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Life and Global Climate Change on Earth

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Introduction

The history of life on Planet Earth, fueled by the solar radiation in which it has bathed throughout the eons of geologic time, records great periods of richness and the evolutionary appearance of an incredible diversity of life forms, punctuated by short intervals of wholesale destruction and partial collapses of the biosphere. Many of these destructive events are related to carbon and its exchange between reservoirs in the ground, (magmatic sources and from the shallow burial of organic matter that is life's debris) and in the atmosphere and oceans. This scenario is happening today as the combined effects of the human burning of fossil fuels is transferring bulk amounts of carbon from the earth into the atmosphere. The exchange (that is, the flux of carbon between the earth and the atmosphere and its effects on life) can be readily determined by observing the ratio of two types of carbon, carbon-12 and carbon-13[1]. Plants preferentially uptake the lighter carbon during photosynthesis and the formation of their sugars and large organic molecules (Fig. 1). During times of abundant burial of plants such as the Pennsylvanian Period, the remains of great ancient forests were buried in the ground where we get most of our coal from today, the relative amount of carbon-12 in the atmosphere decreases, shifting the carbon-12/13 ratio toward the heavier side. The removal of carbon-12 from the

[1] Almost all elements have two types of particles in their nucleus: protons and neutrons. The exception is the protium form of hydrogen, which only has a proton. The neutrons act to hold the nucleus together as it wobbles and vibrates, but too many or too few neutrons make a nucleus unstable, which results in radioactive decay. All carbon has 6 protons, but can have different numbers of neutrons, which determine its different isotopes. The number of protons plus the number of neutrons is the atomic mass number. There are two stable forms of carbon that presumably were formed billions of years ago by some star during nuclear fusion, carbon-12 and carbon-13. Other forms of carbon, such as carbon-14, are radioactive and must be continually created in the atmosphere.

atmosphere indicates that there was less carbon in the form of greenhouses gases, which cooled the planet. Shifts of other isotopes, such as oxygen[2], show that the reduction in the relative amount of carbon-12 is associated with a decrease in temperature. The opposite situation is also true, with an increase in carbon-12 indicating the influx of more carbon into the atmosphere and strengthening of the greenhouse effect and resulting in warmer temperatures.

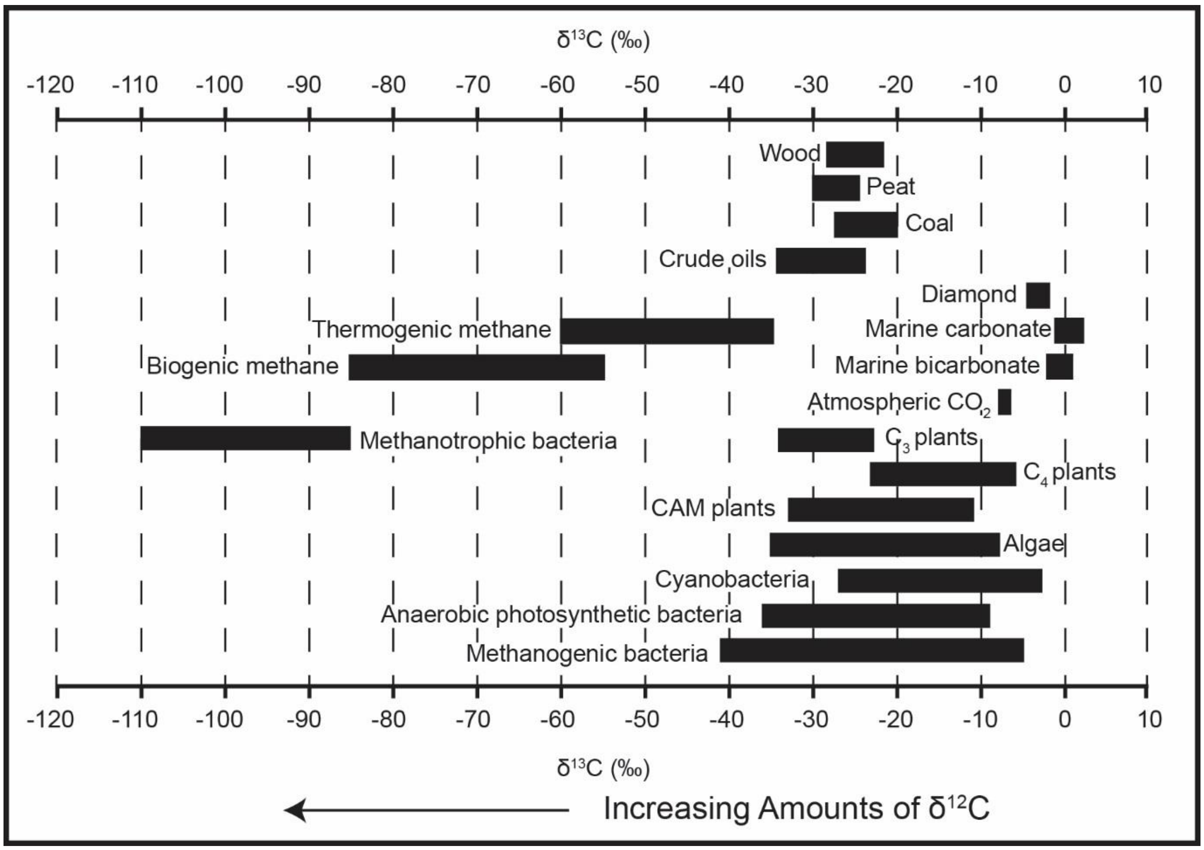

Figure 1. Carbon stable isotope ratios of various carbon-based substances.[3] *All plants are enriched in* δ^{12}C, *so burial of plant material causes a reduction in the relative amount of* δ^{12}C *and consequent increase in the relative amount of* δ^{13}C *in the rock record. Reduction of the amount of* δ^{12}C *indicates a reduction in the amount of* CO_2 *in the atmosphere, weakening of the greenhouse effect (GE) and global cooling. The reverse is also the case: spikes in the amount of* δ^{12}C *in the rock record indicate*

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[2] Two of the stable isotopes of oxygen that are very useful as a thermometer of ancient temperatures are oxygen-16 and oxygen-18. This ratio has long been known to be directly related to temperature, with an increase in the amount of oxygen-18 indicating cooler conditions during the formation of rocks and fossils. Many studies have used this information to infer the past conditions on the surface of the planet, particularly during times of mass extinctions.

[3] A. Vieth and H. Wilkes, "Stable Isotopes in Understanding Origin and Degradation Processes of Petroleum," in *Handbook of Hydrocarbon and Lipid Microbiology*, ed. K.N. Timmis (Berlin: Springer-Verlag, 2010), 97-111.

the release of CO_2, strengthening of the GE and global warming. The light values of methane products on the left are used to define intervals of the release of methane, which is a more powerful greenhouse gas than CO_2.

In his classic 1981 paper, Jack Sepkoski[4] published data demonstrating that there were five major extinction events during the Phanerozoic (Fig. 2), which is the time since the appearance of hard parts in the record of life about 540 million years ago. His analysis did not include our current human-induced mass extinction, which was not well understood at the time. We are now in the sixth mass extinction that is unprecedented in the history of our planet, one that is more severe than any of the others up to this point and is entirely caused by one species—humans. Our activities have such a global effect that it has ushered in a new epoch of geologic time, the Anthropocene. This paper presents data indicating that five of the six mass extinctions are related to shifts in the carbon isotope ratios of the planet and that there are direct analogues of our current extinction event in the geologic past. The exception is the extinction event that resulted in the demise of the dinosaurs, which appears to have been mainly caused by the effects associated with a meteorite impact. Throughout this essay, please refer to Figure 2 for the timing of the mass extinctions and to Figure 3 for the paleogeographic configurations at the time of the mass extinctions.

[4] J.J. Sepkoski, “A Factor Analytic Description of the Phanerozoic Marine Record,” *Paleobiology* 7, no. 1 (1981): 36-53.

