Transactions on Materials, Biotechnology and Life Sciences
ISSN: 2960-1932, eISSN: 2960-2319 | Volume 4
NSCBM 2024

The Permian-Triassic Extinction Event: Causes, Consequences, and Contemporary Relevance

Sirui Shen *

Annie Wright School, Tacoma WA, 98403, US

* Corresponding Author Email: sirui_shen@aw.org

Abstract. This study presents an overview of the Permian-Triassic extinction event — recognized as the most catastrophic biotic crisis that has occurred on Earth. We trace the path of scientific discovery with respect to the timing, scale, and causation of this dual-phased calamity. A comparison is made between its effects on marine and terrestrial ecosystems; note that 96% of all marine species and later 70% of all terrestrial vertebrate species were wiped out during these extinctions. Consider now the intricate weave of environmental maladies — spurred predominantly by Siberian Traps volcanism — which brought forth swift global warming begetting oceanic dead zones along with high acidity levels leading to anoxia on a worldwide scale. An examination of the reasons and repercussions of the PT extinction leads us to make comparisons with present-day anthropogenic climate change and loss of biodiversity, thus underscoring the importance that paleontological investigations have for contemporary environmental challenges. This integration offers hints about ecosystem resilience and vulnerability dynamics which underscore the necessity of differential weighing both the magnitude and rapidity of environmental changes against biological responses toward global perturbations.

Keywords: Permian-Triassic extinction, Mass extinction, Siberian Traps volcanism, Ecosystem recovery, Paleoclimate.

1. Introduction

The Permian-Triassic (PT) extinction event, often referred to as the "Great Dying," stands as the most severe biotic crisis in Earth's history. This review aims to synthesize current understanding of this pivotal event, exploring its causes, impacts, and implications for modern ecology and climate science.

1.1. Evolution of Scientific Understanding of the PT Extinction Event

The understanding of the extinction process has evolved to an intricate level. Instead of one large calamitous event, there were various environmental stressors that acted in unison which led to a situation where life could not be sustained on Earth. The paper will provide a critical analysis of the proposed mechanisms such as massive volcanism, global warming plus ocean acidification and also wide-spread anoxia [1, 2].

In the 1980s, early studies considered the PT extinction as a prolonged affair that lasted several million years [3, 4]. But scientific progress in analysis — especially through high-precision radiometric dating— has allowed scientists to drastically narrow down this timespan. The latest opinion now sees a primary extinction pulse not exceeding 200,000 years; others go so far as to propose around 60,000 years only [5].

In addition, the extinction process has evolved into a more nuanced concept. Instead of just a singular catastrophic event, current data implies that there were multiple environmental stressors that acted together in a synergistic way to drive the biosphere over the edge. The evolution of extinction process has seen birth to high sophistication in its conceptualization. Rather than being a single catastrophic event, the present evidence hints at various environmental stressors that played together and brought the biosphere of the Earth beyond a critical threshold [6].

1.2. Research Background and Objectives

The PT extinction event has potential to provide a different and particular perspective of global ecosystems' strength and weaknesses. Analysis of it is important in the broader picture not only for grasping Earth's biological past but also understanding the challenges that ecological systems can face — now or in future times, especially with regard to climate change driven by human activities and loss of biodiversity. This paper sets out to:

1) Weave together and give your thoughts on the most recent discoveries about the PT extinction using evidence from various sources like paleontology, geochemistry and climate modelling.

2) Look at what the different theories say about how the extinction happened: whether it was caused by Siberian Trap volcanism, methane release or even impacts from outer space.

3) Judge how differently the extinction affected marine life from terrestrial life; then study how plants and animals tried to bounce back after losing so much during that calamity.

4) Delve into what the PT extinction studies could reveal about the crises of the current biodiversity and possible upcoming mass extinctions.

Review methodology is a detailed description of the technique that was used: we carried out an extensive examination of the most recent peer-reviewed scientific papers on PT extinction. We limited our focus to materials released in the past ten years and gave priority to those that made substantial contribution to either deepening existing knowledge or contradicting it. In some cases, we went even further by performing meta-analyses based on available data sets with a view to unveiling generalities in addition to specific details and tendencies.

