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Environmental Effects of Volcanic Eruptions over Geological Timescales

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Abstract. Volcanic eruptions influence the Earth system across timescales ranging from days to millions of years. This paper examines how repeated and large-magnitude volcanism affects the atmosphere, hydrosphere, biosphere, and lithosphere, with emphasis on the distinction between short-term disturbances and cumulative geological impacts. Explosive eruptions can inject sulfur dioxide into the atmosphere, producing sulfate aerosols and temporary surface cooling, whereas prolonged volcanic activity can release carbon dioxide and contribute to longer-term warming. Volcanic gases and ash can also alter soil and water chemistry, promote acidification, modify nutrient supply, and contribute indirectly to marine deoxygenation. At the same time, repeated lava emplacement and intrusive activity reshape landscapes and crustal structure. The environmental significance of large volcanic episodes is further illustrated through the Siberian Traps, Central Atlantic Magmatic Province, and Deccan Traps, which are compared in terms of scale, gas emissions, climatic responses, and biodiversity change. Overall, volcanism produces interconnected environmental effects whose magnitude and persistence depend strongly on eruption duration, frequency, composition, and geological context.

Keywords: Volcanic eruptions, Geological timescales, Climate change, Ecosystem response

1. Introduction

Volcanic eruptions are one of the major processes that changes the environment. They are the manifestation of Earth's internal processes. Volcanic eruptions can be broadly classified as explosive, which produce ash and pyroclastic deposits, or effusive, which produce lava flows. Large explosive eruption can change the global climate and change the terrain after the lava solidifies. Volcanic ash and gases can also alter the chemical properties and pH of soils and surface waters. Volcanic eruptions have received growing attention by society as it can threaten human lives [1]. Recent volcanic activity provides clear examples of the contrasting environmental effects of effusive and explosive eruption. Kīlauea, located in Hawaii, is one of the world's most active volcanoes. Since 23rd December 2024, the volcano has been experiencing episodic effusive eruptions [2]. The lava flow reshaped the terrain by creating volcanic land. Volcán de Fuego (also written as Fuego Volcano), located in Guatemala, has significantly increased its intensity in eruption since early August 2026. Fuego is a typical example of explosive eruption [3]. Large quantities of volcanic ash have affected surrounding areas and degraded local air quality. Observations of short-term volcanic

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impacts provide useful evidence for understanding how repeated eruptions may produce cumulative environmental effects over geological timescales.

Magma generated within the mantle or crust may rise toward the surface because of its buoyancy and internal pressure. When magma reaches the surface through fractures or volcanic conduits, an eruption occur. With repeated eruptions, volcanoes are gradually built, over geological timescale. Therefore, when doing research of volcanic eruptions, taking the timescale into account is vital. The time needed for geological processes to operate can vary, from days to millions of years. Considering the geological timescale also helps to investigate the changes in the Earth's surface, climate and life to ancient age. A single eruption cannot fully reflect long-term impacts. The influence of a single eruption usually shows immediately like the worsening air quality, but it does little help to the change of environment. Cumulative effects are more important to be focused on because repeated eruptions reshape the atmosphere, hydrosphere, biosphere and lithosphere. The magnitude of these effects depends not only on the size of individual eruptions but also on eruption frequency, duration, magma composition, and the environmental conditions present at the time of eruption. Over geological timescales, these factors determine whether volcanic activity produces only temporary disturbances or contributes to persistent environmental transformation.

Previous research on super-eruption shows that super-eruptions are one of those rare events that can cause global catastrophic effects [4]. The ecosystem of the earth is vulnerable, a huge eruption can result in severe disasters. When volcanoes erupt, sulfur dioxide (SO_2) is released into the atmosphere and forms sulfate aerosols. Sulfate aerosols can reflect sunlight, thus decreasing the temperature. Large eruptions may also contribute to the acidification of surface waters through acid deposition, thereby placing additional stress on ecosystems. Many geologists considered the volcanic eruption as a possible cause of the Permian-Triassic Mass Extinction (one of the most severe extinctions in the history). By finding the impacts of volcanic eruption on the earth's environment over geological timescale, the researchers can understand the ancient history. Volcanic activity also plays an important role in the long-term carbon cycle by transferring carbon from the Earth's interior to the atmosphere.