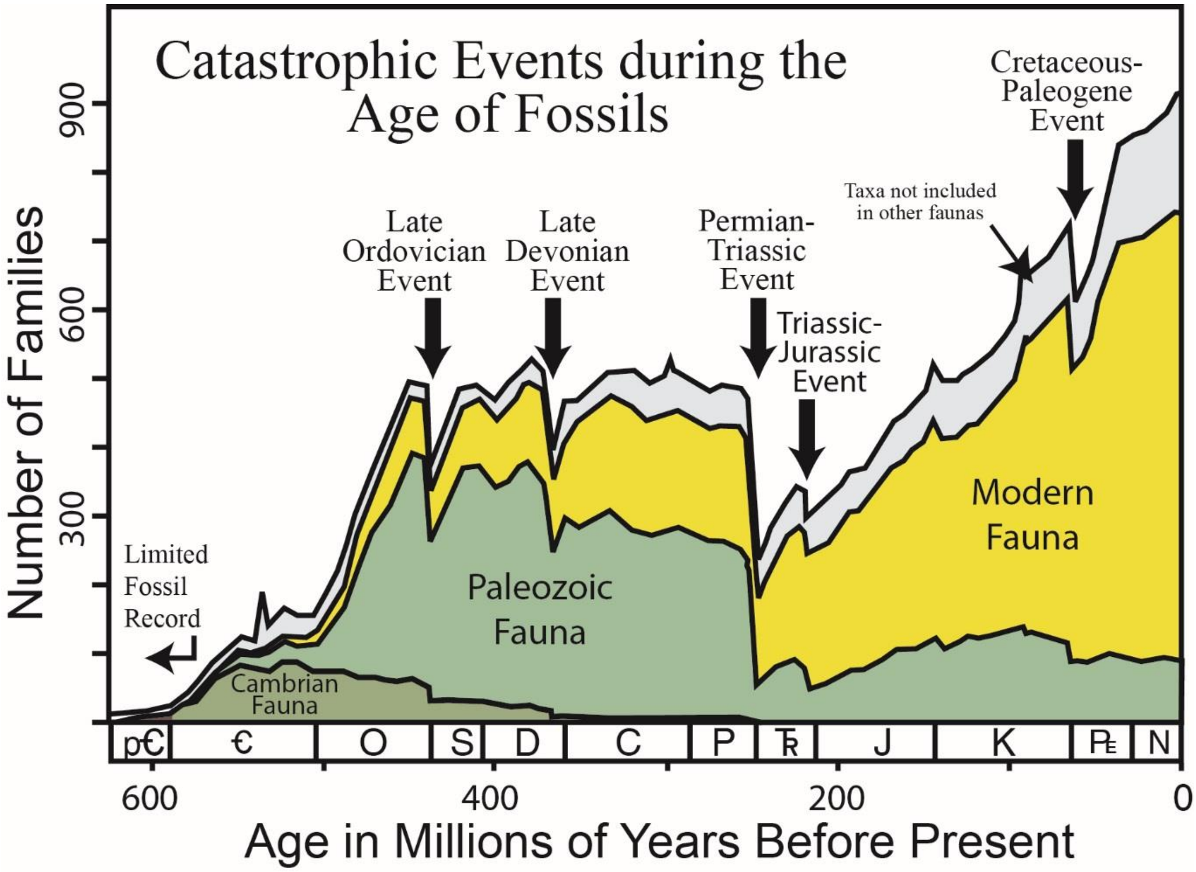

Figure 2. Sepkoski's (1990) evolutionary faunas, showing the diversity of families of marine fossils, the three evolutionary faunas (plus the taxa not included in those faunas), and the five major extinction events in Earth's history. Symbols along the bottom of the chart represent geologic time intervals and include, from left to right, the Precambrian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleogene and Neogene.

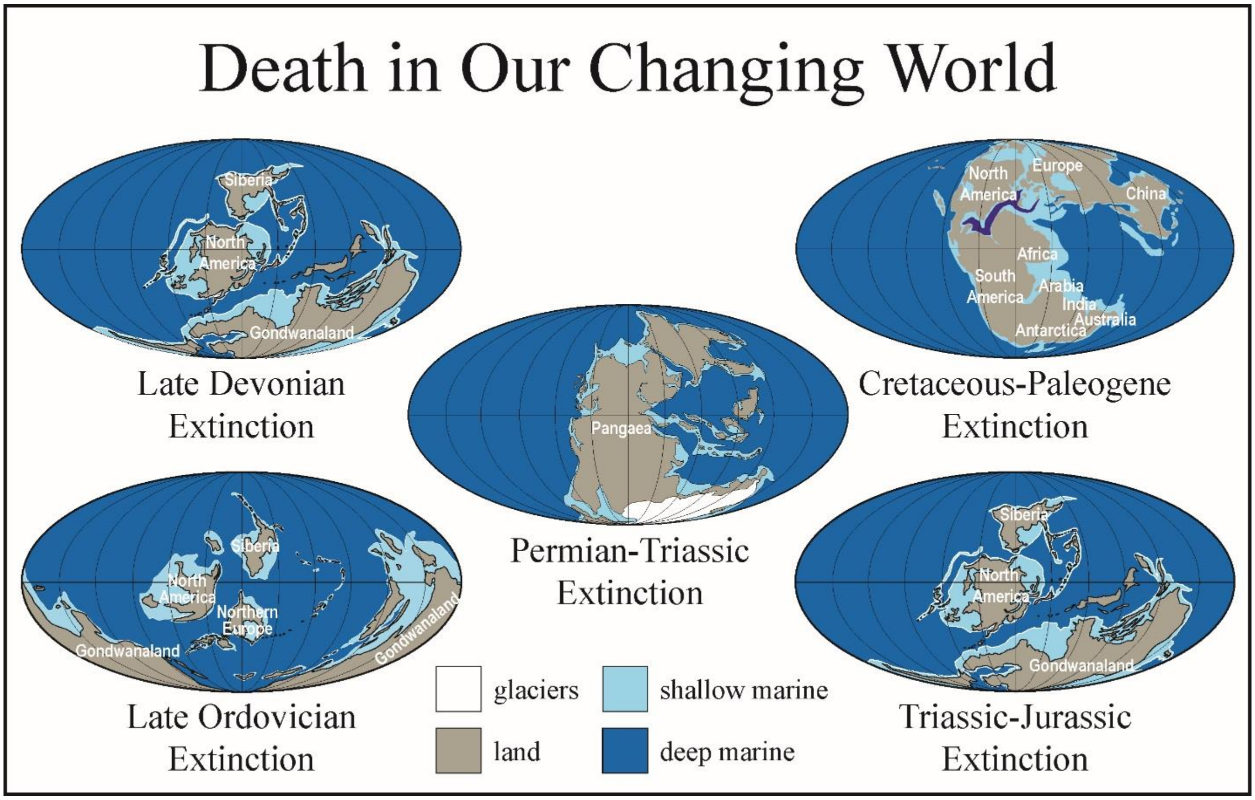

Figure 3. Global paleogeographic configurations of the continents during the times of mass extinction. Maps redrafted after Blakey[5].

Mass Extinctions as Random Events

Throughout the history of life on Earth, there have been many extinction events that have altered the structure of life, most of which were small. However, a few resulted in near-total rearrangement of the types of life that existed; these are termed mass extinctions. Generally, these mass extinctions resulted in the demise of at least 50% of the kinds of life forms on the planet, while one (the end-Permian extinction 251 million years ago) was considerably more devastating than that, causing more than 95% of the species becoming extinct[6] and requiring

[5] "Colorado Plateau Geosystems," *Colorado Plateau Geosystems*, Last modified May 2015, http://cpgeosystems.com/index.html.

[6] D. Erwin, *Extinction: How Life on Earth Nearly Ended 250 Million Years Ago* (Princeton: Princeton University Press, 2006), 320.

nearly five million years to recover from. There are parallels between that extinction event and our current one, which is a main theme of this paper.