This review seeks to reach these goals and therefore hopes to put forth a synthesis that is complete, up-to-date and well informative about the PT extinction event. This way we aspire to enrich the scientific discussions on this epochal period of Earth's history; we also intend to draw attention — through this act — to those areas which demand more investigations since their riddles seem not easily unraveled. Furthermore, by situating paleontological work within the larger framework of environmental science — by drawing analogies between crises that occurred millennia ago and those unfolding before our eyes today — we hope to stress the relevance of such studies to the modern ecological challenges that mankind faces.

2. Impact of the PT Extinction Event on Life

The PT extinction event had profound and far-reaching impacts on both marine and terrestrial ecosystems. This section examines the differential effects of the extinction on various life forms and explores the patterns of ecosystem collapse and subsequent recovery.

2.1. Impact on Marine Life

The end-Permian extinction dealt the most significant blow to the marine realm: estimates indicate that up to 96% of marine species were wiped out [7]. Recent studies have unveiled an intricate pattern of taxonomic selectivity during the PT extinction event. Although severe in all major marine groups, some taxa were more severely affected than others. Those that built reefs suffered greatly; rugose and tabulate corals were wiped out entirely and scleractinian corals almost met the same fate [8]. Articulate brachiopods saw a steep decline with only 5% of their species surviving [9, 10] while among foraminifera, large fusulinids perished but smaller foraminifera had better survival rates [11]. Trilobites, which were already dwindling as a group, were entirely wiped out during the PT event according to Brayard et al. [12]. Ammonoids demonstrated extraordinary rebound despite being heavily impacted with up to 97% of species lost in the Early Triassic also based on another study from Brayard et al. [13].

The PT extinction brought forth significant changes to life on Earth, not just in reducing the diversity of living beings but also in changing the way marine ecosystems worked. The extinction did not act indiscriminately: it took away those at the higher trophic levels more easily than others, which meant that for some time after the event there were less complicated marine food webs. When the major reef-building organisms disappeared because of the extinction, their absence created a gap in reefs that lasted millions of years into the Triassic period.

In place of brachiopod-dominated benthic communities seen prior to this period post-extinction oceans witnessed bivalve-dominated communities take over as well as many other changes [14]. The recovery of marine ecosystems posts the PT extinction was a slow process that spanned over several million years. A full 10 million years were needed for true recovery to take place, during which there were multiple "false starts" with simple low-diversity communities taking over [9]. Also noted was that many lineages surviving the mass extinction experienced a temporary decrease in body sizes — an observation termed the "Lilliput effect" [15]. Some groups completely vanished from the fossil records only to reappear later in the Triassic period which throws light on how complex extinctions can be and also challenges one’s ability to decipher paleontological data; these 'Lazarus taxa' underscore these challenges — and remind us — about how important considering taphonomic biases are when studying extinctions [16].

2.2. Impact on Terrestrial Life

The terrestrial environments were not as greatly affected by the PT extinction compared to marine ecosystems, but they also did undergo significant changes. New studies have refined our knowledge on vertebrate extinctions at that time. The once dominant synapsids such as gorgonopsians and dicynodonts went into sharp decline although some lineages managed to persist [17]. Archosauromorphs, which include the ancestors of dinosaurs and crocodiles, had relatively high rates of survival that led to subsequent diversification [18]. Although temnospondyl amphibians were severely impacted, there are indications that they survived well and later recovered significantly during the Early Triassic [19].

The PT extinction drastically reshaped terrestrial plant communities. Leading Permian plant groups like cordaites and glossopterids were wiped out, causing a complete overhaul of land-based systems [20]. Interestingly, lycopsids and ferns displayed better chances of survival and transitioned as notable entities within early Triassic floras [21]. A number of studies have documented findings that point to a fungal spike right after the extinction event — which could possibly mean widespread decay of terrestrial vegetation [22].

