The end-Permian extinction

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Abstract

The end Permian extinction was the greatest mass extinction of the Phanerozoic Era. It impacted marine and terrestrial plants and animals. Although the rate of the extinction has been controversial in the past, recent evidence suggests that the extinction progressed in two pulses approximately 5-12 million years apart. The second pulse of the extinction is marked by a sharp temperature spike and associated changes in carbon, oxygen, strontium and sulfur isotope ratios. There is evidence of severe marine anoxia and mass volcanic eruptions around this same time period.

Many theories about the cause of the extinctions have been put forth. They include the possibility of volcanism, ocean anoxia, sea-level fluctuations and a bollide impact as the main triggering event. All these theories have evidence supporting them, but no single theory has gained universal acceptance. It is possible that the extinctions were caused by a series of events.

Recent evidence suggests a mass extinction that occurred 2 million years ago was triggered by supernovae explosions within 130 light years of Earth. This paper discusses the possibility of a similar cause for the first pulse of the end-Permian extinction. Furthermore, it is suggested that recovery patterns from the first extinction pulse predisposed surviving species to extinction during the second pulse, when opposite environmental conditions were created by massive volcanism. The paper concludes by speculating about the role of extraterrestrial influences in initiating climate change and mass extinctions.

Introduction

The end of the Permian period is defined by the single greatest known extinction in Earth's history. At no other point in the past 3.9 billion years did life come so close to being permanently extinguished from the planet as it did 250 million years ago. Recent estimates suggest that over 50% of all animal families and 90-95% of all species disappeared during the extinction event. The extinction occurred in both marine and terrestrial environments.

On land, the extinction is known to have affected plants and animals, including amphibians and therapsids, (Erwin, 1990; Erwin, Bowring and Jin, 2000). It is the only mass extinction event known to have included insects (Erwin, 1995; Ward and Brownlee, 2000), and has been described as Athe single most important event affecting insect diversity, separating the Paleozoic Insect Fauna from the Modern Insect Fauna at the highest taxonomic levels@ (Labandeira & Eble, in press). Eight insect orders became extinct during the end-Permian extinction, compared to only 2 orders that have gone extinct since. Extinction patterns among terrestrial vertebrates are at present uncertain, but many species of amphibian and reptiles were eliminated.

In the water, the Permian/Triassic (P-Tr) boundary marked the end of approximately 54% of marine families and possibly up to 96% of all marine species (Erwin, 1990). The extinction event led to the disappearance of metazoan reef communities for an estimated seven to eight millions years. Sessile filter feeders were particularly hard hit. There was a major reduction in diversity of brachiopods, echinoderms and tabulate and rugose corals, while blastoids and trilobites disappeared completely (Erwin, et al, 2002).

Ever since the Permian period was first described by geologist Roderick Impey Murchison in 1841, the cause of the end-Permian extinction has been controversial. Even the rate of extinction has been the subject of debate, with some scientists asserting that the decline was gradual--occurring over a period of 5 to 10 million yearsCand others arguing that it was abrupt, perhaps even as short as a thousand years or less. Recent evidence, however, has dramatically influenced the debate, and much debate is currently focusing on the possibility that the extinction was caused by a series of events triggered by the impact of a large meteor or comet. This paper will review the debate about End-Permian extinction and examine some of the new evidence that is beginning to influence the discussion.

Time Period

There is no universally recognized stratigraphic scheme for representing the time stages of the Middle and Late Permian, but the Middle Permian is often called the Guadalupian stage and the Late Permian the Lopingian. Substage names, however, often vary according to the geographic region being described. For the purposes of this paper the time scale proposed by Weidlich (2001) will be used. The 2 substages most important to this review are the Capitanian and the Changhsingian (also spelt Changxingian). The end of the Changhsingian substage is generally accepted as the P-Tr boundary. In this paper it will be assumed that the Capitanian substage covers the time period from approximately 265 to 260 million years ago, with the Changhsingian spanning the time between 253.4 and 251.4 million years ago. These dates, however, are not universally agreed upon.