As devastating as the end-Permian extinction event was, humans would not be on Earth without it to remove ancient life forms and replace them with new ones. There are vast intervals of time during which little changes occurred. In north Alabama where I live, for example, the Mississippian rocks (roughly 320 million years old) are richly fossiliferous, with a world-class, distinctive fauna including extremely abundant crinoids, fenestrate bryozoans, productid brachiopods, and others. Several years ago, I had the opportunity to visit the Permian Basin of West Texas and New Mexico and was surprised to see some of the same fossils as in Alabama, although those Permian rocks are about 50 million years younger. This is not to say that there was no extinction or evolution during this time, but there were no whole-scale changes in the types of life forms on the planet. Essentially all of those life forms would become extinct very abruptly a few million years later. The devastating event 65 million years ago that brought to a close the age of dinosaurs (and many other highly-evolved animals) allowed for the evolution of mammals, which had been around for more than 140 million years, to rapidly diversify. Thus, the role of extinction in the evolution of life today cannot be overestimated, but in our anthropocentricity, we do not wish for this to happen to humans.

How can we assess the impact of humans on planet Earth? One of the best clues is to look at the carbon cycle, as each of the mass extinctions is associated with changes in the ratios of carbon. Indeed, carbon is a very sensitive indicator of the health of inhabitants on our planet. The arrival of Europeans to North America in 1492 and subsequent population collapse due to diseases, war, enslavement, and famine (which reduced the population from approximately 61 million in 1492 to 6 million people by 1650) and the near-cessation of farming and reduction in fire use lowered the atmospheric level of CO_2 by 7-10 ppm[7].

Understanding the Evidence for Global Climatic Changes

Isotopes

Many of the clues to the global extinction events may be related to changes in the composition of the atmosphere, although the precise cause-and-effect relations are far from completely understood. Circulation of the oceans and atmosphere is coupled, so it acts as a system, with fluxes of huge volumes of common compounds such as carbon dioxide and water. Exchange of these compounds takes place not only near the surface of the oceans, but is driven to great heights and depths as one giant circulating machine. Thus rocks deposited on the land or in the sea can reflect the chemical composition of the planet.

Global climatic patterns are directly linked to deep ocean circulation. In our present world, frigid waters near the surface at high latitudes drive deep ocean circulation, with a constant flow of dense, frigid, well-oxygenated water descending into the ocean basins. In the polar regions, warm, deep ocean circulation can weaken or shut down, leading to widespread anoxic conditions, even in shallow areas. Such anoxia can be devastating to life.

Estimates of the condition of the atmosphere in times past are based largely on the relative percentages of two isotopes: carbon and oxygen. In this essay, we will consider only the carbon isotope signal. Isotopes are different forms of the same element, differing only in the numbers of

[7] J.O. Kaplan et al., "Holocene Carbon Emissions as a Result of Anthropogenic Land Cover Change," *Holocene* 21, no. 5 (2010): 775-791.

neutrons in the nucleus. Generally, isotopes of the same element have similar chemical properties because they have the same numbers of reactive electrons, but the difference in the number of neutrons makes them of different masses, and this affects the rates of certain important chemical reactions. The amount of each isotope in rocks is compared to the ratio in a globally-agreed standard. The lower-case Greek letter delta, δ, symbolizes the atomic mass of a particular substance in reference to this standard, which happens to be, randomly enough, a Late Cretaceous fossil known as *Belemnitella americana* from the Pee Dee Formation of South Carolina. Oxygen isotopes are extremely useful for certain types of studies, particularly as paleo-thermometers, but the ratios of the two stable (non-radioactive) isotopes ($\delta^{16}O$ and $\delta^{18}O$) can be affected by several factors, including glaciation and salinity, and generally are not used to determine the state of the atmosphere *in toto*.

Carbon is extremely useful in studying the condition of past atmospheres (Figure 4). The two carbon isotopes used are carbon-12 ($\delta^{12}C$) and carbon-13 ($\delta^{13}C$), which are measured in ratio. Nearly all of the carbon on Earth is $\delta^{12}C$, so only trace amounts of $\delta^{13}C$ must be measured. High values of $\delta^{13}C$ are generally considered to be the result of the removal of significant amounts of the lighter isotope ($\delta^{12}C$) from the atmosphere, inferring the lowering of the amount of carbon dioxide and cooling of the planet due to the weakening of the greenhouse effect. Elevated levels of the lighter isotope $\delta^{12}C$ generally indicate raised levels of atmospheric carbon dioxide and a warming interval. Four of the five mass extinction events in geologic time are strongly correlated to changes in the carbon isotope ratio, as is our current mass extinction.

For this essay, the carbon isotope signals have been compiled from a variety of sources and calibrated to the most current global geologic time scale[8]. All references to dates of geologic phenomena are in reference to this time scale (Fig. 4).

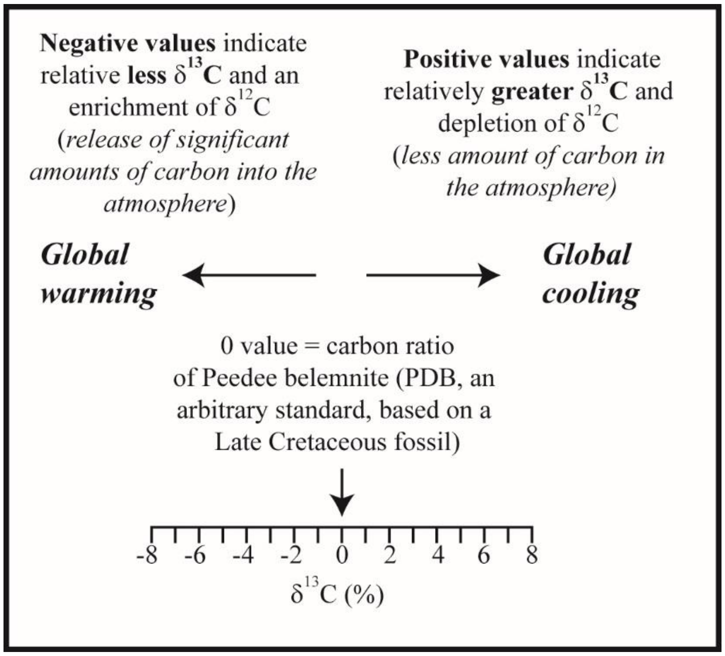

Figure 4. The relationship between carbon isotopes and global temperatures.

What Are these Catastrophic Events and What Caused Them?

Late Ordovician Catastrophe

The beginnings of the kinds of life forms we are familiar with emerged slightly over 540 million years ago, and thus began the Phanerozoic Eon, the age of abundant life. The first period of the Phanerozoic was the Cambrian, during which many bizarre kinds of animals appeared then disappeared in the sea, never to be seen again. When the Ordovician began, about 488 million years ago, marine life began the greatest climb in diversity in Earth's history. Within a few

[8] F.M. Gradstein et al., 2012, *The Geologic Time Scale* (Amsterdam, Elsevier, 2012): 1176.

million years, the seas came alive with great reefs, swimming animals and predators, and ancestors of stocks that would last for hundreds of millions of years.

After the initial burst in diversification, a stasis was reached (Fig. 2). Life had reached a plateau in diversity and changed little for millions of years. Then, quite abruptly at the end of the Ordovician about 445 million years ago, there were major perturbations in the Earth system that brought much cooler waters to the low latitudes, formed glaciers, lowered sea level, and killed many of the kinds of life adapted to the warm climates that had prevailed. The specific cause of both the rapid cooling event and the equally rapid return to warm conditions is not well understood, although it is clear that there were major shifts in atmospheric carbon isotope ratios (Fig. 5) that seem to indicate a reduction in carbon dioxide in the atmosphere (note the increase in $\delta^{13}C$, which indicates a reduction in $\delta^{12}C$, which in turn indicates a reduction in atmospheric CO_2). Many workers consider that glaciation was caused by the southern continents (Gondwana) moving over the South Pole[9], resulting in global cooling and a drop in sea level. Whatever the cause, the planetary shocks lasted perhaps half a million years and not only eliminated 60 percent of the invertebrate fauna, but cleared the way for new forms to evolve. These changes were significant enough to mark the end of a major period in Earth's history. The end-Ordovician event is the second most severe mass extinction in geologic time.

[9] S.M. Stanley and J.A. Luczaj, *Earth System History*, 4th ed., (New York: W.H. Freeman, 2014) 608.