The PT extinction brought significant alterations to the functioning and structure of terrestrial ecosystems. Loss of major plant groups changed the landscape structure, which in turn could affect erosion rates and deposition of sediments into marine environments [23]. The simplification of food webs in the Early Triassic resulted from the extinction of many herbivorous and carnivorous tetrapods [24] indicating that changes were driven primarily by extreme climatic conditions. These include intense warming plus aridification on landmasses [25].

The recovery of land-based environments paralleled and diverged from that of the sea in some interesting ways. A few investigations indicate that signs of recovery appeared more promptly in terrestrial systems than in marine ones although full recuperation was still dragged out [17]. Regional patterns of recovery differed starkly among various parts on the map — likely because differing climates and environmental setups [26]. The Permian extinction wiped out dominant groups which paved way for ecological vacancies thus seeing the ascendancy of archosaurs ushering dominance to Dinosaurs during their era [27].

The PT extinction event resulted in great and long-lasting effects on both aquatic and land ecosystems. Even though it was certainly disastrous, the event acted as a precursor to the reorganization of the biosphere where new ecological structures came into being. Studying these primordial templates of extinction and resurgence is laden with invaluable information on the strength and weak spots that characterize global ecosystems — thus holding possible consequences for conservation biology & climate change science.

3. Causes of the PT Extinction Event

The causes of the PT extinction event have been a subject of intense scientific debate and research. Over the years, our understanding has evolved from simple, single-cause hypotheses to more complex, multi-causal models. This section reviews the development of these ideas and examines the current state of knowledge regarding the potential triggers and mechanisms of this unprecedented biotic crisis.

3.1. Early Hypotheses

Climate change, more particularly rapid global warming and aridification, has been hypothesized to be a potential driver of the PT extinction. Some scientists posited that transitioning towards an arider climate could have led to terrestrial ecosystem stress while warming oceans might have surpassed thermal tolerances for many marine species [28]. Like marine anoxia, climate change is now considered a major player in the extinction, but current models typically portray it as part of a chain of related environmental perturbations.

A different early theory zeroed in on marine anoxia. Discovering the oxygen-depleted situations that prevailed widely in ancient ocean waters, researchers reasoned that a global sprawl of anoxic waters could have smothered marine creatures and thrown off the chemical balance of the oceans [29]. This proposal captured considerable attention at the time and is still recognized as an important part of present extinction models, although not alone but as one link in a chain of more intricate events.

The mass extinction event PT has been said to possibly be caused by climate change, specifically quick global warming and aridification. Some scientists proposed that the reason why more land-based ecosystems could have died is due to a shift towards a drier climate and that the warming oceans could have killed many marine species because it made them go beyond their thermal limits [28]. Just like how marine anoxia is now seen as one of the critical factors in the extinction, climate change is recognized too but current models tend to describe it as part of a chain of related environmental shocks.

3.2. Latest Evidence and Research

Cutting-edge scientific studies have changed how we view the reasons behind the PT extinction event. Most of the new models point towards an effect of large-scale volcanism caused by the Siberian Traps massive igneous province. High-precision dating methods have revealed a dramatic synchrony between the primary outburst of Siberian Traps volcanic activity and maximum extinction pulse [30]. The quantity alone — more than three million cubic kilometers — of lava that would have poured out from these eruptions is mind-boggling and would reach far-reaching global effects.

The Siberian Traps volcanic activity is considered to have resulted in a wide range of changes in the environment. There were huge amounts of carbon dioxide released by these eruptions which would have caused global warming at a very fast pace — with some models suggesting elevations in temperature by 8-10°C [25]. This warming could in turn give rise to ocean stratification leading to expanded anoxic zones and might have triggered release of methane hydrates from ocean sediments — situations that act as positive feedback to greenhouse effects [28].