Ecological Context

Geology and Tectonics

For most of the Permian period all of Earth's continents were joined together in the supercontinent Pangea. The assembly was most complete during the Middle and Late Permian (Weidlich, 2001). The supercontinent began to break up near the end of the period. This break-up led to many large-magnitude events of stress release. Additionally, the end-Permian world is known to have experienced massive basaltic eruptions, particularly the hot-spot eruptions in Western Siberian around 250 million years ago (Golonka, 2002).

The Tethys was bordered by the Eurasian landmass in the North and by Gondwana in the south, creating many potential reef areas. However, continental blocks drifting northward across the Tethys disrupted many of these. The northward drift of the Euramerican plate out of the tropical zone also led to the demise of many reef systems (Weidlich, 2001).

Climate

The mid-to-late Permian period was marked by major climatic change. In general, the climate became warmer and drier, but exhibited increased seasonal and latitudinal variability. Seasonal temperature variation in the temperate zone tended to be more extreme inland without the stabilizing effect of nearby ocean water. Inland areas also were generally more arid. Toward the end of the period this warming trend was briefly reversed, and parts of Pangea drifting toward the North and South Poles, (eastern Australia, Antarctica and Siberia), experienced glaciation (Erwin, 1990). At the Permian-Triassic boundary, however, there is evidence that suggests there was a sharp temperature spike that lasted into the beginning of the Triassic period. Megamonsoons were common during this period (Weidlich, 2001), although other areas experienced increased desertification, as evidenced by the sudden cessation of coal formation (Erwin, et al, 2002).

Volcanism

The end of the Permian period was a time of increased volcanism, including a massive continuous eruption in Siberia forming what is known today as the Siberian Traps, or the Siberian flood basalts. The total flood basalts represent a volume of 2-3 x 10^6 km^3 of magma, covering an area almost two thirds the size of the continental United States in basalt 100m to 3000m thick (Erwin, et al, 2002). The volcanism associated with the flood basalts injected a continuous stream of dust and ash into the atmosphere, possibly blocking sunlight worldwide and creating a prolonged Anuclear winter@ (Conaghan, Shaw and Veevers, 1994).

Sea Level

The subject of sea-level fluctuation is controversial. Many scholars assert that sea levels generally fell during the Middle and Late Permian (Weidlich, 2001) but this view is not universal. Some, suggest that sea levels fell only until the end of the Middle Permian and then rose (Jin, 1994; Hallam and Wignall,1999). Currently there is no consensus that the sea-level fluctuations were global or synchronous (Weidlich, 2001). These differing sea level trends may have been local. Clearly, there were devastating drops in sea-level at the end of the Middle Permian. Many shallow epicontinental seas were drained and their habitats obliterated, although whether this led to more than just localized extinctions is not currently known. The Tethys, however, may have experienced an increase in sea level (Jin, 1994; Hallam and Wignal, 1999) that may have led to a significant decline in benthic groups and their associated carbonate platforms (Erwin, et al, 2002).

Hallam and Wignal (1999) offer evidence from several known Permian-Triassic boundary (P-Tr) sites around the world that suggest the sea-level drop ended by the end of the Middle Permian and rose steadily during the Upper Permian. They suggest that the end-Permian extinction occurred at the period of sea-level highstand, and assert that the extinction could not have occurred as a result of sea-level drop.

Chemostratigraphy

Carbon. Information about the End-Permian extinction has been gained from examination of carbon data trapped in carbonate rocks that formed near the P-Tr boundary. There is a brief positive shift in the $\delta^{13}C/ \delta ^{12}C$ ratio in the stratigraphic record just below the P-Tr boundary. This positive shift is followed by a pronounced drop that continues into the Early Triassic (Erwin, 1990). The change in the carbon isotope ratio is so profound that the negative shift is often used as a marker for the P-Tr boundary in the marine and terrestrial stratigraphic record, and it has been proposed as evidence of a major marine anoxic event. However, there is still some controversy as to whether the shift is globally synchronous (Erwin, et al, 2002).

