Echoes of Life Through Time:

Human's Evolving Views of Fossils and the Patterns They Reveal

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The Nature of Fossils: A Historical Perspective

Fossils are an integral part of our culture. We encounter them in museums, schools, television, and movies. We know so much about fossils; it is difficult to believe our ancestors were so unsure about their nature.

Throughout recorded history there have been both naturalistic and super-naturalistic explanations for fossils. The Greeks believed mammoth fossils were the bones of human giants. Xenophanes (ca. 570-500 BCE), a Greek philosopher, hypothesized that there existed a cycle in which moisture eroded land into mud followed by another beginning. Xenophanes cited marine fossils found on land as evidence to support his ideas (Kirk, Raven, and Schofield 1983, p. 177). Aristotle (384-322 BCE) speculated that ancient fish swam into cracks in the rock and got stuck. Popular conceptions included the ideas that crinoids with star-shaped centers were formed by falling stars and that ammonites were decapitated snakes. The word fossil is Latin for "dug up" and was coined during the Renaissance. People wondered whether fossils are pranks of nature, works of the Devil, or supernatural representations of ideal life forms. Many believed that fossils formed during Noah's flood. Leonardo da Vinci (1452-1519) recognized that fossil shells in the Apennine Mountains of Italy were the remains of ancient sea life and argued they could not have formed during Noah's flood. He recognized that different specimens had been formed at different times (Prothero, 2004, pp. 5 & 6).

Many people in Western cultures were taught to believe in a literal interpretation of the Bible. It was natural to believe every species in existence was made in a single creation event. This idea also extended to rocks, believed to have been formed as we see them during the first days of creation. Thus in the absence of two key concepts, extinction and sedimentary rock formation, a more accurate understanding of fossils was not possible. Robert Hooke (1635-1703) and Niels Stensen (1638-1686) would put science on a more productive path to understanding the origins of fossils and the formation of sedimentary rocks.

Niels Stensen (Latinized to Nicholaus Steno) was an anatomist and naturalist. A chance encounter between determined fishermen and a great white shark off the Tuscan coast in 1666 sparked a chain of events that would help change our views of fossils and of Earth's geologic past (Cutler 2003, pp. 5-8). Steno dissected the head of this shark and realized that fossil tongue stones previously believed to be petrified snake or dragon tongues were actually fossil shark teeth (Prothero 1998, p. 3). One problem still existed: how do fossils become embedded in solid rock? Steno recognized that fossils represent organisms that became buried in sediment, which later turned into rock. The realization that sediments turn into rock was counter to the view that all rocks on Earth formed in a single creation event. Once Steno recognized that fossils he was contemplating (sharks teeth and sea shells) were formed in the sediments of oceans he was able to work out the basic rules that would eventually be the foundations of a new branch of geology called stratigraphy. Steno formalized the laws of superposition, original horizontality, and original continuity in his 1669 publication titled *De solido intra solidum naturaliter contento dissertationis prodromus* (Prothero 2004, p. 6).

The law of superposition is the foundation of Steno's work on stratigraphy. The principle of superposition states that in an undisturbed sequence of strata each layer is older than the one above and younger than the one below. The law of original horizontality states that sedimentary strata are deposited in horizontal sheets. If these layers are not horizontal, subsequent movements have occurred. The law of lateral continuity states that strata extend laterally in all directions and pinch out at the edge of their deposition. Modern forms of these laws include lava flows. Steno's description of how fossils become embedded in water born sediments that later harden into rock also hints at the principle of inclusion. Later, James Hutton, William Smith, Georges Cuvier, and Alexandre Brongniart would add to these basic rules making stratigraphy an effective way to study the distribution, deposition, relative age, and fossil life of rock strata.

Robert Hooke an English scientist and inventor made some of the first accurate illustrations of fossils. He suggested that species may have a fixed "life span" and might be used to order rocks chronologically (Prothero, 2004, p. 7). Hooke argued that there was evidence for three stages in fossil formation. The first stage could be seen in the organic bones, shells and plant matter found in mud, peat and moss. Plant and animal parts that were modified in layers of lignites and brown coal represented the second stage. The third stage could be witnessed by examining plant parts and shells that had turned to coal embedded within layers of coal. The fossils had changed to rock just as the peat had changed to lignite and the lignite into coal (Winchester, 2001, p. 38). Not long after Hooke's discovery of plant cells he was asked at a meeting of the Royal Society to examine petrified wood under his microscope. Hooke discovered the fossil wood had the same structure as living wood. At the time petrified wood was thought to form as stone in rock layers and then into clay that eventually turned to wood. This idea was seemingly supported by a clay deposit in Italy that contained fossil wood in various stages of petrifaction. After examining the fossil wood Hooke came to the conclusion that the wood had soaked in mineral solutions that filled the pores and turned to stone (Cutler, 2003, p. 131). Thus, rock layers did not generate petrified wood that transformed to wood; rather, once living wood buried in sediments turned to stone as minerals replaced the once living material of the tree.

Hooke, like Steno, championed the idea that fossils represented ancient plant and animal life. Hooke and Steno helped jump-start the science of stratigraphy, making it possible to answer the question, "what came first?" Steno recognized that his principles could be used to reconstruct the geologic past (Cutler, 2003, p. 114). The ideas of Hooke and Steno would not be widely accepted for another century; although, Carolus Linnaeus (1707-1778) treated fossil organisms as if they were living organisms in his 1735 publication *Systema Naturae*, which was an attempt to classify life on Earth (Prothero, 2004, p. 7).

