Volcanic Eruptions and their impacts in the Past 13,000 Years

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Abstract. Volcanic eruptions represent the most direct form of material and energy release from the Earth's interior, providing the basis for the origin and evolution of life on Earth, but they can also have significant impacts on human society and the environment. Most of the existing reviews and studies on volcanic eruptions have focused on specific events or eruption patterns in a single year, but there have been few summaries of global long-term volcanic eruption patterns. This article uses 13,000 years of volcanic eruption records to summarize the forms and locations as well as causes of volcanic eruptions, and analyzes and discusses the recorded data to ultimately expound on the impacts of volcanic eruptions. According to their frequency of occurrence, the 20 existing types of volcanoes were ranked in the article, with stratovolcanoes, shield volcanoes, and volcanic fields taking the top three spots. After explaining various forms of volcanic eruptions, including Plinian, Strombolian, Hawaiian, and Vulcanian, this article analyzed and summarized existing data records. Firstly, it evaluated the methods of data recording and found that in recent years, most records were made through direct instrument observations. Based on this, it concluded that volcanic eruptions have been increasing in the past 100 years. Finally, the impacts of volcanic eruptions are identified, including temperature, climate, plants, air and water quality, human society, and the polar environment. This article provides a reference for future research on volcanic eruptions, particularly on their impacts in polar regions.

Keywords: Vlcanic eruptions; long-term record; impacts; Polar Regions.

1. Introduction

Volcanoes are a common geological phenomenon. Volcanic eruptions are usually sudden and violent, which are highly destructive and pose a significant natural hazard to human survival and development [1]. According to incomplete statistics, there are over 1,500 active volcanoes (which have erupted in the past 10,000 years) and tens of thousands of dormant volcanoes worldwide, mainly distributed in the four major volcanic belts: the Circum-Pacific Volcanic Belt, the Mid-Oceanic Ridge Volcanic Belt, the Mediterranean-Himalayan Volcanic Belt, and the East African Rift Valley Volcanic Belt. Since 1980, volcanic disasters with historical records have caused nearly 300,000 deaths worldwide and economic losses of billions of dollars [2]. The data and records of volcanic eruptions have reached a certain scale, and the summary of volcanic eruption phenomena and impacts has sufficient socioeconomic value [3].

Currently, many scholars around the world are conducting research on volcanic eruptions. Approximately 800 million people worldwide live within 100 km of active volcanoes (those that have erupted within the past 10,000 years), and potential volcanic eruption disasters pose the greatest threat to the lives and property security of these regions (even globally). Research conducted by Guo et al. has shown that volcanic activity is the main way in which volatile substances such as CO_2 are emitted from deep within the Earth, which has an important impact on the evolution of global climate [4]. In particular, the mega eruption of the Hunga Tonga-Hunga Ha'apai volcano on the island of Tonga in January 2022 has once again brought the dangers of volcanoes to the public's attention [5, 6]. The tsunami it caused could have serious impacts on the globe, including Polar Regions [7]. However, existing studies have not yet summarized the abundant data on volcanic eruptions over the past 13,000 years, and information on the effects of volcanic tsunamis on Polar Regions is lacking.

The main purpose of this article is to analyze the forms and eruption styles of volcanoes and to summarize and analyze their impacts. Starting from the summary and generalization of the main forms of volcanoes, including stratovolcanoes, shield volcanoes, pyroclastic cones, and calderas, this article explains the eruption styles of volcanoes, such as Plinian, Strombolian, Hawaiian, and Vulcanian eruptions. The article also analyzes the existing records of volcanic eruptions, identifies the main methods of recording volcanic eruptions, summarizes the gradual increase in the number of volcanic eruptions, and finally elucidates the main impacts of volcanoes, particularly on Polar Regions.

2. Types and locations of volcanoes

The information presented here is sourced from the Smithsonian Institution Global Volcanism Program (GVP) [3].

2.1. Types of volcanoes

Volcanic types and structures are characterized by the diverse features and forms that can be observed on and around volcanoes. Volcanoes are classified into different types based on their shape and composition, such as stratovolcanoes, shield volcanoes, pyroclastic cones, and calderas. The classification of the 20 main types of volcanoes is presented in Fig. 1(a), with stratovolcanoes being the most common type. Shield volcanoes and pyroclastic cones rank second and third, respectively. On average, there are 47.6 of these 20 types of volcanoes.