It is also possible that the drop in the $\delta ^{13}C/ \delta ^{12}C$ ratio at the P-Tr boundary is associated with a massive release of methane hydrates from clathrates in ocean sediments. Since methane is formed by bacterial processes, it is low in $\delta ^{13}C$. A massive influx of methane into ocean water could account for this drop. Moreover, methane is a greenhouse gas. On a large enough scale, its release into the atmosphere would increase greenhouse induced warming and could create the distinctive temperature spike seen at the P-Tr boundary. Krull, Retallack, Campbell and Lyon (1999) present evidence that supports this possibility through chemostratigraphic analysis of the Maitai Group of sandstone outcroppings in New Zealand. There is a striking similarity between the carbon isotope and temperature curves for the P-Tr boundary and those seen at the Late

Paleocene thermal maximum, a period known to have experienced a massive methane release (Brassell, 2003).

Marine Anoxia. Marine anoxic events are characterized by a sudden depletion of oxygen in marine waters, which can lead to the suffocation of marine species. A shift in the carbon isotope ratio is often taken as evidence of a major marine anoxic event. There is much other evidence that reinforces this view. Wignall and Twitchett (1996) document evidence for ocean anoxia from many different sites around the world. They characterize this event as “superanoxic,” claiming that it may have been the most severe ocean anoxia of the Phanerozoic. Their research suggests that it began suddenly at the end of the Middle Permian, quickly reached global proportions and lasted until well into the Triassic.

The timing of the ocean anoxic event suggests a link to a methane hydrate release. A large release of subsurface methane would create a mixing of ocean layers, stirring up anoxic deep waters into upper layers. It would bring waters under great pressure into lower pressure zones. The sudden drop in pressure could lead to CO_2 outgassing, as deep waters were no longer able to retain dissolved CO_2. The released CO_2 would create a chain reaction, causing more and more dissolved CO_2 to be liberated as it moved up toward the surface, potentially poisoning everything in its path (Knoll, Bambach, Canfield and Grotzinger, 1996). However, this scenario is far from universally accepted, and the extant and impact of the marine anoxia is still being questioned. Evidence suggests that the anoxia occurred in shallow, epicontinental seas and phototropic ocean waters, but its origin from deep ocean waters is still being debated.

Strontium. The stratigraphic record also shows a shift in the strontium isotopic composition of seawater. Erwin, et al (2002) discuss a study by Martin and Macdougall published in 1995 that shows strontium levels were at a minimum at the end of the Middle Permian and then rose rapidly during the Late Permium. The authors suggest that this shift represents an abrupt change from weathering to mantle sources for strontium at the P-Tr boundary.

Sulfur and Oxygen. Erwin (1990) notes that changes in sulfur and oxygen isotope ratios were concurrent with similar changes in carbon and strontium isotopes. Together the isotopic data portray Adramatic changes in ocean water chemistry and perhaps in atmospheric oxygen@ (p. 80).

Iridium. The discovery by Alvarez and Alvarez in 1980 of worldwide elevated levels of iridium in rocks marking the Cretaceous/Tertiary (K-T) boundary was interpreted as solid evidence in support of the hypothesis that a bollide impact was the triggering event of the end-Cretaceous extinction. (Ward and Brownlee, 2000). Discovery of elevated iridium levels in rock layers near the P-Tr boundary led to similar speculation about the end-Permian being similarly impact induced. Iridium is rarely found at the Earth=s surface, so finding elevated iridium levels in a specific stratigraphic layer raises the possibility of its extraterrestrial origin. The fact that shocked quartz spherules are also found at the level adds weight to the argument for an impact trigger. However, the level of iridium is much lower at the P-Tr boundary than at the K-T boundary (Erwin, et al, 2002). Although it is about 10 times higher than normal background levels, it is still about 10 times lower than the levels found at the K-T boundary (Bhandari, 1998; Ward and Brownlee, 2000; Brassell, 2003).

Fullerenes and Helium Isotopes. The bollide impact theory as the trigger for the end-Permian extinction received more support with the discovery of trapped gases in fullerenes found at the P-Tr boundary by Becker, Poreda, Hunt, Bunch and Rampino in 2001. Fullerenes are ball-shaped molecules of linked carbon atoms large enough to trap minute quantities of gases inside. Becker, et al, examined the isotope levels of helium and argon recovered from fullerenes associated with the P-Tr boundary and concluded that the isotope ratios could not be accounted for by a terrestrial origin. They noted that the ratios closely matched ratios found in meteorites and suggest that the fullerenes are evidence of a comet or meteor impact.