The Siberian Traps eruptions, apart from greenhouse gases would also have emitted large amounts of sulfur dioxide which leads to short-term cooling events due to acid rain. Additionally, the injection of halocarbons into our atmosphere might have caused ozone depletion— an interesting consequence— that leads to an increase in UV-B radiation at the Earth's surface [31]. Recent investigations have unveiled a potential role played by mercury emissions from the Siberian Traps. Evidence showing anomalies of mercury has been found in multiple PT boundary sections worldwide [32].

Although the Siberian Traps volcanism is generally acknowledged as the main cause of the PT extinction, other researchers have suggested more secondary contributing agents. For example, there has been discussion concerning whether an extraterrestrial impact played a role or not. While some research works have noted presence of impact markers at the PT boundary — like shocked quartz and a suspected impact crater in Australia — these findings are controversial and do not enjoy universal acceptance [33, 34].

3.3. Possibility of Combined Factors

New ideas about the PT extinction highlight the combination of several environmental tensions which were brought mainly by Siberian Traps volcanism and perhaps made worse from other causes. This confluence of disparate effects in environmental changes probably pushed global systems into a state of overshoot resilience-wise, resulting in coextinction cascades among both marine and terrestrial biota.

Positive feedback loops have attracted more interest due to their ability to magnify initial disturbances. For instance, the warming triggered by CO_2 emissions from volcanoes could later lead to a release of methane hydrates — which would cause more warming in turn. In a similar fashion, if primary producers in the oceans collapse this reduces the biological pump and affects ocean chemistry along with nutrient cycling thus further stressing marine ecosystems might be other feedback loops [35].

Recent research has even noted the possible high significance of rate-dependent effects. The speed at which changes took place in the environment during the PT extinction event might have been equally — if not more — important than their size, since they could have overtaken many species' ability to adapt [36]. This view stresses that we should take into account not only the changes in environmental conditions as such, but also how quickly those changes happened.

To sum up, even though the Siberian Traps volcanism is presently acknowledged as the primary initiator of the PT extinction event, the true cause probably resulted from a convoluted interaction between various environmental alterations acting at distinct temporal scopes. Comparisons between the PT extinction and contemporary human-induced modifications to Earth's system emphasize why investigating prehistoric extinction events holds relevance. With each step taken towards improving our knowledge about what led to the PT extinction and how it unfolded, we obtain this precious mosaic of information on what today's ecosystems can be lacking — and also what they might yet lose due to current global changes.

4. Conclusion

The PT extinction event is considered to be the worst biotic crisis that ever happened on Earth and it affected both land and sea greatly. In the oceans, almost all species died with losses amounting to 96% where the most affected were reef-building organisms plus brachiopods and marine reptiles, which were highly susceptible to quick changes in their environment. Even though terrestrial ecosystems did not suffer as much, they experienced drastic changes leading to end of many synapsid lineages and notable turnover in plant communities. The recovery was long and complicated; it took about 10 million years for marine ecosystems to restore back to normal, with several unsuccessful attempts marked by simple opportunistic communities signifying low biodiversity. While terrestrial ecosystems showed quicker initial bounce back in some areas, they too had to take a considerable amount of time before regaining full complexity. The disappearance came from a perfect storm of interacting forces, some of which were probably made worse by loops that make the Earth more effective. This co-occurrence of changes, happening at the same time and affecting one another, exceeded the ability of the world's ecosystems to respond to them due to their global reach in turn causing widespread collapse and revealing an event teeming with intricacy whose consequences rippled across all corners of the planet.

The PT extinction reveals modern environmental challenges and future ones, which would tell us that it is the rate of change rather than its amount that can be even more critical in the impacts on living organisms. With contemporary rates surpassing those of the PT extinction event — often — this perspective finds direct implications towards anthropogenic climate change as well as biodiversity loss. The PT extinction underscores paradoxically both life's fragility and resilience on Earth's stage: it paints a picture of how disturbances to Earth's environment could echo down through millions of years upon generations yet unborn even while it also shows us— with time lapse photography, so to speak — that life does go on (albeit changed). Therefore, this duality underscores these profound lessons we can learn from deep time about what might threaten us today. To unravel mechanics behind extinction drivers, high resolution environmental proxy records need further fine-tuning for their detail fidelity — likewise sophisticated models are needed for understanding ecosystem dynamics under stressors. The synthesis of observations on the PT extinction with other mass extinctions and modern ecological transformations under a single scheme would yield a complete understanding of biospheric reactions to global disturbances. Studying this ancient catastrophe helps us gain valuable insights into the functioning of the Earth system — which can be instrumental in dealing with challenges that mark our age, such as climate change, demonstrating the importance of paleontology in addressing contemporary environmental issues and securing a sustainable future.