Stratovolcanoes, or composite volcanoes, are steep-sided volcanoes composed of many layers of volcanic ash, pumice, and lava. They are predominantly found in subduction zones, where one tectonic plate is forced beneath another. Stratovolcanoes have more explosive eruptions than shield volcanoes due to their more viscous magma, which contains more trapped gases. Shield volcanoes are broad, gently sloping volcanoes built from many layers of fluid lava flows. They are named "shield" volcanoes because they resemble a warrior's shield lying on the ground. Hawaii's Mauna Loa is the largest shield volcano on Earth. Shield volcanoes typically have a lower viscosity of lava that is easy to flow and spread over large distances. Pyroclastic cones are the simplest type of volcano, built from particles and blobs of lava ejected from a single vent. They typically have a bowl-shaped crater at the summit and rarely reach heights greater than 300 meters. Pyroclastic cones are formed from small, short-lived eruptions that release a relatively small amount of magma. Calderas are large, basin-shaped depressions that form when a volcano collapses after a massive eruption or series of eruptions. Calderas can be several kilometers wide and may contain a lake or other body of water. Fissure vents are long, narrow cracks in the Earth's surface through which lava erupts. They can be found in groups or as single features, producing large lava flows covering extensive areas. Lahars are volcanic mudflows composed of ash, rock, and water that can occur during and after volcanic eruptions. They can be very destructive and can cause significant damage to infrastructure and homes.

2.2. Locations of volcanoes

The global distribution of active volcanoes is of significant interest to geologists and volcanologists. According to the data sourced from GVP, there are approximately 1,500 active volcanoes worldwide that have erupted within the last 10,000 years, with over 500 of these having erupted during human history. However, a significant number of these volcanoes are located on the ocean floor, and their eruptions rarely reach the surface, making them challenging to observe and record accurately.

The circum-Pacific region hosts approximately 80% of the world's active volcanoes, and countries such as Indonesia, the Philippines, and Japan are situated on the southwestern edge of the Pacific plate, accounting for one-third of the world's active volcanoes. Notably, the United States has the highest number of volcanoes of any country, as illustrated in Fig. 1(b). Fig. 1(c) provides a summary

of regions worldwide where volcanoes are present. Collectively, volcanoes in these countries represent the overwhelming majority of active volcanoes globally.