Magnetostratigraphy

The Middle Permian was the end of a long period of magnetic stability. For perhaps as much as 60 million year previous the Earth=s magnetic field apparently maintained a constant negative polarity relative to its current polarity. (Menning, 2001, raises the possibility that there were zones of brief positive polarity during this period.) This period of uniformity, known as the Permo-Carboniferious Reversed Superchon (PCRS) apparently ended during the Capitanian. The end of the PCRS is called the Illawarra Reversal (IR). The proposed date and stratigraphic level of the IR has changed significantly in recent years. At one time it was presumed to mark the end of the Capitanian and hence, mark the transition from the Middle to Late Permian. Numerous attempts to correlate magnetostratigraphic, isotopic and biostratigraphic data have resulted in the date and stratigraphic level of the IR being revised backward. Recent estimates have placed the IR near the beginning of the Capitanian substage, around 265 mya (Menning and Jin, 1998; Menning, 2001).

The period following the IR is called the Permo-Triassic Mixed Megazone (PTMM). There were frequent polarity reversals during this time. Menning and Jin (1998) claim a minimum of 13 reversals between the IR and the end of the Permian. The impact of these frequent polarity reversals is not known, but Conaghan, Shaw and Veevers (1994) suggest that they created a thermal perturbation at the core/mantle that created a magma plume that eventually rose to the

Earth=s surface, creating the Siberian flood basalts. It should be noted, however, that others refute this possibility (Menning, pers. comm., 2003).

Possible Causes

The cause of the extinction has long been subject to much discussion and disagreement. The extent of the extinction is so profound that it is difficult to imagine a triggering event that would not leave incontrovertible evidence of its occurrence.

Rate and Sequence

For many years there was no agreement on whether the extinction was gradual, stepwise or abrupt. A slow, gradual extinction might argue for a geological cause, such as habitat loss due to tectonic changes. A sudden, abrupt extinction would seem to indicate a more cataclysmic cause. The available fossil record suggested that the extinction was the culmination of a long, gradual decline, taking approximately 10 million years to reach its maximum devastation. However, in 1982 Signor and Lipps published a paper documenting how reduced sampling size and availability (called sampling bias) and random truncation of stratigraphic ranges create the appearance of a gradual extinction even if a sudden mass extinction actually occured. This tendency of sudden extinctions to appear as gradual extinctions in the fossil record has been called the Signor/Lipps effect and suggests that it is impossible to determine the rate of a mass extinction from the fossil record alone.

Subsequent studies of the P-Tr boundary tend to take the Signor/Lipps effect into account and rely on additional methods to assess the rapidity of the decline. One of the ramifications of this effect is that the rarer a species is, the less likely its last fossil appearance is to be found at the stratigraphic level of its actual extinction. In another words, probability dictates that uncommon species tend to disappear from the fossil record before their actual extinction. Rampino and Adler (1998) examined fossilized foraminifera collected from P-Tr boundary sections in the southern Alps of Italy. After allowing for the Signor/Lipps effect, they concluded that 88% of late Permian foraminifera taxa disappeared in less than 30,000 years.

Jin, Wang, Wang, Shang, Cao and Erwin (2000) used statistical analysis to help interpret fossils collected from 5 sections of the Meishan sections of South China. They compensated for the Signor/Lipps effect by assuming that the last appearance of a species was not necessarily at its highest appearance in the fossil record. They discovered that 95% confidence levels of last occurrence pushed the extinction of many scarce species that had previously been assumed to have died out before the P-Tr boundary into the same time range of the most abundant species that disapperaed at the boundary. They found no support for the proposed step-wise extinction originally suggested for the fossil beds that they examined. Instead, they propose that the Meishan extinction occurred suddenly at 251.4 million years ago and was followed by the gradual extinction of a small number of surviving species over the next 1 million years.