References

[1] G L, Anbar A D, Barling J, et al. Molybdenum isotope evidence for widespread anoxia in mid-Proterozoic oceans. Science, 2004, 304(5667): 87-90.

[2] Thamdrup B, Dalsgaard T, Revsbech N P. Widespread functional anoxia in the oxygen minimum zone of the Eastern South Pacific. Deep Sea Research Part I: Oceanographic Research Papers, 2012, 65: 36-45.

[3] Schubert J K, Bottjer D J. Aftermath of the Permian-Triassic mass extinction event: Paleoecology of Lower Triassic carbonates in the western USA. Palaeogeography, Palaeoclimatology, Palaeoecology, 1995, 116(1-2): 1-39.

[4] Benton M J. More than one event in the late Triassic mass extinction. Nature, 1986, 321(6073): 857-861.

[5] Burgess S D, Bowring S, Shen S Z. High-precision timeline for Earth's most severe extinction. Proceedings of the National Academy of Sciences, 2014, 111(9): 3316-3321.

[6] Yin H, Feng Q, Lai X, et al. The protracted Permo-Triassic crisis and multi-episode extinction around the Permian–Triassic boundary. Global and Planetary Change, 2007, 55(1-3): 1-20.

[7] Payne J L, Clapham M E. End-Permian mass extinction in the oceans: an ancient analog for the twenty-first century?. Annual Review of Earth and Planetary Sciences, 2012, 40(1): 89-111.

[8] Martindale R C, Berelson W M, Corsetti F A, et al. Constraining carbonate chemistry at a potential ocean acidification event (the Triassic–Jurassic boundary) using the presence of corals and coral reefs in the fossil record. Palaeogeography, Palaeoclimatology, Palaeoecology, 2012, 350: 114-123.

[9] Chen Z Q, Benton M J. The timing and pattern of biotic recovery following the end-Permian mass extinction. Nature Geoscience, 2012, 5(6): 375-383.

[10] Brayard A, Vennin E, Olivier N, et al. Transient metazoan reefs in the aftermath of the end-Permian mass extinction. Nature Geoscience, 2011, 4(10): 693-697.

[11] Liu X, Song H, Bond D P, et al. Migration controls extinction and survival patterns of foraminifers during the Permian-Triassic crisis in South China. Earth-Science Reviews, 2020, 209: 103329.

[12] Brayard A, Krumenacker L J, Botting J P, et al. Unexpected Early Triassic marine ecosystem and the rise of the Modern evolutionary fauna. Science Advances, 2017, 3(2): e1602159.

[13] Brayard A, Escarguel G, Bucher H, et al. good genes and good luck: ammonoid diversity and the end-Permian mass extinction. Science, 2009, 325(5944): 1118-1121.

[14] Chen Z Q, Tong J, Liao Z T, et al. Structural changes of marine communities over the Permian–Triassic transition: ecologically assessing the end-Permian mass extinction and its aftermath. Global and Planetary Change, 2010, 73(1-2): 123-140.

[15] Twitchett R J. The Lilliput effect in the aftermath of the end-Permian extinction event. Palaeogeography, Palaeoclimatology, Palaeoecology, 2007, 252(1-2): 132-144.

[16] Wignall P B, Benton M J. Lazarus taxa and fossil abundance at times of biotic crisis. Journal of the Geological Society, 1999, 156(3): 453-456.