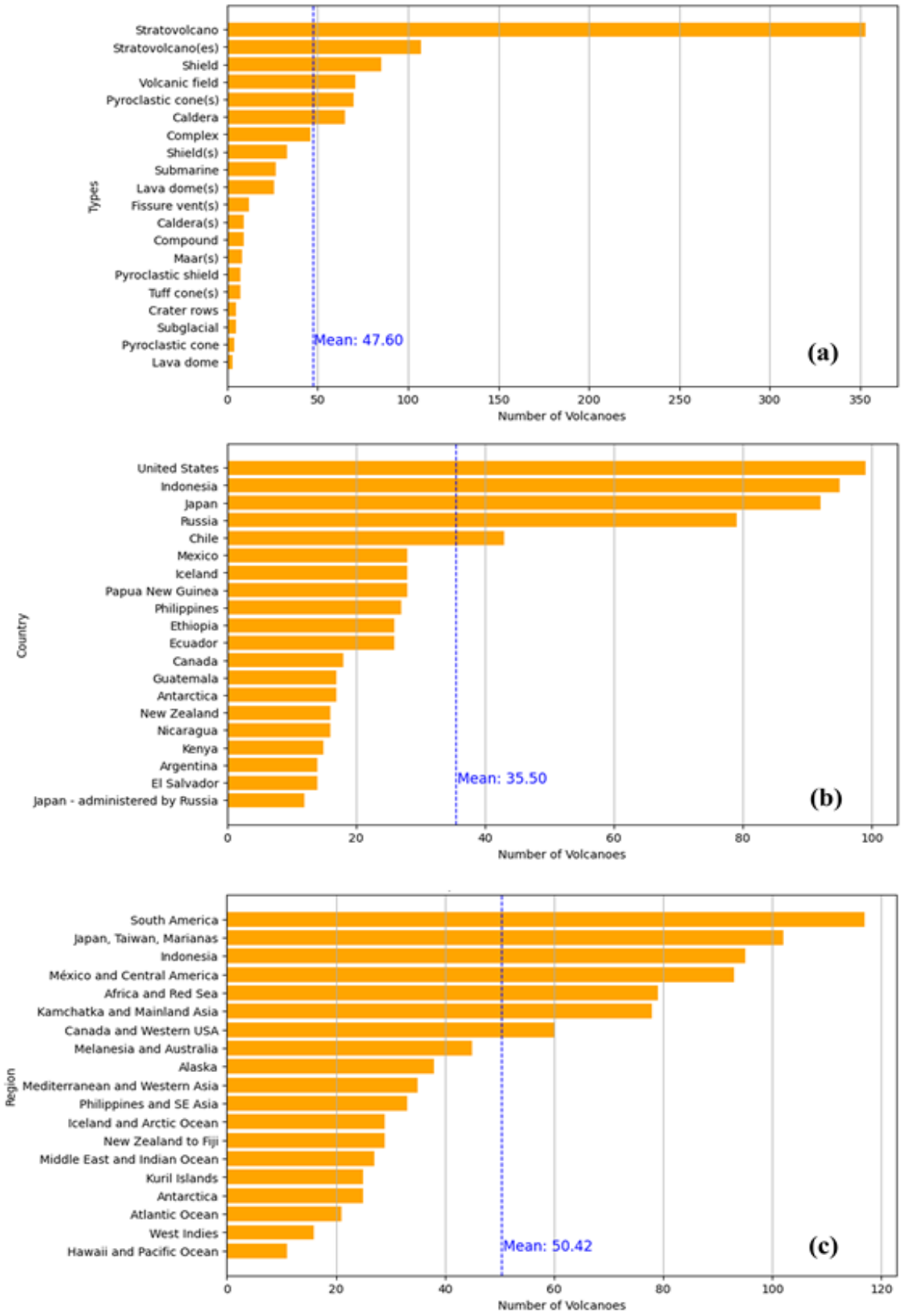


Figure 1. The classifications of volcanoes. (a) Classification of the 20 main countries with volcanoes; (b) Classification of the 20 main regions with volcanoes; (c) Classification of the 20 main types of volcanoes.

3. Causes of volcanic eruptions

There are over 5,000 volcanic eruptions of various types each year, mostly due to frequent eruptions of submarine volcanoes. However, there are also several dozen volcanic eruptions recorded each year, which can be mainly attributed to four styles.

3.1. Plinian volcanic eruption

A Plinian volcanic eruption is an exceptionally explosive event that typically involves the eruption of silica-rich magma under high pressure and with high volatile content. As a result, the magma can violently explode and be ejected from the volcano at high velocities [8]. The resulting volcanic ash can form deposits that extend over several thousand square kilometers in the vicinity [9, 10]. The eruption of Mount Vesuvius in AD 79, a Plinian eruption, provides a famous example of the destruction caused by such events, as it buried the ancient cities of Pompeii and Herculaneum under volcanic ash in a single night [11, 12]. The distribution characteristics of volcanic ash formed by Plinian volcanic eruptions have been studied by Walker [13], who introduced the concept of "sub-Plinian deposits" with a relatively limited distribution range. This suggests that the degree of fragmentation and distribution range of volcanic ash deposits can serve as a useful indicator for identifying the type of volcanic eruption. In practical research, therefore, the observation of sedimentary deposits can be utilized to identify Plinian volcanic eruptions.

3.2. Strombolian volcanic eruption

A Strombolian volcanic eruption is a volcanic eruption with moderate intensity characterized by a sequence of frequent explosions. The explosions are believed to be triggered by one or more ascending gas bubbles exsolved from magma, and the strength of the explosion is directly related to the pressure within the bubbles [14]. During the eruption, small amounts of magma fragments are carried by hot gases and ejected almost vertically from the volcanic vent, often accompanied by steam clouds. Unlike Plinian volcanic eruptions, Strombolian eruptions do not have a sustained eruptive column and carry relatively little lava material from magma gases. They occur several times per hour, with rest periods ranging from several tens of minutes to several tens of days, and often occur in magma with lower viscosity [15]. The exsolved gas bubbles can separate from the magma at the vent, leading to the explosion and the observed eruption phase, while the melt phase transitions smoothly from vertical ascent to horizontal lava flow [16].