Most previous research mainly focuses on short-term influences of volcanic activity instead of long-term and pays attention to one single area that the eruption affect. Indeed, those researches illustrate the damage of volcanic activity and some effects. However, the previous study can demonstrate a lava flow creates a new rock but cannot demonstrate how Hawaii Island formed; those study can explain a big volcanic activity decrease global temperature for two years but cannot explain long-term climate evolution; those study can illustrate how many lives died instantly in an eruption but cannot illustrate the secondary environmental consequences that causes the animals died like the Mass Extinction. Those integrated analyses and long-term environmental impacts are still lacking. However, the ecosystems in the Earth are highly related, volcanic eruptions affect these systems simultaneously. Therefore, this paper aims to integrate the effect of volcanic eruptions in atmosphere, hydrosphere, biosphere and lithosphere and expand to geological timescale. The following sections first examine atmospheric and hydrological responses before comparing major volcanic events and their longer-term climatic and biological consequences.

2. The mechanism of volcanic eruption effects

Volcanism also plays a fundamental role in shaping the lithosphere and the long-term evolution of landscapes. Repeated lava flows can build volcanic plateaus, islands, and mountain systems, while intrusive magma can modify the structure and composition of the crust. Weathering and erosion later

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reshape these volcanic landforms, meaning that the geological legacy of volcanism may persist long after eruptive activity has ended.

2.1. The temporary global cooling effect caused by sulfur dioxide

Eruptions can cause short-term cooling. When explosive eruptions happen, large amounts of sulfur dioxide will be released into the atmosphere. Sulfur dioxide can be oxidized in the atmosphere by hydroxyl radicals. These reactions eventually produce SO_3, it reacts with water vapor rapidly into sulfuric acid. Sulfuric acid then condenses with water and to form tiny liquid droplets, and it is called sulfate aerosols. These aerosols will reflect and thus reducing solar radiation. Therefore, the global temperature cools down. However, in most situations, that low temperature will only remain for only a short time.

2.2. Global warming caused by cumulative carbon dioxide

Carbon dioxide is also released into the atmosphere. Carbon dioxide is a greenhouse gas. A single eruption may not produce enough carbon dioxide to change the climate. However, large-scale and cumulated volcanic activity can release large amounts of carbon dioxide. That cumulated carbon dioxide can create a barrier which traps the heat and prevents from escaping from the earth. In the long run, this will cause long-term global warming. Overall, volcanic activities can cause both global high temperature and low temperature. Except for climate change, ocean warming will also happen. Ocean may absorb the excess heat from the atmosphere after that, seawater temperature rises. That may affect ocean lives. Warmer seawater holds less dissolved oxygen, which can increase physiological stress and contribute to marine deoxygenation. Volcanic activities will not only cause climate change, but also environmental change.

2.3. Acid rain and volcanic biochemical change of the ecosystem

eruption can release acidic gases such as hydrogen chloride. Those gases react with the water in the atmosphere and form acid rain. Acid rain is harmful to the whole environment. Acid deposition can reduce soil pH, alter nutrient availability, and potentially reduce soil fertility. When acid rain goes into the river, the PH of the water will reduce, which means it will not be available for fishes to live, causing damage to the natural animals. Intensed eruption will trigger more severe consequences. Except for river acidification, ocean acidification is also a concerning problem. Carbon dioxide will also dissolve in ocean. Acid rain will affect shells.

However, volcanic eruptions do not only bring harmful consequences. For example, volcanic ash can enter the ocean. Volcanic ash contains many nutrients like iron. In some cases, those nutrients may stimulate the activities of sea animals. But eutrophication of water body will produce more organic matter. When those matters decompose, they consume oxygen, and it will lead to the same result. Therefore, volcanic eruption will lead to deoxygenating.

3. Typical geological events and the response of ecosystem

There were several typical geological events related in huge volcanic eruptions in the history. For instance, the Siberian Traps, the Central Atlantic Magmatic Province (CAMP) and the Deccan Traps. The Siberian Traps is mainly caused by mantle plume. When decompression melting, huge amounts of magma produced. After cooling, magma becomes sills intrusion. For Deccan Traps, it was similar to the Siberian Traps. CAMP is highly related to Pangaea breakup. When Pangaea began

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to break apart, the continent rifted after that, there was crustal extension. Then magma generated. At last, a basaltic volcano formed.