By matching sea level fluctuations recorded in sediments to Milankovitch cycles, Rampino, Prokoph, Adler and Schwindt (2002) were able to use statistical analysis of last taxa appearances and estimation of sedimentation rates to determine the rate of faunal change at the P-Tr boundaries in formations in the southern Alps of Italy. They concluded that there was a sudden, dramatic extinction occurring in less than 10,000 years at the end of the Changhsingian.

However, there is still evidence that many marine species died out much earlier at the end of the Capitanian, in particular among corals, bryozoans, crinoids, and blastoids (Knoll et al, 1996). Statistical research has shown that the earlier die-off of benthic marine species is not just an artifact of the Signor/Lipps effect (Stanley and Yang,1994) and it is now generally accepted that the extinction was a two-stage event, with two extinction Apulses:@ one at the end of the Capitanian and a second at the end of the Changhsingian (Erwin, et al, 2002).

Geosynchroneity

Another question inhibiting possible causal explanations is that of simultaneity and global synchroneity of the extinction. It is not yet known with certainty if the extinction affected different environments and regions of the globe at the same time. Current research, however, is trying to answer that question, and there are attempts to correlate worldwide stratigraphic data with the record of magnetic polarity reversals (cf., Menning and Jin, 1998; Menning, 2001).

Twitchett, Looy, Morante, Visscher and Wignall, (2001) examined sediments in East Greenland. According to the authors, trace fossils do not display the same Signor/Lipps sampling bias that shelly fossils do. They argue that the trace fossils at the site indicate an abrupt benthic ecosystem collapse that took between 10,000 and 30,000 years. Furthermore, the terrestrial ecosystem shows a similar collapse at the same stratigraphic level. They conclude that, in Greenland, marine and terrestrial extinctions occurred simultaneously and within a few tens of thousands of years.

However, none of the studies mentioned so far prove that the P-Tr boundaries recorded at different part of the world occurred at the same time. A study by Bowring, Erwin, Jin, Martin, Davidek and Wang (1998) used U/Pb analysis of zircons in a layer of volcanic ash to address this issue. They conclude that the age of the P-Tr boundaries for 3 different sites approximately 1500 km apart in southern China is within 300,000 years of 251.4 million years ago. (An ash layer from a site in Texas yielded a much different date and was attributed to a different volcanic event.)

Unfortunately, the 300,000 year margin of error is still quite broad, and this date has yet to be confirmed at other sites around the world.

Current Theories

No single theory of the cause of the end-Permian extinction has yet to receive broad acceptance. All of the currently discussed theories still leave questions insufficiently answered.

Habitat loss due to tectonics and sea-level fluctuations. Sea levels fell during the Early and Mid Permian, then rose during the Late Permian. Dropping sea levels would have reduced the size of marine habitats and removed many shallow shelf areas from productivity. Benthic communities surviving the sea fall would have drowned during the sea level rise. However, the rate of sea-level change was gradual, taking as much as 5 million years to go from maximum regression to peak (Wignall and Twitchett, 1996; Hallam and Wignall, 1999). The current evidence suggesting the end-Permian Extinction event was sudden and occurred in less than 30,000 years argues against this hypothesis. Also, sea-level changes would not account for terrestrial extinctions. Similar arguments can be made against the beginning of the break-up of Pangea at the end of the Changhsingian as the cause of the extinction; tectonic changes may account for a gradual overturn of flora and fauna and localized extinctions, but they seem unlikely to initiate rapid worldwide mass extinction.

Ocean anoxia, CO_2 and/or methane release. There is strong evidence that the ocean anoxia was a profound event that could have completely disrupted many marine ecosystems. However, ocean anoxia alone could not account for the terrestrial extinctions. A sudden, massive release of CO_2 or methane could have led to terrestrial asphyxiation, but the deaths would have been most likely confined to low-lying areas near the shoreline and would not have severely affected plants.

Moreover, calculations by Erwin (1995) show that the amount of methane released would not be great enough to account for the ocean anoxia or to cause significant global warming.

