Life* (7th ed.; J. Challice, C. Lee, K. Schiaparelli, B. Sweeten, E. Thomas, & T. Benfatti, Eds.). Pearson Education.

Queiroz, N., Humphries, N. E., Couto, A., Vedor, M., da Costa, I., Sequeira, A. M. M., … Sims, D. W. (2019). Global spatial risk assessment of sharks under the footprint of fisheries. *Nature*, *572*(7770), 461–466. https://doi.org/10.1038/s41586-019-1444-4

Raup, D. M. (1981). Extinction: bad genes or bad luck? *Paleontology*, *19*, 25–33.

Raven, P. H., Hassenzahl, D. M., & Berg, L. R. (2012). *Environment* (eighth). John Wiley and Sons Inc.

Ross, J., & Ross, C. (1999, July 26). Permian Period | geochronology . Retrieved March 25, 2020, from Britannica website: https://www.britannica.com/science/Permian-Period

Sallan, L., & Galimberti, A. (2015). Body-size reduction in vertebrates following the end Devonian mass extinction. *Science*, *350*(6262), 812–815. https://doi.org/10.1126/science.aac9819

Schoene, B., Guex, J., Bartolini, A., Schaltegger, U., & Blackburn, T. (2010). Correlating the end Triassic mass extinction and flood basalt volcanism at the 100 ka level. *Geology*, *38*(5), 387–390. https://doi.org/10.1130/G30683.1

Schulte, P., Alegret, L., Arenillas, I., Arz, J. A., Barton, P. J., Bown, P. R., … Millumsen, P. S. (2010). The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary. *Science*, *327*, 1214–1218.

Smit, J., & Smit, J. (1990). Meteorite impact, extinctions and the Cretaceous-Tertiary Boundary Mass extinctions-drivers for evolution? View project Iodp exp 364 chicxulub crater drilling View project Meteorite impact, extinctions and the Cretaceous-Tertiary Boundary*. In *Geologie en Mijnbouw* (Vol. 69). Retrieved from https://www.researchgate.net/publication/27710988

Song, H., Wignall, P. B., & Yin, H. (2013). Two pulses of extinction during the Permian-Triassic crisis. *Nature Geoscience*, *6*, 52–56. https://doi.org/10.1038/ngeo1649

Stanton, A. (2003). *Finding Nemo*. United States: Disney/Pixar.

Turner, S., Shneider, J., & Hampe, O. (2008). The Survivors: Devonian-Triassic xenacanthiform sharks across Gondwana. *Faunas and Paleoenvironments of the Late Palaeozoic*, 50.

Willson, M. (1984). *Vertebrate Natural History*. CBS College Publishing.

Appendices