This section will compare the three events under same criteria. First, duration and scale. Siberian Traps and Deccan Traps are both large-scale flood-basalt volcanism, while CAMP is associated with breakup of Pangaea. Siberian Traps had several eruptive phases, but Deccan Traps had multiple eruptive pulses. Siberian Traps formed around the time of the End-Permian mass extinction [5]. CAMP concentrated around the End-Triassic period [6]. Secondly, the gases and the environmental changes. Three events all release CO_2, SO_2 into the atmosphere. CO_2 will increase the greenhouse effect, cause more serious global warming whereas SO_2 will cause short-term cooling by reduce sunlight radiation. CO_2 will also increase the ocean acidification. Third, differences in environmental response. For Siberian Traps, still emplacement will release volatile-rich sediments, then additional greenhouse gas releases [5]. Fourth, biodiversity response. Severe global warming, ocean acidification has extreme stress on the ecosystem. Siberian Traps caused the End-Permian mass extinction, CAMP caused End-Triassic extinction and Deccan Traps caused K-Pg extinction. Those events had caused severe biological extinction.

Overall, those three volcanic has similar patterns for which they are all large eruptions and they all caused serious extinctions and also ocean and climate changes. However, the volatile released and the duration have some differences. Furthermore, although these three large igneous provinces occurred in different geological periods, their environmental impacts follow similar causal pathways. Large-scale magmatic activity can release vast amounts of CO_2, SO_2, and other volatile substances over relatively short geological timescales, altering atmospheric composition and subsequently affecting global temperature, ocean chemistry, and ecosystem stability. However, the intensity of these environmental effects depends on factors such as eruption rate, duration, source of volatiles, and interactions between magma and sedimentary layers [7]. Studies on the end-Permian period indicate that the combined effects of rapid warming and oceanic anoxia can account for a significant portion of marine biodiversity loss, suggesting that volcanic impacts on the biosphere are not limited to direct emissions but can be amplified through cascading changes in climate-ocean systems [8]. Research on the Central Atlantic Magmatic Province (CAMP) further reveals that its magmatic activity released substantial deep-sourced CO_2, likely contributing to global warming and ocean acidification at the end of the Triassic [9]. In contrast, high-precision geochronology of the Deccan Traps shows that their massive eruptions spanned the Cretaceous–Paleogene boundary; thus, when discussing the K–Pg mass extinction, it is essential to consider multiple environmental perturbations—including both Deccan volcanism and the Chicxulub impact—rather than attributing extinction solely to a single factor [10].

4. Conclusion

The magma erupted can create new terrains, the gases released can change the climates and the gases dissolved in the ocean can cause ocean acidification. What' s more, Massive some biological extinctions are caused by huge eruptions. To conclude, Volcanic activity plays an important role in changing the geologic porcess on the Earth. Individual eruptions may produce short-lived effects, whereas repeated or exceptionally large volcanic episodes can generate cumulative changes that persist for thousands to millions of years. Understanding volcanism over geological timescales therefore requires integrating atmospheric, hydrological, biological, and lithospheric responses rather than considering each environmental system in isolation. On longer geological timescales, the environmental impact of volcanic activity is not determined by individual eruptions alone, but rather by eruption frequency, duration, gas emissions, and their interactions with oceans, land, and

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ecosystems. In the short term, sulfate aerosols may cause cooling and acid deposition; in the long term, sustained large-scale volcanic activity releases carbon dioxide, leading to ocean warming, acidification, and deoxygenation, which can exert more lasting pressures on ecosystems and biodiversity. Thus, volcanic activity serves not only as a key process for transferring Earth's internal materials and energy to the surface, but also as a major geological driver linking climate change, oceanic changes, landscape evolution, and biological evolution. Future research should further focus on the long-term cumulative effects of different types and scales of volcanic activity, and strengthen integrated analyses among geological records, geochemical evidence, and paleoclimatic data. In particular, studies of large igneous provinces and mass extinction events should pay greater attention to eruption duration, gas emission rates, and the temporal relationships between these factors and responses in various environmental systems, thereby enabling a more accurate assessment of volcanic activity's role in major environmental changes. By comparing characteristic events across different geological periods, our understanding of the long-term connections between volcanic activity and global climate change, oceanic evolution, and biodiversity shifts can be further deepened.

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