Siberian Traps Volcanism. Bowring, et al, (1998) present a good argument for the Siberian flood basalts triggering the extinction. The amount of volcanism necessary to produce the volume of basalt in the Siberian Traps would have injected a large amount of ash, CO_2 and SO_2 into the atmosphere, possibly creating a nuclear winter initially, and then following that with a greenhouse effect that would raise temperatures worldwide. Acid rain caused by the airborne SO_2 could have led to ocean anoxia and the release of methane hydrate. However, their own analysis of zircons found in ash layers at the P-Tr boundaries leave open the possibility that the extinction had already begun when the eruptions began. Also, volcanism alone would not account for the widespread marine devastation or the end-Capitanian extinction.

Bollide Impact. The idea of a bollide impact has steadily gained momentum in the past few years, supported by the discovery of trapped noble gases in fullerenes found in stratigraphic layers near the P-Tr boundary (Becker, et al, 2001). The view is supported by recent studies that show the end Changhsingian extinction occurred very rapidly in geological terms. Other corroborating evidence include the iridium layer and shocked quartz crystals near the P-Tr boundary and the discovery of a large crater in Australia that may date to around this time period.

However, the theory is far from universally accepted. Precise dating of the proposed impact crater has yet to be accomplished (Erwin, et al, 2002). The shocked quartz spherules were found to be far less abundant and of a different character than those found at the K-T boundary (Retallack, Seyedolali, Krull, Holser, Ambers and Kyle, 1998) raising the possibility that they may have a volcanic origin. Retallack, et al, also found that peak iridium levels occurred as much as 1 meter below the P-Tr boundary. Even the existence of trapped extraterrestrial gases in fullerenes, originally thought to strongly suggest a bollide impact, is not yet conclusive. Recent studies have been unable to confirm Becker, et al=s results. Not all P-Tr boundary sites had detectable fullerenes, and when fullerenes have been found, researchers have been unable to confirm similar isotopic patterns indicative of extraterrestrial noble gases. Furthermore, the samples analyzed by Becker, et al came from a point 0.8 meter below the P-Tr boundary. Finally, a bollide impact does not account for the double pulsed nature of the extinction.

The Search Continues

The search for the cause of the end-Permian extinction continues. Any proposed explanation will have to consider several conundrums, the first being the sheer magnitude of the extinction. Raup (1982) ran mathematical models to determine the size of the Alethal radius@ needed to account for the extinction of varying percentages of the Earth=s families and genera. His research suggests that any single cause for an extinction event of this magnitude would have to have a lethal radius of 17-18,000 km., within 2-2.5% of the size needed to lead to 100% extinction. In order words, whatever caused the extinction came within a whisper of permanently erasing all life from the planet. The idea that an event so profound should leave such an ambiguous footprint is confounding.

Combinative Effects

One possibility is that there was no single cause for the extinction, but rather a combination of events that impacted different groups of species with different vulnerabilities. An event that led to the extinction of 30% or 40% of the Earth=s species would not necessarily leave as great a geological footprint as an event that led to the extinction of over 90%. If there were several different events within a short time period that created different environmental stresses, their cumulative effect could create a much more massive extinction than any of the events could individually (Erwin, 1995). This would also leave the inconclusive and occasionally contradictory trail of evidence that we see today in the stratigraphic record. Considering the random repetitive nature of extinction events, both major and minor, and the length of time of the Phanerozoic Era, it is reasonable to assume that some of these events might cluster together.

Examining the end-Permian extinction in this light raises the possibility that several of the current theories are correct. The ocean anoxia may have caused some of the extinctions, large-scale volcanism may have caused others, methane release or temperature increases may have caused others. This, however, increases the difficulty of determining which was the event and which was the result. Did volcanism raise global temperatures that led to a methane release, or did a methane release raise global temperatures that led to ocean anoxia caused by the stirring of deep waters from glacial melting? If there were multiple, coincidental causes for the extinction, then the task of sorting out the exact sequence becomes much more difficult. This also raises the possibility that, even if there is not a single cause, there may have been a single trigger that ultimately led to the seemingly coincidental occurrence of several different extinction causing events.