Deep Time & Extinction

Steno and Hooke argued for a naturalistic interpretation of fossils. Perplexing questions remained, such as the age of rock layers and the proper interpretation of the unfamiliar organisms that appear in the fossil record.

James Hutton (1726-1797) often considered the father of geology developed the theory of uniformitarianism, which states that geologic events are caused by natural processes, many of which are operating in our own time. Put another way, the natural laws that we know about in the present have been constant over the geologic past. Hutton argued that many of Earth's surface features were formed through a slow cycle of land erosion, seabed deposition, and uplift. Hutton's theory of uniformitarianism and the principles of stratigraphy would be fully developed and made popular by another Scottish geologist Charles Lyell (1797-1875) with his classic three volume work, first published from 1830 to 1833, entitled *Principles of Geology: being an attempt to explain the former changes of the Earth's surface by reference to causes now in operation* (Levin, 1999, p. 9).

Hutton formulated three principles used in the science of stratigraphy that must be considered when seeking relative dates for rock layers. The principle of inclusion states that any inclusion is older than the rock that contains it. An inclusion may be a fossil or rock fragment contained in another rock. Care must be taken with this law as crystals and concretions may be deposited by groundwater within already formed rock. The principle of crosscutting states that any feature that cuts across a rock or sediment must be younger than the rock or sediment through which it cuts. Examples include fractures, faults, and igneous intrusions. Igneous intrusions are sometimes referred to as a separate principle, the principle of intrusive relationships. Unconformities represent gaps in geologic time when layers were not deposited or when erosion removed layers. This principle includes three types of unconformities. A disconformity is an unconformity between parallel layers. An angular unconformity exists when younger more parallel strata overlie tilted strata. A nonconformity is formed when sedimentary layers are deposited on igneous or metamorphic rock.

The concept of geologic time or deep time was a logical consequence of Hutton's theory. In 1788 John Playfair (1748-1819), a Scottish geologist and mathematician, came to see Hutton's Unconformity in Inchbonny. The angular unconformity at Siccar Point in Eastern Scotland consists of many vertical tilted layers of grey shale overlaid by many layers of horizontal red sandstone. Playfair later commented that, "the mind seemed to grow giddy by looking so far into the abyss of time." McPhee (1998) points out that Hutton removed humans from a specious place in time just as Copernicus had removed humans from a specious position in the universe (p. 74).

Today, extinction, the permanent disappearance of a species, is an all too familiar concept. In recent history we have witnessed the extinction of many species due to human activities of hunting and habitat destruction. As little as 200 years ago many people thought extinction was impossible. Theology fueled opposition to the idea of extinction. People believed that the biosphere constituted a perfect creation. The concept of extinction was contrary to several deeply held Christian beliefs. First, was the concept of divine providence. An all-powerful and all-loving God would never allow any creature to become extinct. This is illustrated in the story of Noah's ark. God would not suffer any species to become extinct and thus ordered Noah to populate the ark with two of each creature. Second, was the idea of the plenitude or fullness of nature. God's creation was perfect and an organism's extinction would render it incomplete. Finally, was the concept of a "Great Chain of Being." This chain linked animals to human to angels to God. Extinction would take away links in the chain leading to its destruction (Prothero, 2004, p. 8).

Thomas Jefferson (1743-1826) initially resisted the idea of the extinction of species. In his "Notes on the State of Virginia," published in 1789, he denied that the Mammoth is extinct on the grounds that the economy of nature would not allow any break in nature's "great work" to be broken (Peterson 1975, p. 86). Jefferson and many others argued that the strange organisms found in the fossil record must still exist in unexplored parts of the world. A large fossil claw prompted Jefferson to ask Lewis and Clarke to look for a giant prairie lion on their expedition. This claw was later found to be a part of the extinct giant ground sloth. By the end of his life, however, Jefferson had apparently become convinced of the fact of extinction, for in an 1823 letter to John Adams, he clearly accepts the idea that "certain races of animals go extinct" (Adams 1983, p. 411).

The great French anatomist Georges Cuvier (1769-1832) established extinction as a fact in a historic lecture given to the French Institute in 1796. Cuvier talked about mammoths, woolly rhinos, giant cave bears, and the sea reptile mosasaur in his lecture. In his paleontological studies Cuvier came to recognize what we now call mass extinctions at the end of the Permian and Cretaceous periods. Cuvier developed the Theory of Catastrophism. Cuvier believed supernatural cataclysms occurred before Noah's flood (antideluvial) and were regional not global (Prothero, 2004, p. 82).

Stephen J. Gould (1941-2002), American paleontologist and writer, believed that extinction is needed to tell time and is the motor of evolution. If all the species stayed the same there would be no way to tell geologic time. Furthermore, if species didn't disappear there would be no room for new ones to evolve. For example, during the reign of the dinosaurs, mammals never got bigger than an ordinary house cat. If the dinosaurs had not died out there is no reason to believe that mammals would have increased in size and, in that case, we would not be here (Infinite Voyage, 1988).