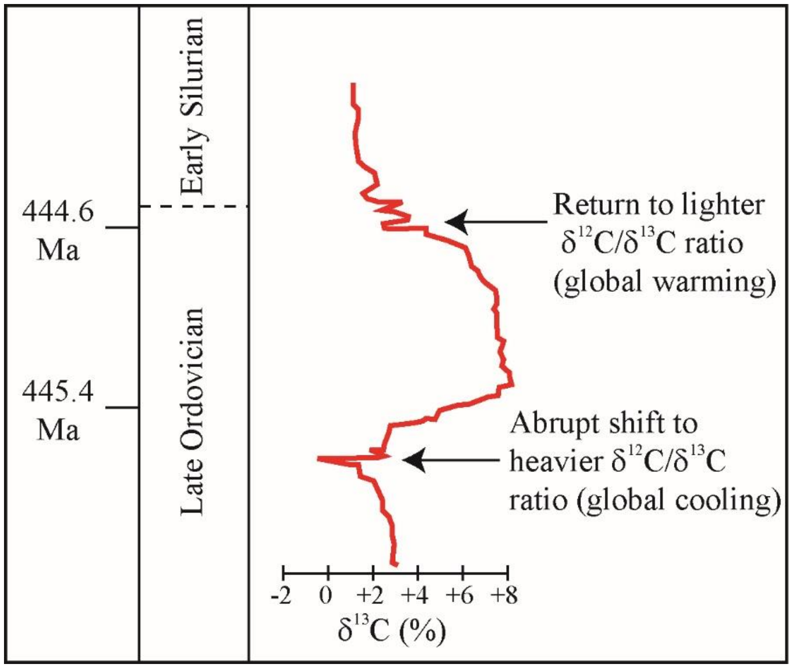

Figure 5. These carbon isotope data, collected from strata exposed in Nevada, indicate a major reduction in atmospheric carbon dioxide and weakening of the greenhouse effect[10].

Late Devonian Catastrophe

The Late Devonian extinction event (around 374 million years ago) is unusual in that the Devonian-Mississippian boundary is not placed at the event itself but at the end of the epoch *after* the event. All of the other extinction events, quite logically, define boundaries between major geologic time periods. It was hardly an "event," as life declined over some three million years. Many life forms, including giant reef builders, were hit so hard they never recovered, although many squeaked by for another 200 million years before succumbing to the end-Paleozoic extinctions.

[10] W.B.N. Berry, R.L. Ripperdam, and S.C. Finney, "Late Ordovician Extinction: A Laurentian View," *Geological Society of America Special Paper 356 (2002)* 463-471.

The record of carbon and oxygen isotopes reveals the most fascinating part of the Late Devonian catastrophe: the close coupling of the atmospheric, oceanic, geologic, and biologic systems on Earth. Major perturbations occur almost synchronously in carbon (Fig. 6) and oxygen isotopes in the stratigraphic record. A heavier $\delta^{13}C$ ratio indicates burial of substantial amounts of carbon (and presumably lowering of atmospheric carbon dioxide) and an abrupt shift to shallower water conditions, all occurring at the same time. Viewed as a system, it seems clear that the lowering of atmospheric levels of carbon dioxide is linked to colder water conditions *and* the drop of sea level, because of the growth of glaciers associated with the colder conditions. (Note: Although glaciers are not generally shown on paleogeographic maps, Late Devonian glacial deposits are known to exist in many parts of the world, particularly in South America, which was over the South Pole during the Late Devonian.)

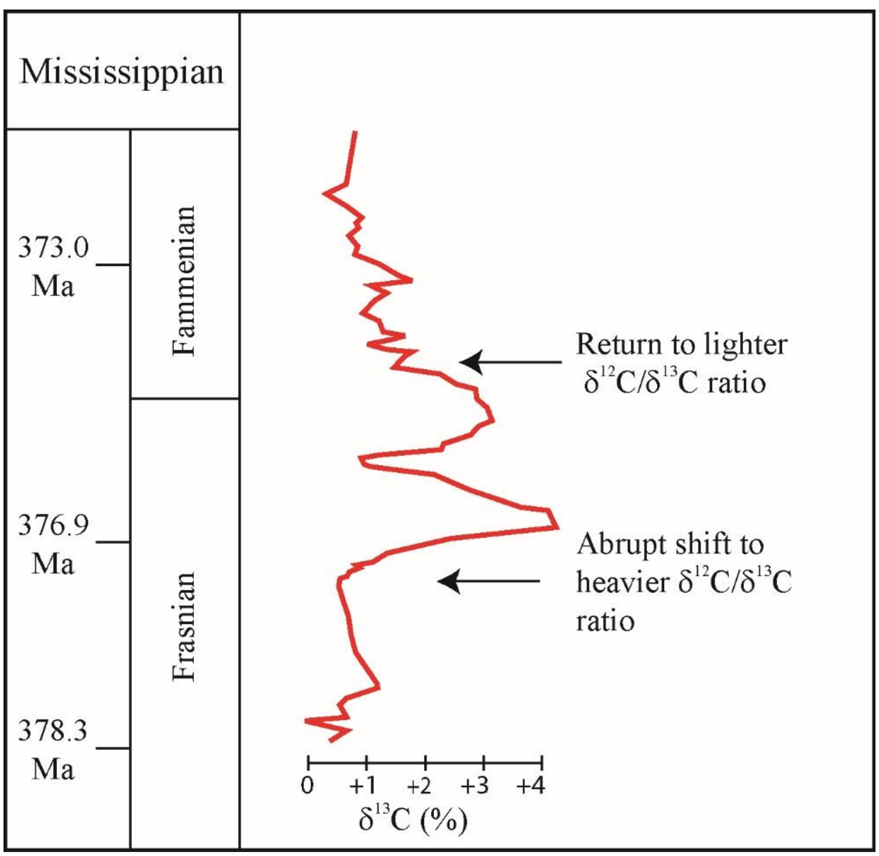

Figure 6. Shifts in carbon isotope values during the end-Ordovician extinction event collected from samples in Germany[11].

Many Earth scientists think it is no coincidence that these global perturbations are related to the emergence of land plants. For more than four billion years, the land surfaces of Earth were barren until the evolution of plants that appeared in the Silurian that were capable of piping nutrients and water through a vascular system from the ground. By the Late Devonian, these earliest vascular plants had grown to the size of trees, and giant forests spread out over the land surface unrestrained. It is thought that the spread of land plants increased the rates of weathering of rocks on the continents, which requires copious use of atmospheric carbon dioxide. So, in this scenario, the evolution of land plants caused greatly increased rates of erosion of continental rocks, that caused the lowering of carbon dioxide in the atmosphere, that caused colder water conditions in the oceans, that caused the buildup of glaciers, that caused the lowering of sea level, that caused the mass extinctions. The precise cause-and-effect triggers are, however, far from understood, as they are even for the relatively recent Pleistocene glaciations.

Permian-Triassic Catastrophe

Now we come to the greatest catastrophe in Earth's geologic history, the end-Permian extinction, also known as "The Great Dying." This event is also the most closely allied to the changes being brought about by human activity. The most disturbing part is that human-caused changes to the planet are occurring at a faster rate than that which occurred at the end of the Permian. Further, it appears that the initial loading of the atmosphere by CO_2 lasted a relatively short time interval,

[11] M.M. Joachimski and W. Buggisch, "Conodont Apatite δ^{18}Signatures Indicate Climatic Cooling as a Trigger of the Late Devonian Mass Extinction," *Geology* 30, no. 8 (2002): 711-714.

but was followed by a cascading series of events that lasted for millions of years. In a geological blink of an eye, 96 percent of marine species and 70 percent of land species disappeared.

It has long been known that the end-Permian extinction was accompanied by major shifts in both carbon and oxygen isotopes, with carbon ratios becoming very enriched in $\delta^{12}C$ (indicating the release of massive amounts of CO_2 and probably methane) into the atmosphere and oxygen ratios becoming enriched in the lighter isotope $\delta^{16}O$ (indicating global warming)[12],[13],[14],[15] (Figure 7). The tough part was to refine the time resolution of the sequence of events in both the marine and non-marine realms, which is not an easy task given that the events occurred about a quarter of a billion years ago. Recent information, particularly from researchers at MIT working in geologic sections in China, has clarified what happened.

[12] R.J. Twitchett et al., "Rapid and Synchronous Collapse of Marine and Terrestrial Ecosystems During the End-Permian Biotic Crisis," *Geology* 29, no. 4 (2001): 351-354.