Supernova Explosion

One possible trigger that has not yet been widely discussed in the current literature is an astronomically Anearby@ supernova explosion. When a star of sufficient mass uses up enough of its nuclear fuel that it can no longer maintain gravitational equilibrium, it explodes into a supernova, sending out bursts of highly charged cosmic radiation. This radiation, if originating close enough to Earth, is likely to have severe consequences, including the destruction of the ozone layer (Samuel, 2002b). It has been estimated that a supernova explosion within 25 to 30 light years of Earth would initiate events on Earth of potentially catastrophic consequences (Ward and Brownlee, 2000; Science@NASA, 2003). Some estimates predict an environmentally disruptive distance of up to 130 light years (Samuel, 2002a; Samuel, 2002b).

Recent research has supported the possibility of supernovae explosions leading to mass extinctions. There is evidence that suggests a supernovae explosions over 120 light years away may have played a role in a major extinction event at the end of the Pliocene epoch 2 million years ago (Schwarzschild, 2002; Phillips, 2003a). Statistically, a supernova explosion within 30 light years of Earth can be expected to occur as often as every 200 to 300 millions years (Ward and Brownlee, 2000). The end of the Capitanian, around 260 million years ago, would be a reasonable time to expect one.

<u>Immediate effects</u>. A nearby supernova occurring at the end of the Capitanian might create the following scenario. A high enough level of cosmic radiation would be lethal to many organisms. At lower levels it could damage or even strip the Earth of its ozone layer, exposing most terrestrial and phototropic marine life to ultraviolet radiation from the Sun (Cockell, 1999; Ward and Brownlee, 2000; Schwarzschild, 2002; Phillips, 2003a). The sudden exposure of UV radiation could cause a gradual decline of non-resistant plant species (Cockell, 1999). As plants and animals declined, insects dependent on them would also decline.

In the oceans, the effects could be even more profound. Many sessile marine organisms are sensitive to UV radiation. Coral, for example, are known to experience bleaching when exposed to elevated levels of UV radiation (Brown, 1997). Marine organisms were particularly hard hit at the end of the Pliocene (Phillips, 2003a). It is possible the same fate befell similar organisms at the end of the Capitanian. This would explain the apparent disproportionate die-off of sessile filter feeders at this time. It is also possible that increased radiation would have led to decimation of phytoplankton populations, leaving sessile organisms vulnerable to starvation (Cockell, 1999; Schwarzschild, 2002). The massive death of phytoplankton could have leeched oxygen out of shallow tropical waters, creating the ironic situation that, rather than ocean anoxia creating widespread marine death, widespread marine death may have been responsible for the shallow water anoxia.

Delayed effects. The phototropic marine deaths would have been very abrupt, but other results may have been gradual, creating environmental stresses, but not yet leading to mass extinctions. Long term stresses made have influenced short-term evolution.

Eventually, the Earth would have been enveloped in the (greatly dissipated) gas cloud given off by the supernova. Moving into this cloud would have deposited extraterrestrial materials on the Earth and been the cause of the elevated iridium levels and the trapped noble gas-containing fullerenes. Moving into the cloud might also have drastically compressed the heliosphere that normally protects the Earth from cosmic radiation and further disrupted the chemistry of the atmosphere (Koppes, 1996; Phillips, 2003b).

The gas cloud from a supernova would likely have regions of differing densities. The Earth is presently inside a gas Abubble@ caused by supernova explosions several million years ago (Schwarzschild, 2002; Phillips, 2003a). We are currently experiencing a long period a stability because the Earth is moving through a very diffuse part of the cloud, (less that 1 atom of interstellar material in every 10 cm^3 [Phillips, 2003a]). However, the density of the cloud varies. Over many millions of years the Earth will move through denser areas, possibly compressing the heliosphere to less than the distance between the Earth and the Sun. Since the heliosphere protects the Earth from cosmic radiation, a severely compressed heliosphere would expose the Earth to ozone depleting radiation and resultant elevated UV levels (Phillips, T, 2003b). If the Earth was in a similar situation during the Permian period, then ozone layer disruptions could have occurred as a result of a supernova explosion thousands or even millions of year after the actual explosion. It is possible that Earth experienced several periods of damaging UV radiation, each time followed by the gradual rebuilding of the ozone layer.