It is ironic, that in the last two hundred years scientist have gone from believing that extinction was impossible to establishing that 99.9% of all plant and animal species that have ever existed on Earth are now extinct.

The Fossil Record & A History of Life on Earth

As already noted, Cuvier established the revolutionary idea of extinction. It is said that Cuvier could identify the remains of an organism from just a few bones. Several people were key to ordering fossils chronologically and thus building a history of life on Earth.

The Industrial Revolution helped enlarge our understanding of fossils and the history of life on Earth. Large machines used for digging coal, making railroad beds and canals removed great volumes of earth exposing many rock layers and their fossils. William Smith (1769-1839), a British engineer, was in charge of building the Somerset Canal. Smith realized that fossils exhibited a regular pattern in different strata. Thus Smith could recognize a particular rock layer from the combination of fossils present. This observation allowed Smith to predict the locations of different rock layers making him more efficient and successful when surveying for canal construction. Smith was able to map out the succession of fossils found in different rock formations. His geologic maps showed that life forms appear and disappear through time (Winchester, 2002, pp. 117-119).

At about the same time, Cuvier and Alexandre Brongniart (1770-1847), a French naturalist and geologist, were mapping the Paris Basin. In reconstructing the changing sea levels of the Atlantic Ocean, Brongnairt and Cuvier showed that fossils had been laid down during alternating fresh and salt-water conditions thus establishing the fact that there existed a succession of fossils in different formations representing different environments. Thus, Smith, Cuvier, and Brongniart added another basic principle to the growing science of stratigraphy. This is the principle of faunal succession, which states that fossil organisms succeed one another in a definite, irreversible, and determinable order (Prothero, 2004, p. 8). Embedded within the principle of faunal succession is the concept of an index fossil. Good index fossils possess several characteristics that make them excellent tools for determining the age of the rock layer in which they are found. Index fossils are abundant and have a wide geographic distribution, that is, they are found in many locations. Index fossils are easy to identify even when the specimens are incomplete. Finally, index fossils existed for only a short geologic time. Thus, index fossils help to pinpoint the age of a geologic formation with precision. Index fossils are often used to correlate the age of related formations.

Cuvier noticed that the more ancient a fossil the less it resembled present day organisms. In ordering fossils chronologically Cuvier, like Smith, was constructing a history of life on Earth using geologic strata. Thus began the science of biostratigraphy. Smith did not know why each unit of rock had a particular fauna. Cuvier was opposed to early theories of evolution and viewed faunal succession as evidence for a cycle of creation and extinction known as the Theory of Catastrophism. Cuvier's contributions to our understanding of geologic time, extinction, and fossil vertebrates were essential in developing the concepts of deep time and evolution. And yet, as Michael Benton (1956-), an English paleontologist, points out Cuvier himself was unable to " . . . make two vital connections: between extinction and evolution, and between geological change and time (2001, p. 99)." Later, the work of Charles Darwin (1809-1882), the great English naturalist and geologist, would make it possible to see that rock units of different ages contain different assemblages of fossils because life has evolved continuously.

One of the chief legacies of these 19th century efforts is the geological time scale. The present day scale or column divides geologic time into intervals separated from each other by changes in rock type and abrupt changes in fossil groups. Gould believed the geologic time table to be one of the greatest contributions to human understanding. According to Gould:

> The establishment of a time scale, and the working out of a consistent and worldwide sequence of changes in fossils through the stratigraphic record, represents the major triumph of the developing science of geology during the first half of the nineteenth century.... By 1850, geology had developed a coherent global chronology based on life's history. This discovery and construction of history itself must rank as the greatest contribution ever made--indeed, I would argue, ever makeable--by geology to human understanding (Gould 2001, p.15).

The science of stratigraphy allowed geologists to work out the spatial and temporal relationships of rock layers making possible a relative time scale. The biogeographical distribution of species through time and space revealed by this work would be a critical influence on Charles Darwin’s Theory of Evolution by Natural Selection published in 1859 (Darwin, 1859/2009, pp. 223-225). In the 20th century scientists would develop and apply radiometric dating which places absolute dates on the relative time scale. Whereas relative dating only specifies the chronological sequence of events absolute time is measured in units such as years. Radiometric dating confirmed and reinforced the consistency between deep time, relative time and Darwinism (Miller, 1999, pp. 68 & 69).

The science of stratigraphy changed our view of the world. Where before the world was viewed as static, now it is seen as dynamic and changing. Fossil deposits of different ages reveal that different organisms have lived at different times. The rock in which these fossils are embedded is geologic truth, speaking to the fact that environments change. The fossil record affords only pieces of the past. Science has learned to use these pieces to work out the evolution of life on Earth using a system of independent empirical verification. Together, impressions of the past explored by this most important human epistemology work out to be a way for nature to remember itself.

Mass Extinction

Cuvier not only established extinction as fact, he was also the first to recognize that mass extinctions have occurred at the end of what we now call the Paleozoic and Mesozoic eras (Stanley, 1987, p. 2). Extinction is the total disappearance of a species and is represented by the contraction of the geographical range of the species and the reduction of the population to the number zero. This contraction and reduction is governed by limiting factors. Limiting factors include the physical environment, competition, predation, and chance factors. Climate is one of the most important environmental factors (Stanley, 1987, p. 10).