[13] J.L. Payne et al., "Large Perturbations of the Carbon Cycle During the Recovery from the End-Permian Extinction," *Science* 305 (2004): 506-509.

[14] P. Gorjan, K. Kaiho, and Z.Q. Chen, "A Carbon-isotope Study of an End-Permian Mass-Extinction Horizon, Bulla, Northern Italy: A Negative $\delta^{13}C$ Shift Prior to the Marine Extinction," *Terra Nova* 20 (2008): 253-258.

[15] G. Luo et al., "Stepwise and Large-Magnitude Negative Shift in $\delta^{13}C_{carb}$ Preceded the Main Marine Mass Extinction of the Permian-Triassic Crisis Interva," *Palaeogeography, Palaeoclimatology, Palaeoecology* 299 (2011): 70-82.

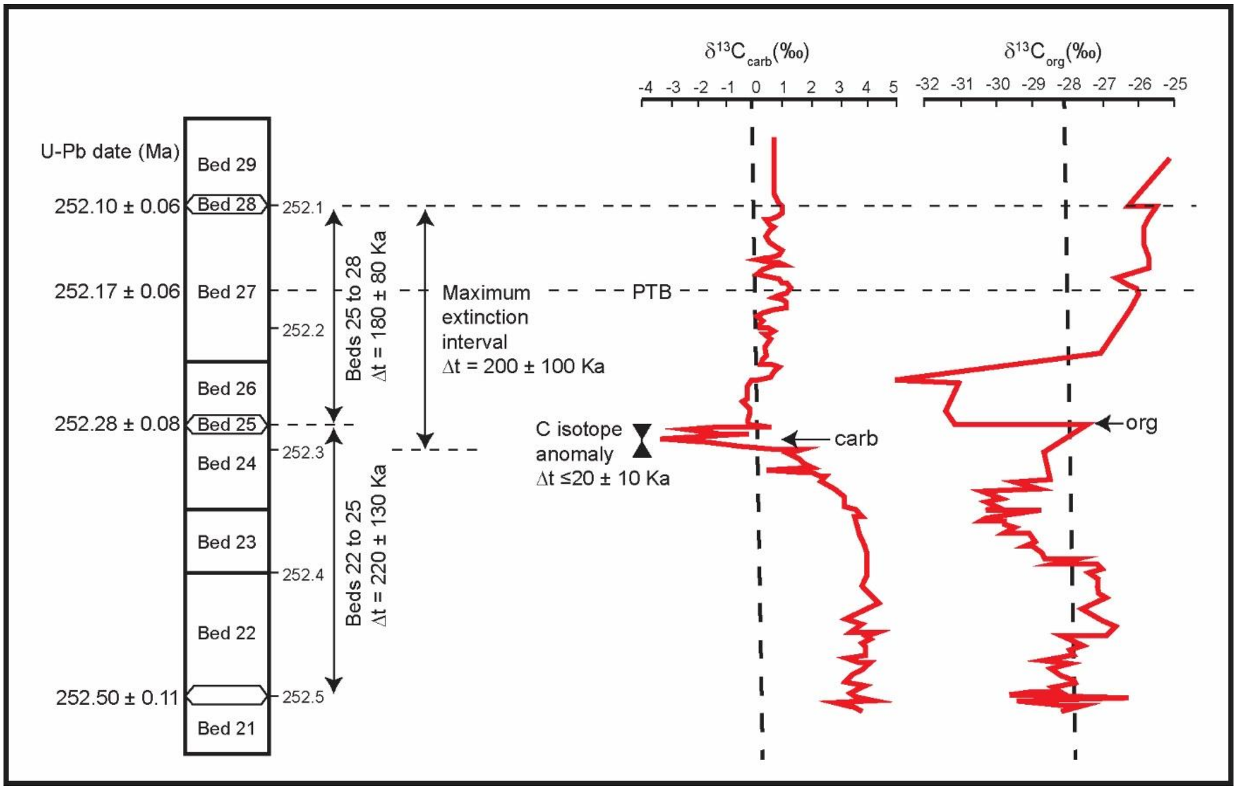

Figure 7. Carbon isotope shifts associated with the end-Permian extinction events[16]. Ma is mega-annum (millions of years), PTB is Permian-Triassic Boundary, C_{carb} is inorganic carbon and C_{org} is organic carbon. Note that the spike in organic carbon occurred after the negative spike in $\delta^{12}C$, demonstrating that the release of massive amounts of $\delta^{12}C$ later trigger mass death.

Slightly more than 252 million years ago and about 300,000 years before the main extinction event, gigantic, explosive volcanic eruptions occurred in Siberia. The total volume of eruptions and intrusions is almost unimaginable, it being enough to cover the United States in kilometer-deep magma[17]. These volcanic rocks are known as the Siberia Traps. Most unfortunately for life on Earth, this magmatic activity erupted through massive carboniferous coal deposits (the same ones we burn today in our coal-fired power plants) and ignited them. This combustion loaded the

[16] S.Z. Shen et al., "Calibrating the End-Permian Mass Extinction," *Science* 334 (2011): 1367-1372.

[17] Chu, J., "Siberian Traps Likely Culprit for End-Permian Extinction," *MIT News on Campus and Around the World*, Last modified November 24, 2015, http://www.dailygalaxy.com/my_weblog/2013/11/the-great-dying-new-insights-into-the-most-severe-mass-extinction-in-earths-history.html.

atmosphere and oceans with isotopically light CO_2 from the burning of the plant debris and heavy metals from the fly ash. Estimates of this event indicate that it spanned only 20,000 years[18], but led to a catastrophic sequence of events.

The first effect was a dramatic and sudden warming of the atmosphere by at least 10°C[19] due to the greenhouse effect associated with the injection of massive amounts of CO_2 into the atmosphere. The world's ocean (there was one main ocean at that time due to almost all of the continents being together in the supercontinent Pangea) became acidified due to absorption of CO_2. The increased atmospheric temperature caused the ocean in the polar regions to warm considerably, which eliminated the downwelling of cold, oxygen-rich water, shutting down global oceanic circulation and causing stagnation. As the vast amount of dead organisms rotted, aerobic microbes consumed the organic debris, but during this respiration process, oxygen quickly became depleted in the ocean and it became anoxic, leading to the proliferation of sulfate-reducing bacteria and the release of massive amounts of hydrogen sulfide into the atmosphere[20]. During the oxidation process, oxygen was used up and the level of oxygen in the atmosphere also plummeted[21]. The increased atmospheric temperatures caused increased rainfall due to high levels of oceanic evaporation, but this rain was more acidic than before because it combined with the high levels of CO_2 in the atmosphere. This acidic rain caused increased weathering of rocks at the surface, which sent more nutrients into the ocean, that fed explosions

[18] S.Z. Shen et al., "Calibrating the End-Permian Mass Extinction," *Science* 334 (2011): 1367-1372.

[19] M.M. Joachimski et al., "Climate Warming in the Latest Permian and the Permian-Triassic Mass Extinction," *Geology* 40, no. 3 (2012): 195-198.

[20] L.R. Kump, A. Pavlov, and M.A. Arthur, "Massive Release of Hydrogen Sulfide to the Surface Ocean and Atmosphere During Intervals of Oceanic Anoxia," *Geology* 33, no. 5 (2005): 397-400.

[21] P. Ward, *Gorgon: Paleontology, Obsession, and the Greatest Catastrophe in Earth's History* (New York, Viking Press, 2005), 288.

of life such as algal blooms, the decay of which accelerated the depletion of oxygen[22]. Evidence from Canada, which was downwind from the Siberian eruptions, indicate loading of the world's ocean by heavy metals from the fly ash created during combustion of the coal[23], which further poisoned the already stinking marine environment. In summary, it appears that an initial rapid and massive loading of the atmosphere CO_2 caused a poisoning of the ocean and atmosphere that killed most of the living organisms on both the land and in the sea, which led to further deteriorating conditions that lasted for millions of years.

If all of these factors were the result of an initial, powerful injection of CO_2 into the atmosphere caused by the burning of fossil fuels, then we can expect a similar Earth response to occur by continued burning of fossil fuels by humans.