[17] Benton M J, Tverdokhlebov V P, Surkov M V. Ecosystem remodelling among vertebrates at the Permian–Triassic boundary in Russia. Nature, 2004, 432(7013): 97-100.

[18] Ezcurra M D, Butler R J. The rise of the ruling reptiles and ecosystem recovery from the Permo-Triassic mass extinction. Proceedings of the Royal Society B, 2018, 285(1880): 20180361.

[19] Matamales-Andreu R, Peñalver E, Mujal E, et al. Early Middle Triassic fluvial ecosystems of Mallorca (Balearic Islands): Biotic communities and environmental evolution in the equatorial western peri-Tethys. Earth-Science Reviews, 2021, 222: 103783.

[20] Cascales-Miñana B, Cleal C J. The plant fossil record reflects just two great extinction events. Terra Nova, 2014, 26(3): 195-200.

[21] Schneebeli-Hermann E, Kürschner W M, Kerp H, et al. Vegetation history across the Permian–Triassic boundary in Pakistan (Amb section, Salt Range). Gondwana Research, 2015, 27(3): 911-924.

[22] Vajda V, McLoughlin S. Extinction and recovery patterns of the vegetation across the Cretaceous–Palaeogene boundary—a tool for unravelling the causes of the end-Permian mass-extinction. Review of Palaeobotany and Palynology, 2007, 144(1-2): 99-112.

[23] Smith R M, Botha-Brink J. Anatomy of a mass extinction: sedimentological and taphonomic evidence for drought-induced die-offs at the Permo-Triassic boundary in the main Karoo Basin, South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 2014, 396: 99-118.

[24] Roopnarine P D, Angielczyk K D. Community stability and selective extinction during the Permian-Triassic mass extinction. Science, 2015, 350(6256): 90-93.

[25] Sun Y, Joachimski M M, Wignall P B, et al. Lethally hot temperatures during the Early Triassic greenhouse. Science, 2012, 338(6105): 366-370.

[26] Irmis R B, Whiteside J H. Delayed recovery of non-marine tetrapods after the end-Permian mass extinction tracks global carbon cycle. Proceedings of the Royal Society B: Biological Sciences, 2012, 279(1732): 1310-1318.

[27] Viglietti P A, Benson R B, Smith R M, et al. Evidence from South Africa for a protracted end-Permian extinction on land. Proceedings of the National Academy of Sciences, 2021, 118(17): e2017045118.

[28] Benton M J, Newell A J. Impacts of global warming on Permo-Triassic terrestrial ecosystems. Gondwana Research, 2014, 25(4): 1308-1337.

[29] Twitchett R J, Wignall P B. Trace fossils and the aftermath of the Permo-Triassic mass extinction: evidence from northern Italy. Palaeogeography, Palaeoclimatology, Palaeoecology, 1996, 124(1-2): 137-151.

[30] Burgess S D, Bowring S A. High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. Science Advances, 2015, 1(7): e1500470.

[31] Bais A F, Bernhard G, McKenzie R L, et al. Ozone–climate interactions and effects on solar ultraviolet radiation. Photochemical & Photobiological Sciences, 2019, 18(3): 602-640.

[32] Sanei H, Grasby S E, Beauchamp B. Latest Permian mercury anomalies. Geology, 2012, 40(1): 63-66.

[33] Becker L, Poreda R J, Basu A R, et al. Bedout: a possible end-Permian impact crater offshore of northwestern Australia. Science, 2004, 304(5676): 1469-1476.

[34] Tohver E, Cawood P A, Riccomini C, et al. Shaking a methane fizz: Seismicity from the Araguainha impact event and the Permian–Triassic global carbon isotope record. Palaeogeography, Palaeoclimatology, Palaeoecology, 2013, 387: 66-75.

[35] Hotinski R M, Bice K L, Kump L R, et al. Ocean stagnation and end-Permian anoxia. Geology, 2001, 29(1): 7-10.

[36] Joachimski M M, Lai X, Shen S, et al. Climate warming in the latest Permian and the Permian–Triassic mass extinction. Geology, 2012, 40(3): 195-198.