In 1973, Leigh Van Valen (1935-2010), an American evolutionary biologist, published a study that compared the duration of certain groups of organisms against the number that survived. He found that species do not become better at avoiding extinction as they persist through time; old species have the same probability of becoming extinct as young ones. He inferred from this data that organisms could never be perfectly adapted as environments are not static. Thus, natural selection enables organisms to maintain not improve adaptation. Van Valen called this the Red Queen Hypothesis. The Red Queen in Lewis Carrol's *Alice Through the Looking Glass* told Alice that she must keep running to stay in the same place. Thus, species must constantly evolve to avoid extinction (Milner, 1990, p. 387; Prothero, 2004, p. 86).

In 1982 David Raup (1933-2015) and John Sepkoski (1948-1999), American paleontologists, plotted the number of extinctions in marine invertebrate and vertebrate families during the last 560 million years. They discovered a steady background rate of 2 to 4 family extinctions per million years. However, five intervals stood out in which 10 to 20 families became extinct per million years. They also identified 10 mass extinctions of the second order over the last 600 million years (Stanley, 1987, p. 13).

What is the nature of these five extinctions and how do they differ from background extinctions? In 1986 David Jablonski (1953-), an American geophysical scientist, published a study comparing the extinction of Cretaceous aged molluscan species with different larval developments. In one type of development larvae feed while floating on the ocean for weeks, thus attaining a wide geographic distribution. In the second type of development larvae do not feed and float for hours, days or not at all. During background extinctions the mollusks with a wider geographic range were more extinction resistant. However, both groups suffered equally during the terminal Cretaceous extinction (Stanley, 1987, p. 17). Jablonski's study suggests that during mass extinctions organisms with extinction-resistance qualities, such as wide geographic distributions, are just as likely to become extinct as those without these properties. Thus, mass extinctions seem to be fundamentally different from normal background extinction.

Looking for the causes of mass extinction has fired the imagination of the public and scientists from various backgrounds. Steven Stanley (1941-), an American paleontologist and evolutionary biologist, in his book *Extinction* identifies five themes in mass extinction (1987, pp. 17 & 18).

- Extinction occurs on land and sea.
- On the land, animals suffer extinctions repeatedly while plants seem to be more extinction resistant.
- There is preferential disappearance of tropical life forms in mass extinction.
- Some groups experience extinction repeatedly (trilobites & ammonoids).
- There might be a periodicity to mass extinction.

The themes identified by Stanley may imply a common agent or agents of destruction.

Theories of Extinction & Seeking Patterns

A multitude of factors that are associated with or might contribute to mass extinction have been put forward. A brief overview of proposed agents of biological catastrophe is in order.

Glaciation

Glaciation occurs as a result of global cooling. Much of the Earth's water can be locked up in ice sheets that expand over oceans and land. Evidence for glaciation comes from deposits containing glacial sediments and the disappearance of warmer climate species from the fossil record. Global cooling and the drop in sea levels obviously disrupt many ecological niches. Ocean salinity and oxygen content may also change during periods of glaciation. A quick cooling event may also result in an overturn of ocean water. Cold, nutrient rich, but oxygen poor water may be brought to the surface. This water may be toxic to benthic life in shallow warmer waters. It is clear that glaciation is associated with climate change.

Extraterrestrial Impacts

In 1980 Luis Alvarez (1911-1988), an American physicist, hypothesized that a large extraterrestrial impact had caused the great Cretaceous extinction. A large asteroid could trigger global fires, earthquakes, tidal waves, atmospheric dust, acid rain, and global warming. Atmospheric dust could cause a nuclear winter in which the Sun's light is blocked out to such an extent that plants have problems photosynthesizing. Evidence for the Late Cretaceous impact comes from the presence of a rare element called Iridium found in a layer at the K-T boundary (Cretaceous-Tertiary boundary). Iridium is rare in Earth's crust, but can be common in asteroids and volcanoes fed by the Earth's mantle. Shock quartz or quartz grains that are formed from high pressures are also found in these layers as well as a form of carbon formed under intense heat and pressure. Finally, in 1981 a large crater 65 million years old and of the correct size to fit Alvarez's theory was found in the Yucatan Peninsula of Mexico. The name of this crater is Chicxulub. Some have suggested that asteroids could cause a large distribution of the element nickel, which can prevent plants from photosynthesizing.

Marine Regression

Sea level changes known as marine regressions can cause major disruptions in ecological niches. The movement of the Earth's crustal plates can cause sea level changes. As two plates come together seaways can slowly drain away. Sea levels drop and rise as glacial periods come and go. Sea level changes can also affect the salinity and gas content of the water.

Volcanic Activity

Volcanic activity can fill the air with large volumes of dust and gases causing climate change. Carbon dioxide and sulfur dioxide emissions from volcanic activity act as greenhouse gases. However, sulfur dioxide quickly reacts with moisture in the air forming sulfate aerosols that absorb and scatter sunlight, which can cause global cooling (Wignall, 2001, p. 2). As with asteroids, volcanic activity can produce iridium. In the geologic past there have been extremely large accumulations of intrusive or extrusive igneous rocks within a short geologic time, a few million years or less. These large eruptions of mostly basaltic (mafic) magmas are known as Large Igneous Provinces (LIP) and are unrelated to normal sea-floor spreading and subduction. LIP's occur as continental flood basalts, oceanic flood basalts, ocean plateaus, and volcanic rifted margins (Ernst, 2014).