Triassic-Jurassic Catastrophe

The Triassic-Jurassic extinction event is perhaps the most difficult one for most people to get their heads around, for several of the groups that were wiped out are not familiar to most of us and it's difficult to assess the significance. One of these groups is the conodonts, which are one of the most important fossils for dating the Paleozoic extinctions. In almost all cases, these remains consist only of a set of tiny teeth that belonged to small, wormy-looking predators that had existed for hundreds of millions of years. Another group that became extinct is called therapsids, which were generally dog-sized animals that are thought to be the ancestors of all modern mammals. The relation between the therapsids and modern mammals is as enigmatic as

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[22] K.M. Meyer, "$\delta^{13}C$ Evidence that High Primary Productivity Delayed Recovery from End-Permian Mass Extinction," *Earth and Planetary Science Letters* 302, no. 3-4 (2011): 378-384.

[23] S.E. Grasby, H. Sanei, and B. Beauchamp, "Catastrophic Dispersion of Coal Fly Ash into the Oceans During the Latest Permian Extinction," *Nature Geoscience* 4 (2011): 104-107.

the corals described earlier. Although mammals are known to have existed throughout the age of dinosaurs, the bulk of their fossil record consists of small teeth and jaws of tiny animals that lived in the shadows of the dinosaurs and remained an insignificant part of the fossil record.

Perhaps the greatest benefit of the Triassic-Jurassic extinction was to the dinosaurs. After the disappearance of the therapsids, dinosaurs evolved and diversified to become one of Earth's most spectacular groups of animals, dominating the land biotas for more than 140 million years. The immensity of this length of time is almost incomprehensible, and would have continued if not for the event 65 million years ago.

So what happened? The record of the carbon isotopes (Fig. 8) indicates that there was a major environmental shift very close to 200 million years ago during which massive amounts of light carbon ($\delta^{12}C$) were released into the atmosphere, causing major disruptions in both the marine and terrestrial realms. The source of this carbon appears to be associated with one of the major events in Earth's history: the breakup of the supercontinent of Pangaea and the opening of the Atlantic Ocean, in this case the South Atlantic. This extinction event is relatively short, lasting less than 600,000 years[24]. If it had not been for this event, there would never have been a *T. rex*, a velociraptor, or any of the great long-necked dinosaurs—or any of us.

[24] S.P. Hesselbo et al., "Terrestrial and Marine Extinction at the Triassic-Jurassic Boundary Synchronized with Major Carbon-cycle Perturbation: A Link to Initiation of Massive Volcanism?" *Geology* 30, no. 3 (2002): 251-254.

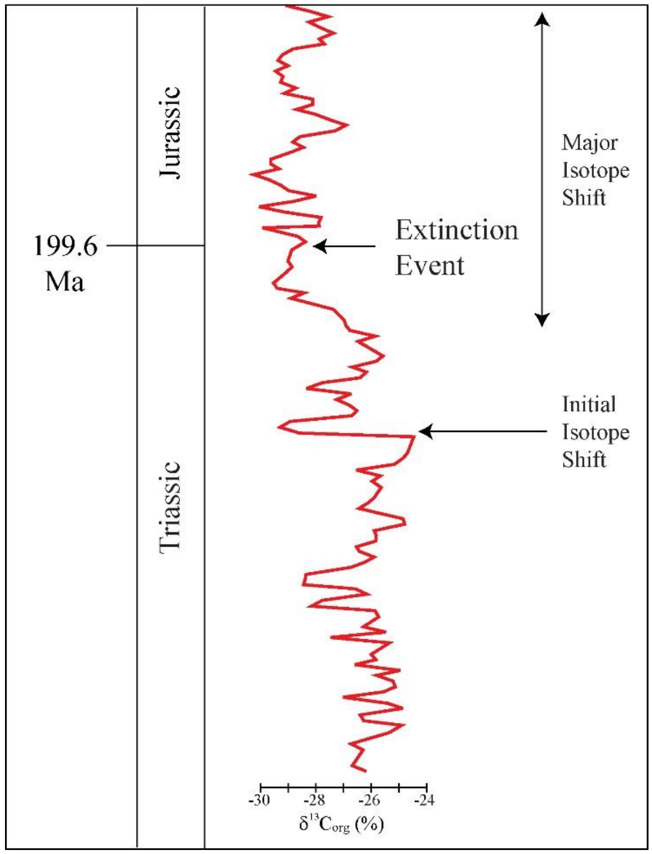

Figure 8. Carbon isotope shift near the Triassic-Jurassic boundary[22].

Cretaceous-Paleogene Catastrophe

Perhaps the best known of the extinctions is the one that killed off the dinosaurs at the end of the Cretaceous Period. The cause of this extinction is now well-established and was the result of a meteorite impact in northwest Yucatán. I have seen the deposits of this event in western Cuba, where hundreds of meters of debris, including building-sized boulders, rained down from the skies. The effects of this event on life are vexing: whereas some groups of organisms that had been around for hundreds of millions of years (dinosaurs and ammonoids, for example) were wiped out forever, other groups were completely unaffected. In any case, if this extinction event had not occurred, if that meteorite had not crossed Earth's orbit at that exact moment, dinosaurs might still reign supreme.

The Anthropocene

One of the most exciting fields in the geosciences today is the study of the Anthropocene, which is a proposed new epoch of geologic time in which human activity is of global significance. Humans have clearly had a global influence and generally not in a positive way. We have caused massive changes in the distribution of sediment, such as clearing away entire mountains in our search for coal; cleared forests for shipbuilding, farming, pastures, fuel, and many other reasons, all of which has resulted in a change in the stratigraphic distribution of spores and pollen; caused widespread deposition of human-manufactured products such as plastics; nearly completely rearranged the biogeographic distribution of plants and animals; caused mass extinction due to the destruction of habitats, hunting, and many other causes; and transferred massive amounts of carbon and metals from the ground to the atmosphere and oceans, among other global changes. Human activities have released 555 petagrams of carbon[25] (where one Pg = 1 billion metric tons, so 555 Pg = 555 billion metric tons), which can clearly be seen in figure 9. (Aside: If 555 billion metric tons of *anything* were pumped into the atmosphere, we should expect some sort of side effect, much less it being a greenhouse gas.) In figure 9, notice that the values of $\delta^{13}C$ are decreasing to the right, starting at around 1850 and accelerating until today, which is a reflection of the accelerating influx of $\delta^{12}C$ from the burning of fossil fuels.

[25] S.L. Lewis and M.A. Maslin, "Defining the Anthropocene," *Nature* 519 (2015): 171-180.