Repeated incidents of ozone depletion could have prolonged and reinforced an evolutionary push toward UV radiation tolerance. Over a few millions of years a propensity toward UV resistance may have developed on the planet. The slow rebuilding of the Earth=s ozone layer, combined with the effects of vast quantities of smoke, dust and ash injected into the atmosphere by large scale Siberian volcanism would have dramatically reduced the amount of sunlight reaching the Earth=s surface, most affecting the very plant and animals best adapted to survive the elevated UV conditions created 5 million years earlier. There is evidence that suggests that the Siberian volcanism lasted as long as 600 thousand years, (Campbell, Czamanske, Fedorenko, Hill and Stepanov, 1992), which could have devastated photophyllic flora and fauna. However, plants and animals most resistant to UV radiation could also be most vulnerable to an interruption in sunlight. Perhaps the devastation of the Changhsingian was amplified by the patterns of survival from the Capitanian extinction. In effect, the selective extinction of the end-Capitanian stage extinction created conditions favorable for a massive extinction at the end of the Changhsingian, when conditions were suddenly reversed by the Siberian flood basalts.

Implications for Current Climate Change

Even if the end-Capitanian extinction was caused by a supernova explosion, the case for its culpability in the end-Changhsingian extinction 7 million years later is tenuous at best. Yet, examining the Earth=s present position in the gas bubble created by supernovae explosions millions of years ago suggests climatic influences can be experienced many millions of years after the initial explosion. Any connection between the Capitanian and Changhsingian extinctions would be sobering, because it suggests that the Earth could still experience major climatic disruptions and possible extinction events resulting from the supernovae explosions suspected of causing the end Pliocene extinction two million years ago.

It has recently become generally accepted that a meteor impact was a significant influence on, perhaps even the primary cause of, the end-Cretaceous extinction. The recent discovery of unstable iron isotopes with a half-life of 1.5 million years in layers of the ocean floor has added support to the theory that a supernova explosion was the catalyst for the end-Pliocene extinction 2 million years ago (Samuel, 2002a; Schwartzschild, 2002). If the end-Permian extinction was also initiated by extraterrestrial events, then three of the 6 largest extinctions of the Phanerozoic were initiated by extraterrestrial events. One is tempted to wonder how many of the other major disruptions of the Earth=s ecosystems have had extraterrestrial origins.

Clearly, the Earth=s climate is influenced by terrestrial events. Tectonics, geographical alignment, ocean currents and atmospheric chemistry all play a large role in shaping climate. Yet terrestrial influences can also help to stabilize climate. Climate changes initiated by one influence can be muted by counter-balancing responses in other parts of the Earth.

Yet the Earth has experienced major climatic perturbations and mass extinctions; at times the mechanisms for maintaining life-supporting conditions seemingly go haywire. Scientists are still at a loss to explain many of these incidences. Perhaps these occur because of extraterrestrial influences. One must remember that the Earth=s main source of heat is extraterrestrial. It is possible that even as the ameliorative effect of the complex interplay of different terrestrial influences works to dilute climate change, dramatic climatic shifts occur because of sudden disruptive extraterrestrial intrusions into what would otherwise be a stable adaptive system

Conclusions

This essay did not provide any new information or the results of any new research about the end-Permian extinction. Rather, it attempted to review much of the research currently reported and to synthesize the often confusing and contradictory information currently available. In the process of interpreting and evaluating current research, the author has raised three main conjectures:

1. that the end-Permian extinction did not have a single cause but rather a series of different causes that occurred within several million years of each other;

2. that survival patterns and subsequent environmental conditions predisposed organisms surviving the first pulse of the extinction to extinction during the second pulse.

3. that the initial series of causes for the extinction may have been triggered by a supernova explosion within 30 light years of Earth at the end of the Capitanian.

Additionally, the author reflects on the possibility that extraterrestrial events play a important role in initiating climate change and subsequent mass extinctions. While he admits that the evidence supporting these suppositions is not conclusive, he suggests that they are worthy of further discussion and would welcome the addition of these ideas to the debate about the causes of the most devastating extinction of the Phanerozoic period.

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