Methane Clathrate

Methane clathrate is a solid similar to ice in which large amounts of methane are trapped within the crystaline structure of water. Deposits of methane clathrates are found in sedimentary structures at shallow depths under cold or deep oceans and in continental polar permafrost regions. During global warming episodes the release of methane from these repositories could significantly contribute to the warming trend (Wignall, 2001, p. 14).

Cosmic Radiation

Cosmic radiation could increase to dangerous levels from a nearby supernova. This cosmic radiation could cause mutation and increased cancer rates among organisms.

Periodicity

The idea that mass extinction occurs at regular intervals is heavily debated. There have been many attempts to explain the proposed periodicity of mass extinctions, these include: comet showers, the existence of a planet X, the existence of a companion star to our Sun called Nemesis, sudden overturns of the Earth's mantle causing pulses of volcanism, Earth's oscillation through the Milky Way galactic plane, meteor impacts, basalt floods, climatic cooling, marine regressions and species-species interactions (Interactions between species may occasionally lead to an instability that cascades through an ecosystem). Some believe that these periods between extinctions just represent the time it takes for extinction sensitive species to evolve (Stanley, 1987, p. 215). Some of these ideas, such as planet X, a companion to our Sun, and sudden overturns of the Earth's mantle have been discredited (Prothero, 2004, pp. 93 & 94). However, as we look at the "Big Five" we will see evidence pointing to some of these proposed causes.

The Five Major Mass Extinctions

Stanley defines mass extinction as "the extinction of many taxa on a global scale during a brief interval of geologic time" (Stanley 1987, p. 238). Five intervals of extinction stand out as the most devastating. Scientists look for common patterns within these events in the hope of developing a general theory of extinction. We will give a brief overview of the effects and possible causes for the "Big Five."

Ordovician

The marine ecosystems experienced extinction on a global scale towards the end of the Ordovician period. The Ordovician extinction may be second only to the mass extinction that would end the Paleozoic Era. Heavy extinction occurred in the reef communities. Graptolites, bryozoans, brachiopods, nautiloids, and trilobites were especially hard hit. Nearly 25 percent of all animal families were wiped out (Selden & Nudds, 2004, p.36). Over fifty percent of trilobite families went extinct (Nudds & Selden, 2008, p. 69). There is evidence of glaciation and with this a lowering of sea level, and the expansion of cold water adapted species to lower latitudes as the Ordovician extinction event unfolded (Stanley, 1987, pp 71-75). An ocean turn over may have accompanied the cooling event bringing deep ocean water to the surface, which would have been toxic to the sensitive shallow marine benthic community. The Ordovician event took place over a span of 2 million years (Prothero, 2004, p. 90).

Devonian

The mass extinction that occurred in the Late Devonian affected mainly the marine environment with terrestrial plants escaping the crises. It is estimated that up to 75% of marine species and 50% of marine genera were lost (Prothero, 2004, p. 90). Brachiopods, trilobites, conodonts, ammonoid, corals, and stromatoporoids were hit hard. Reef building communities were decimated. Tabulate corals and stromatoporoids would never again be major reef builders after the Devonian crises. The rest of the Paleozoic would see very little reef building. Reef building would recover in the Mesozoic with the appearance of modern corals (Stanley, 1987, pp. 78-79). The Devonian crisis seems to be correlated with cooling. Coral reefs were in decline as cold water glass sponges expanded. Shallow, warm water marine species declined. Freshwater fish that were adapted to seasonal environments survived, while warm water marine fish experienced heavy extinction. As these shallow warm water species declined the stromatolites had a small resurgence in reef building. There is evidence of glaciation and lower sea levels. Both the Ordovician and Devonian cooling events may be tied to the movement of Gondwanaland over the South Pole (Stanley, 1987, pp. 86-89). The cooling event may also explain Late Devonian carbon and oxygen isotope anomalies. A severe cooling would trigger a massive overturn within the ocean. This overturn would bring deep ocean water to the surface. The deep ocean water is nutrient rich, but cold and oxygen poor. The Devonian crises lasted for 4 million years (Prothero, 2004, p. 90).

Permian

The Permian period ended with the largest recorded mass extinction that hit both aquatic and terrestrial environments. It is estimated that 75 to 90 percent of all living species became extinct over a period of 10 million years (Stanley, 1987, pp. 96-97). Sixty percent of marine families became extinct (Palmer, 1999, p. 90). In the marine realm crinoids, brachiopods, bryozoans, and ammonoids were hit hard. Fusulinids, trilobites, graptolites, blastoids, rugose corals, tabulate corals, and eurypterids met with extinction. Among the fish Acanthodians and Placoderms became extinct. Rhipidistians, lobe-finned fish (Osteichthyes) that are the ancestors of land vertebrates also went extinct. Extinction in the marine realm marked a change from a Paleozoic dominated fauna composed of crinoid, coral, bryozoan, and brachiopods to a modern fauna dominated by bivalves, gastropods, and echinoids (Prothero, 2004, p. 86).