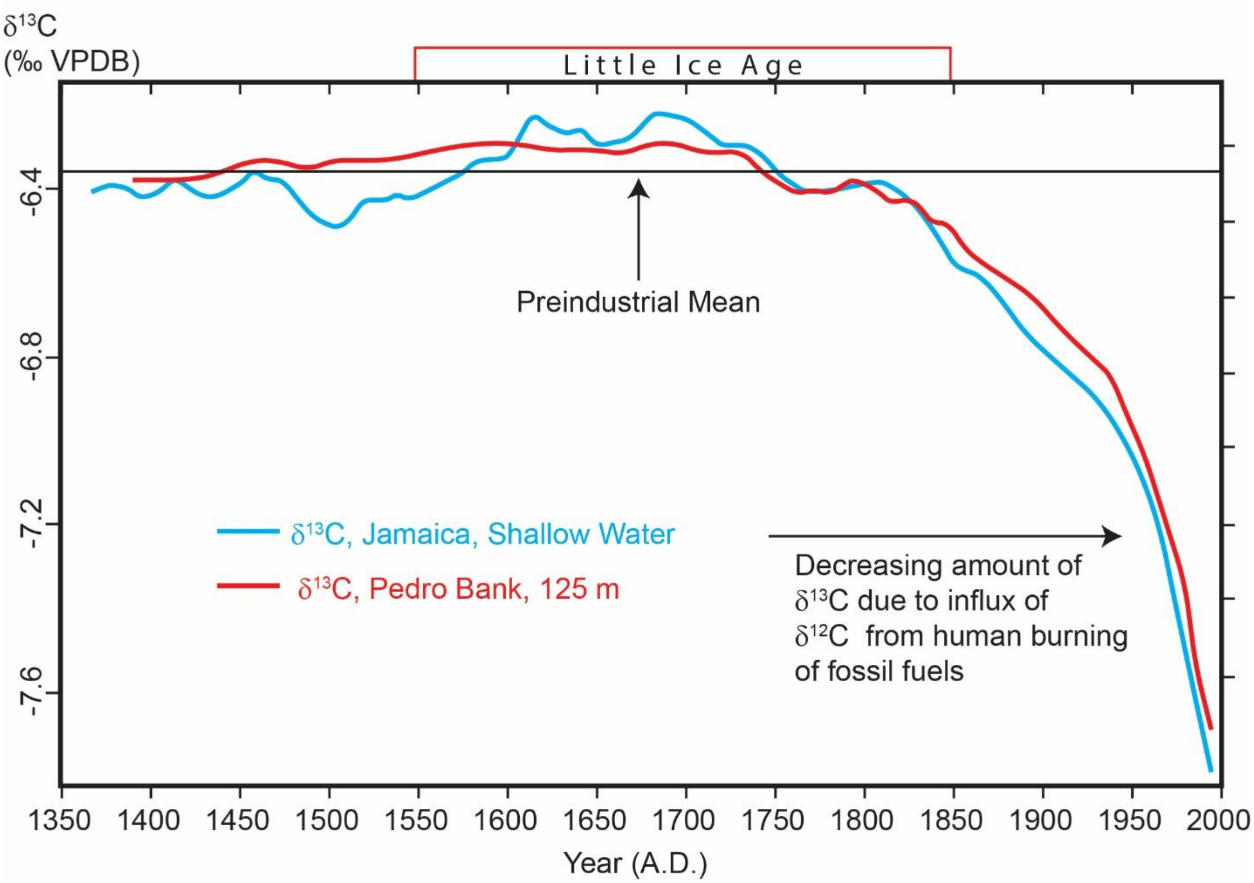

Figure 9. The amounts of δ13C in rocks and reefs deposited during the last 650 years in Jamaica. VPDB refers to Vienna Pee Dee Belemnite, which is a standard for carbon ratios that has been adopted since the exhaustion of the original Pee Dee Belemnite from North Carolina. This figure demonstrates that the increase in CO_2 *content in the atmosphere is due to human-caused emissions from the burning of fossil fuels.*

Another way to look at the influence humans have had on Earth is to look at the natural cycles of glaciation and CO_2 through time. Figure 10 shows data collected from the Dome C ice core in Antarctica, with CO_2 level peaking at about 280 ppm over the course of the last 800,000 years. The level of CO_2 in March 2016 was 404.83 ppm and peaked at 409.34 ppm on April 10, 2016[26], a level not seen on the planet for millions of years. Projections for future levels, based on a series of scenarios and published by the Intergovernmental Panel on Climate Change, is presented in

[26] Michael McGee, "CO2-Earth," ProOxygen, last modified 2016, https://www.co2.earth.

comparison. At this point, it seems unlikely that the concentration of CO_2 will be less than 600 ppm by the end of the century and very well may be 800 ppm, with catastrophic consequences that may last millions of years. Recent calculations show that the greenhouse gas emissions have delayed the next Ice Age by at least 100,000 years[27]. Certainly, with the extinction of so many species (as many as 100,000 per year[28]), Earth will never be the same. As the increased concentration of CO_2 in the atmosphere and in the rock record is gradual, where exactly do we place the "golden spike?" The questionable placement for the beginning of the Anthropocene based on emissions of greenhouse gases makes it an unlikely criterion.

[27] A. Ganopolski, R. Winkelmann, and H.J. Schellnhuber, "Critical Insolation-CO_2 Relation for Diagnosing Past and Future Glacial Inception," *Nature* 529 (2016): 200-205.

[28] WWF, "How Many Species Are We Losing?" World Wide Fund for Nature, last modified 2016, http://wwf.panda.org/about_our_earth/biodiversity/biodiversity/

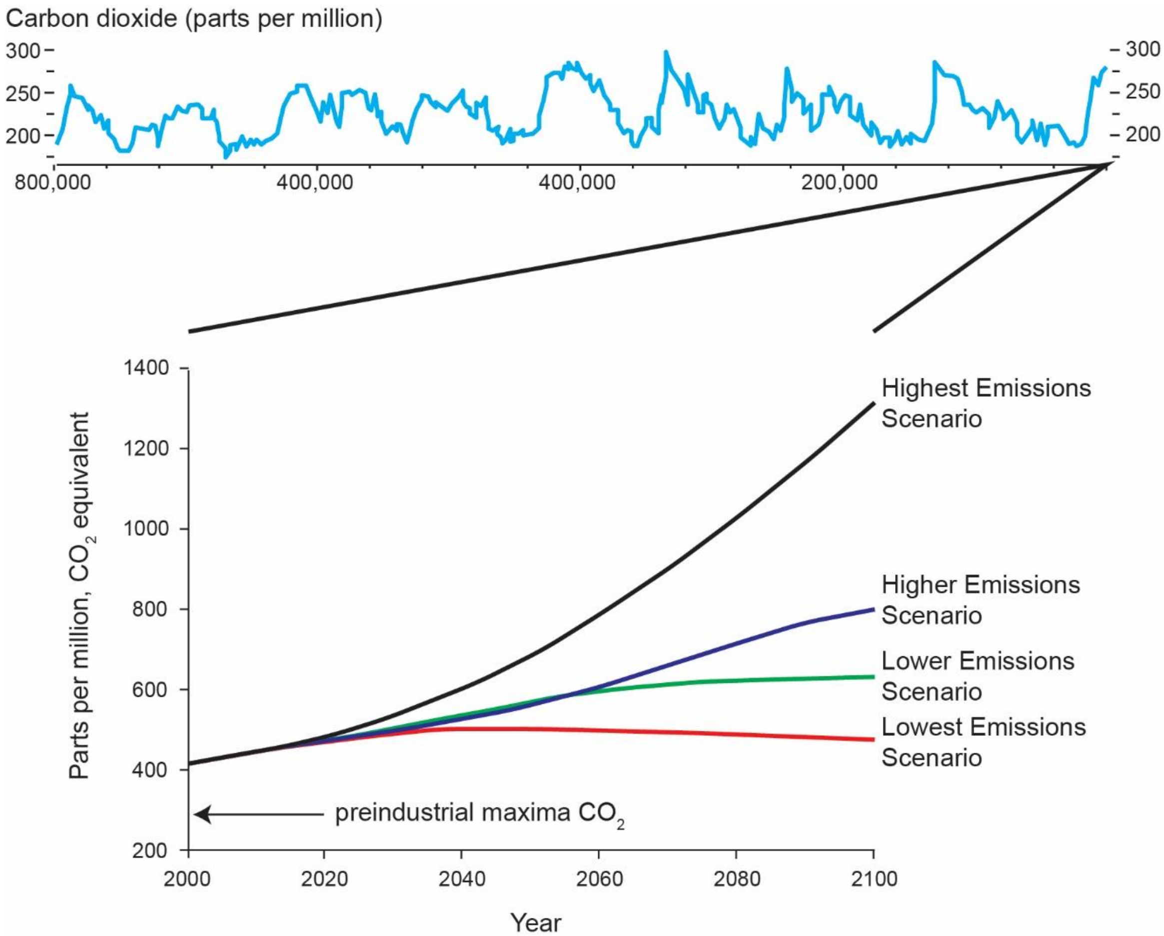

Figure 10. Concentration of CO_2 during the past 800,000 years based on ice core data. The cycles are driven by orbital cycles called Milankovitch cycles, and include the precession (Earth's wobble that cycles every 20,000 years), obliquity (which is the amount of wobble and cycles every 41,000 years) and the eccentricity of Earth orbit (cycling from more circular to more elliptical shape every 100,000 years). Note that the concentration of CO_2 has not peaked above about 280 parts per million in the past 800,000 years. Data from the top graph taken from http://earthobservatory.nasa.gov/Features/CarbonCycle/page 4.php, and lower graph taken from https://www3.epa.gov/climatechange/science/future.html.