Two-thirds of the amphibian and reptile families met with extinction. The larger terrestrial vertebrates did not fare as well. Thirty-three percent of amphibian families went extinct at the end of the Permian (Palmer, 1999, p. 90). Among the amphibians some labyrinthodonts would survive into the Triassic. Lepospondyls (Lepospondyli) amphibians went extinct by the end of the Permian. All but one group of anapsid type reptiles died out. The fossil evidence for diapsid reptiles is sparse during the mid-Permian, although many new groups make their first appearance during the late Permian. The most primitive groups of diapsids went extinct at the end of the Permian (Dixon, 1988, p. 84). The first synapsids were the pelycosaurs, which made up 70% of the vertebrate terrestrial fauna in the early Permian. During the middle Permian another group of synapsids, the therapsid, would evolve and displace the pelycosaurs. Pelycosaurs died out in the middle Permian. Therapsids would lose 21 families at the end of the Permian (Palmer, 1999, p. 90).

For the first time insects suffered a mass extinction. Many of the primitive orders of insects went extinct during the Permian event. Among the fixed-winged insects (Paleoptera) the following orders went extinct: Palaeodictyoptera, Megasecoptera, Diaphanopterodea, and Protodonata. Among the folded-winded insects with incomplete metamorphosis (exopterygota Neoptera) the following orders went extinct: Protorthoptera, Caloneurodea, Protelytroptera, and Miomoptera) (Carpenter & Burnham, 1985, p. 302). Insect fossils found after the Permian belong mostly to modern groups.

Globally, plants experienced their greatest losses during the Permian extinction. Only 9 out of 22 known families survived into the Triassic (Cleal & Thomas, 2009, p. 209). As noted earlier, the swamp forests of the Carboniferous contracted during the Permian. As the clubmosses waned, ferns and primitive conifers expanded to take their place. The change from Paleophytic to Mesophytic flora occurred over a period of 25 million years. Tropical plant ecosystems suffered major disruptions with some extinction at the end of the Permian period. Cordaites went extinct as well as the seed fern *Glossopteris*. The dominant conifer families (Walchiaceae, Ullmanniaceae, and Majonicaceae) of the time went extinct. For a geologically short time, woody coniferous forests were replaced by herbaceous species of clubmosses and quillworts (4-5 million years). In the Triassic, woody coniferous forests of a different type would be reestablished (Kenrick & Davis, 2004, p. 154).

Uranium-lead zircon geochronology has been used to date ash layers, associated with the Siberian Traps, at the Permian-Triassic boundary in Southern China. The results establish a date of 251 Ma (Wignall, 2001, p. 8). The extinction interval is thought to be very short on the order of 165,000 years or less (Prothero, 2004, p. 87). What caused the "mother of all extinctions?"

An increase in dune deposits, evaporite salts, and a lack of coal forming swamps may indicate arid conditions in some terrestrial environments. There is evidence of a marine regression, which would reduce habitat in shallow marine environments. A rapid warming trend occurred at the end of the Permian. A shift in oxygen isotopes may record this event. An increase in O-16 over O-18 indicates global temperatures may have increased by as much as 6^0C. An increase in C-12 found in terrestrial and marine sections could be an indication of increased volcanic activity and massive death in the marine and terrestrial realms (Benton, 2003, p. 38). Like the Ordovician and Devonian events a reduction in the formation of marine limestone and reef building occurred after the Permian extinction. Layers containing abundant pyrite above the limestone layers indicate a low oxygen environment. Onset of flood basalts making up the Siberian Traps occurs at the Permian-Triassic boundary. This LIP formed in northern Asia and may have been the source of carbon dioxide that started a global warming event. As the climate warmed methane may have been released from methane clathrates accelerating the warming trend. The release of these gasses into the atmosphere is called the "big belch" and may have increased temperatures and lowered oxygen levels (Cleal & Thomas, 2009, p. 209). Climate change may have also altered oceanic circulation in such a way as to bring stagnant deep water rich in carbon dioxide and hydrogen sulfide to the surface. The Permian crises would usher in a new era represented by different flora and fauna evolved from the small percentage of survivors who were, at first, cosmopolitan in their distribution.

Triassic

The Triassic ended with mass extinctions in marine and terrestrial environments. The terrestrial extinctions took place millions of years before the marine crises. The Triassic crisis is actually several extinctions that took place over a 17 million year time span (Prothero, 2004, p. 91). Labyrinthodont amphibians and dicynodonts (a group of mammal-like reptiles) went extinct. Land plants were hit hard, especially the gymnosperms with 23 of their 48 known families going extinct during the last third of the Triassic (Cleal & Thomas, 2009, p. 211). In the marine realm placodonts, nothosaurs, and conodonts went extinct. Ammonoids, brachiopods, gastropods, and bivalves took heavy losses. It is estimated that 20% of marine families went extinct during the Triassic crises. Reef growth was greatly reduced as well as marine limestone and dolomite deposition.

What caused the end-Triassic extinction (ETE) 201 million years ago? There is some evidence for sea level changes and some cooling. An abundance of black shales and geochemical anomalies indicate massive oceanic changes. Some believe the rifting of the North Atlantic may have released large volumes of volcanic gasses contributing to global climate change (Prothero, 2004, p. 91). The Central Atlantic Magmatic Province (CAMP) is a LIP that formed from the rifting of Pangea and spans the Triassic-Jurassic boundary. CAMP is associated with the breakup of the supercontinent Pangea and the formation of the Atlantic Ocean basin. At an estimated 11 million km^2 CAMP covers the largest area of any known LIP. It is also one of the most voluminous at an estimated 2 to 3 million km^3.