In fact, there are two main contenders for the beginning of the Anthropocene: a significant decrease in the amount of CO_2 in the rock record in the year 1610 and a spike in $\delta^{14}C$ that occurred in 1964 due to the cumulative effects of the testing of atomic bombs, both effects of human activities. The cause of the decrease in atmospheric carbon was noted earlier in this essay, that is, the collision of the Old World and the New World. Europeans had been living in crowded conditions for millennia, catching diseases, passing them to others and building resistance. The

Native Americans were generally much more spread out and isolated from the European diseases, foremost of which was smallpox, although there were other diseases such as measles, scarlet fever, typhoid, and influenza. From 1492 until 1650, disease, famine, war and enslavement caused the Native American population to collapse, dropping from 61 million to 6 million people[6]. This resulted in less farming and fewer fires, both of which tended to transfer CO_2 from the air to be buried in the ground. The greatest drop occurred in the year 1610, when the level dropped from what had been a steady average of about 282 ppm to about 272 ppm; the data are primarily derived from two ice cores in Antarctica[23]. It was during this time interval that the global distribution of plants and animals started to shift, which was also due to human activity, in the Columbian Exchange, which includes almost all of the plants and animals that we eat or use for labor[29]. The dip in atmospheric carbon is the most prominent feature in pre-industrial atmospheric CO_2 records over the past 2000 years[30] and is therefore a precise target for the beginning of the Anthropocene.

The other contender is a spike in $\delta^{14}C$ that occurred as a result of the detonation of atomic devices. In fact, this bellicose activity doubled the amount of $\delta^{14}C$ in the air[31]. There are other secondary correlated markers of radioactive elements associated with the bomb testing. These chemical changes are part of The Great Acceleration that began about 1950, in which many socio-economic and Earth systems parameters show a dramatic increase. These parameters

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[29] A.W. Crosby, "Columbian Exchange: Plants, Animals, and Disease between Old and New World," *The Encyclopedia of Earth*, 2009, last modified May 5, 2015, http://www.eoearth.org/view/article/151313/.

[30] C. MacFarling Meure et al. "Law Dome CO_2, CH_4 and N_2 Ice Core Records Extended to 2000 years BP," *Geophysical Research Letters* 33, no. 14 (2006).

[31] R. Eveleth, "Nuclear bombs made it possible to carbon date human tissue," *SmartNews*, 2013, Last modified February 19, 2013, http://www.smithsonianmag.com/smart-news/nuclear-bombs-made-it-possible-to-carbon-date-human-tissue-20074710/?no-ist.

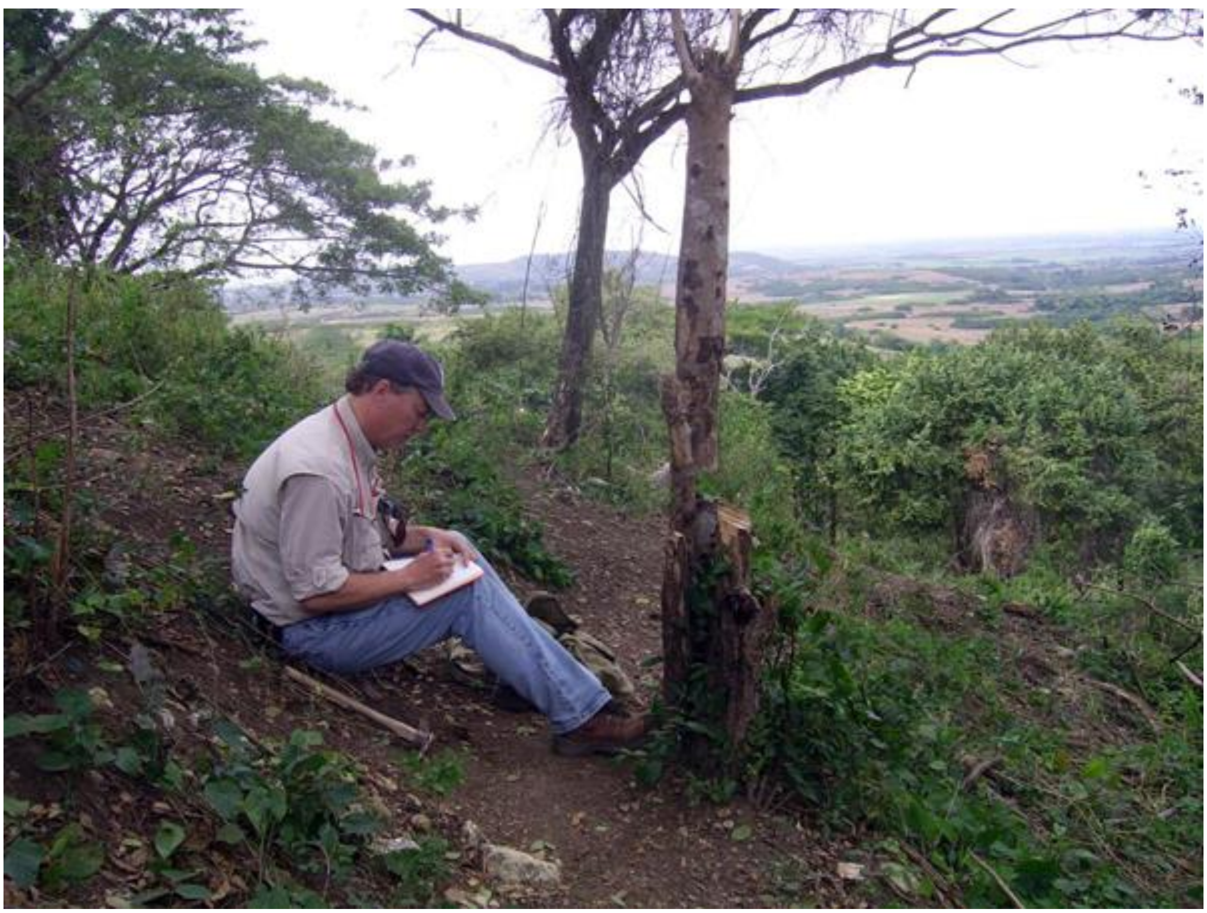
include population, fertilizer consumption, water use, CO_2, N_2O, CH_4, marine fish capture, nitrogen to coastal zones, and many others. Although it is clear that the environmental degradation that is causing the current mass extinction began to accelerate in 1950, we are left with the precise placement of the "golden spike," and the $\delta^{14}C$ is a good candidate.

Summary and Conclusions

Life on planet Earth has enjoyed times of great fecundity extending for millions of years that were punctuated by relatively brief catastrophic events that closed the door on the old forms and opened up new pathways for life to evolve. For most of geologic time, these extinction events are very poorly understood, as the main types of life were relatively simple bacteria that left a poor fossil record. More complex life forms that were capable of secreting hard parts that left a good fossil record emerged about 542 million years ago at the beginning of the Cambrian. Since that time, there have been five catastrophic intervals during which most of the kinds of life were eliminated forever. These were the end of the Ordovician (about 445 million years ago), the near-end Devonian (about 372 million years ago), the end-Permian (about 252 million years ago), the end-Triassic (about 201 million years ago) and the end-Cretaceous event (about 65 million years ago). The end-Permian event was the worst—until now.

The end-Permian extinction event has strong parallels to the current human-caused mass extinction. The triggering event for the end-Permian event was the eruption of great quantities of magma in Siberia and the burning of the vast coal fields in the region that loaded the atmosphere with CO_2 and other greenhouse gases, dramatically warmed the planet, shut down oceanic circulation, poisoned the atmosphere and ocean, and lead to the collapse of life on the planet. It took millions of years to recover from this event. Today, humans are burning those same fossil fuels, loading the environment with greenhouse gases, cutting down forests, and poisoning the oceans and freshwater, which not only degrades our planet but attenuates her ability to renew herself. Our effects will last millions of years, and in fact forever in the case of the hundreds of thousands of species that have already become extinct directly because of human activity. At this point, the best we can hope for is to minimize the damage by turning to a sustainable lifestyle. We make choices every day that can help or hinder our effects, including our diet, transportation, and the manufactured products we purchase.

Choose wisely.



Dr. Mark Puckett in Cuba, December, 2010

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