Remnants of CAMP are found on four continents including North America, South America, Europe, and Africa. Using samples from these remnants Blackburn et al. (2013) demonstrated that zircon uranium-lead geochronology provides a temporal link between the ETE and CAMP. The release of magma and associated atmospheric flux occurred in four pulses over 600,000 years. The earliest known eruptions took place at the same time as the extinction events. Further pulses of CAMP occurred as life was recovering from the extinction event. Although a temporal link between early pulses of CAMP and ETE has been established, we still do not understand the details of how these massive eruptions induced biologic crises on a global scale (Blackburn, 2013, p. 943). As a group, dinosaurs benefited from this extinction event, as they would undergo a great adaptive radiation during the Jurassic period.

Cretaceous

At the end of the Cretaceous, 65 million years ago, 85% of all species would go extinct, making this event second only to the Permian mass extinction (Hooper Museum, 1996). Sixteen percent of marine families went extinct. Ammonoids, belemnoids, rudist bivalves, inoceramid bivalves and many brachiopod groups went extinct. Most of the large marine reptiles (ichthyosaurs, plesiosaurs, and mosasaurs) were lost. Some families of sharks and teleost fishes went extinct. Eighteen percent of terrestrial vertebrate families would go extinct (Siegel, 2000). Dinosaurs, pterosaurs, many lineages of early birds, and some mammals went extinct. In fact most terrestrial animals more than 1 meter in length would go extinct (Nudds & Selden, 2008 p. 169). One third of higher-level plant taxa went extinct and for a short time ferns became dominant over the angiosperms and conifers in North America (Stanley, 1987, p. 157). Some of these organisms mentioned went extinct before the K-T (Cretaceous-Tertiary) boundary, while others were on the decline. Some groups disappeared catastrophically right at the KT boundary. Some interesting ecological patterns can be observed.

The hardest hit marine organisms were free-swimming or surface forms (plankton, ammonites and belemintes). On the sea floor filter feeders (corals, bryozoans, and crinoids) were hit hard while organisms that fed on detritus were little affected. Open water fish fared well. Mollusks with wide geographic ranges had a higher survival rate than those with a small geographic distribution. Tropical species were affected more than those who were cold tolerant. In the terrestrial realm, as we have already mentioned, being large was a disadvantage. The only large land animals to survive were crocodilians (Benton, 2005, pp. 248-251). Amphibians seem not to have been affected by the extinction event. At the family level, 70 to 75% of taxa survived the event (Benton, 2005, p. 255). What contributed to this mass extinction?

Scientists at the University of California at Berkeley including Luis and Walter Alvarez, Frank Asaro, and Helen Michel discovered an iridium anomaly in a fine-grained clay layer in several K-T (Cretaceous/Tertiary) boundary sites around the world (now the Cretacous/Paleogene boundary or K-Pg). These K-T boundaries are found in both marine and terrestrial deposits and show the same succession, an ejecta layer followed by the clay enriched iridium layer (Benton, 2005, p. 250). The group recognized that iridium is abundant in stony meteorites and proposed that the fallout from a meteorite on the order of 10 kilometers could explain the anomaly and possibly the extinction event. Subsequently, a crater was found beneath the Gulf of Mexico off the Yucatan Peninsula during exploration for oil. The Chicxulub crater is of the right size and age. Volcanic activity may also act as a source of iridium. The Deccan Traps in India represent a large terrestrial flood basalt. Ironically, the Deccan Traps would have been positioned on the opposite side of the Earth at the time of the Chicxulub impact.

There is also evidence for climatic changes as well as flora and fauna changes leading up to these events. Many organisms were already on the decline during the Late Cretaceous. Planktonic foraminiferans experienced major losses before the end of the Cretaceous. Calcareous nonoplankton were also on the decline. Ammonoids, inoceramid bivalves, and the reef-building rudists experienced attrition. Multiple lines of evidence, including preferential survival of cold-water tolerant organisms and isotopic ratios, suggest the climate was cooling. There is also evidence to support a decline in abundance and diversity of dinosaurs (Stanley, 1987, pp. 133-171).

However, the iridium anomaly, which in some areas is also associated with shocked quartz grains (quartz grains that bear crisscrossing lines produced by meteorite impacts), glassy spherules close to the impact site (produced from melted material under the crater and then ejected into the air), carbon particles associated with massive fires, the spike in ferns (associated with ash falls), and the Chicxulub crater support that a meteor impact may have caused a final pulse of extinction that occurred on a global scale. Whether this mass extinction was the result of multiple factors or primarily one, its effects on the evolution of life had great consequences.

The largest mass extinction at the end of the Permian period provided reptiles with the opportunity to become the dominant vertebrate life forms on Earth. Roughly, one hundred and eighty-six million years later the second largest mass extinction would take away Mesozoic reptilian dominance and usher in the Cenozoic, an age for mammals. Mass extinctions of the past have severely reduced biodiversity, but ironically have also provided opportunities for survivors to evolve and diversify.

Pulses of extinctions can be seen within each mass extinction event. The timing and duration of these pulses appears to be different for each of the "Big Five." This may indicate that there is not a common cause for mass extinction (Prothero, 2004, p. 93). It is clear that climatic cooling, marine regressions, large igneous provinces, and at least one of the many meteor impacts recorded in the geologic record can be implicated in mass extinction events. The study of extinction is in its infancy, but has major implications for our own time.

A Sixth Mass Extinction?

The study of mass extinctions and their causes is important because it allows humans to look to the past to anticipate future possibilities. Programs designed to monitor extraterrestrial objects that may impact Earth, such as NASA's Near Earth Object Program are steps to possibly diverting such objects (NASA, 2013). USGS monitors volcanic activity around the world (USGS, 2008). At this point the monitoring of volcanic activity can save lives in local areas. The monitoring of both local and global threats is in its infancy; however, these efforts are informed by knowledge of past events deciphered from the geologic record.

Many scientists argue that we are in the midst of a sixth mass extinction as revealed by contemporary extinction rates that are on the order of 100 to 10,000 times greater than background rates calculated from the fossil record (Holsinger, 2011, p. 8; Center for Biological Diversity, 2013). The sixth mass extinction event may have started in the Pleistocene and continued in the Holocene with the loss of mammals known as megafauna roughly 50,000 to 10,000 years ago. Both climate change and the proliferation of humans are thought to be factors in the extinction of megafauna.

Today, the Holocene extinction event continues with humans playing an ever-larger role. The global human population is now at 7 billion (Worldometers, 2013). Humans need resources and space for their growing populations. The quest for these needed resources and space play a role in this possible sixth mass extinction. Habitat destruction, invasive species, pollution, burning fossil fuels, and commercial hunting place incredible stress on ecosystems worldwide.

Alterations to the environment in North America since 1600 illustrate how humans can affect entire ecosystems. In the lower 48 states since the year 1600 over 90% of old growth forests have been cut down, over 50% of wetlands have been drained, and over 98% of grasslands have been plowed under (EPA: Wetlands, 2013; EPA-Smart Growth, 2013; Global Deforestation, 2010; Pieper, R.D. (2005). Similar patterns of habitat destruction can be found worldwide (Holsinger, 2011, p. 5).

As humans have spread over the globe a massive biotic exchange has taken place. Humans have directly and indirectly introduced non-native species to many ecosystems. Non-indigenous species that have an adverse effect on the ecosystem to which they are introduced are referred to as invasive species. The introduction of invasive plants, animals and disease has had devastating effects on both human and non-human populations across the globe (Crosby, 2003; National Invasive Species Information Center, 2013; Natural History Museum 2013).

Human use of fossil fuels is having a global impact on the atmosphere and climate. The burning of fossil fuels has released large amounts of carbon dioxide thereby increasing the amount of greenhouse gases in the atmosphere. The rise in greenhouse gasses can be correlated with an increase in Earth's surface temperature (EPA-Causes of Climate Change, 2013). Coal burning power plants and the combustion of gasoline in cars contribute to the formation of acid rain. Our massive use of fossil fuels leads to other kinds of pollution, such as oil spills.

In fact, the industrial revolution has created human societies that consume Earth's resources at increasingly alarming rates. Waste products resulting from this massive consumption often pollute the environment. Humans create government agencies in an attempt to manage the production and disposal of waste products that pollute the environment (EPA, Home 2013).

Oceans cover 71% of the Earth's surface and are not immune to the effects of human activity. Many marine ecologists rank commercial overfishing as the greatest threat to our oceans (DUJS, 2012). Humans even try to keep track of the threats posed to Earth's biological diversity and attempt to organize solutions with governments worldwide (IUCN, 2009). In this fact, there is hope.

Conclusion

A naturalistic interpretation of rock and fossil genesis allowed us to decode principles that govern the formation of the geologic record. Applying these principles through a system of independent empirical verification has afforded us a glimpse of the 3.8 billion year history of life on Earth, a history that includes our own origins.

Modern humans (*Homo sapiens*) range from 160,000 years ago to the present (Benton, 2005, p. 385). The Cro-Magnon people of Europe (40,000-30,000 years ago) are associated with Upper Paleolithic tools, carved art objects, and the cave paintings of France. Archaic *H. sapiens* increasingly used bone, ivory, and wood to make more sophisticated tools. Benton (2005, p 387) recognizes major benchmarks in human evolution:

- Bipedalism (10-5 Ma)
- Enlarged Brain (3-2 Ma)

- Stone Tools (2.6 Ma)
- Wide Geographic Distribution (2-1.5 Ma)
- Use of Fire (1.5 Ma)
- Art (35,000 years ago)
- Agriculture (10,000 years ago)

We can include two more benchmarks, the awareness of the evolutionary history of life on Earth as revealed by the geologic record (200 years ago) and the awareness of our own species role in a mass extinction event (50 years ago).

Scientists and philosophers debate whether or not evolution is progressive. Is there a trend in efficiency, complexity, and intelligence? When examined in detail the fossil record of each group of organisms, even humans, exhibits an evolutionary pattern that is very bushy. The branch that ends with humans is only one of thousands of mammalian evolutionary lines; however, it is special in that it represents a way for the universe to know itself. Modern humans are the first organisms to comprehend and appreciate the history of life on Earth.

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