3.3. Hawaiian volcanic eruption

Hawaiian volcanic eruption is a type of volcanic eruption that is represented by the Hawaiian Islands in the United States, which is of low power and low intensity. The main eruptive product is a basaltic lava flow. If the magma has a high volatile content, the lava will have greater eruptive pressure and may form lava fountains as the gas bubbles expand. The duration of the eruption (several hours) and the eruptive cycle (several weeks) are relatively long compared to the Strombolian volcanic eruption (several seconds, several tens of minutes) [17].

3.4. Vulcanian volcanic eruption

Hawaiian volcanic eruption is a type of volcanic eruption that is represented by the Hawaiian Islands in the United States, which is of low power and low intensity. The main eruptive product is a basaltic lava flow. If the magma has a high volatile content, the lava will have greater eruptive pressure and may form lava fountains as the gas bubbles expand. The duration of the eruption (several hours) and the eruptive cycle (several weeks) are relatively long compared to the Strombolian volcanic eruption (several seconds, several tens of minutes) [17]. The Vulcanian volcanic eruption consists of a series of discrete explosions that occur near the volcano’s surface, with time intervals ranging from several tens of minutes to several hours [16]. The erupted magma is mostly andesite or basaltic andesite. If some of the magma formed early in the eruption does not reach the surface, it

will form a thick, solidified crust on the upper part of the volcano. The gas accumulates beneath the solidified crust, causing the volatile content in the melt to become saturated, the pressure to increase, eventually leading to an explosion. Explosions are usually accompanied by cauliflower-shaped eruption clouds rich in volcanic ash. The increase in pressure may be due to the exsolution of gas from the magma or contact with shallow groundwater [18, 19].

4. Records and impacts of volcanic eruptions

4.1. Record method counts

Record of volcanic eruptions within the past 13,000 years. Between the years dating back to 11,000 BCE and 2019, there were a total of 9,891 volcanic events recorded by GVP. These records were collected through various methods, including Historical Observations, Radiocarbon, Varve Count, Ice Core, Magnetism, and Tephrochronology, totaling 19 different methods.

Based on the statistics presented in Table 1, historical observations emerge as the most prominent method for documenting volcanic eruptions. This method has been predominantly employed in recent years and dates back to as early as 1500 BCE, as evidenced by the dataset. Radiocarbon dating, which estimates the age of a sample by measuring its 14C/12C ratio, is susceptible to inaccuracies due to the variability of this ratio across different carbon exchange reservoirs. Consequently, Table 1 includes an "uncorrected" radiocarbon category to account for this uncertainty.

Table 1. Statistics of Methods to Record Volcanic Eruptions.

Number	Method	Counts
1	Historical Observations	6383
2	Tephrochronology	1046
3	Radiocarbon (uncorrected)	981
4	Radiocarbon (corrected)	852
5	Varve Count	187
6	Ice Core	116
7	Hydrophonic	68
8	Magnetism	58
9	Anthropology	38
10	Uranium-series	31
11	Ar/Ar	29
12	Surface Exposure	29
13	Potassium-Argon	22
14	Dendrochronology	15
15	Thermoluminescence	11
16	Hydration Rind	11
17	Uncertain	6
18	Fission track	3
19	Seismicity	3
20	Lichenometry	2

4.2. Annual count of volcanic eruptions

The criterion for the volcanic eruption year in this study is the initial eruption year of volcanic activity. In fact, a volcanic activity often lasts for multiple years, but in this study, subsequent ongoing eruptions are not counted as the year of the volcano's initial activity.

During the 13,000 years of recorded volcanic activity, the number of observed eruptions has been increasing each year, as shown in Fig. 2(a). The most likely reason for this is the gradual development of observation methods as human society has progressed and the growing awareness of the importance of recording natural phenomena for studying natural laws. However, in fact, observations from the last 100 years, during which modern observation methods have been available, only account

for 33.84% of the total data. Therefore, volcanic eruption records from 1919 to 2019 were analyzed separately, as shown in Fig. 2(b).

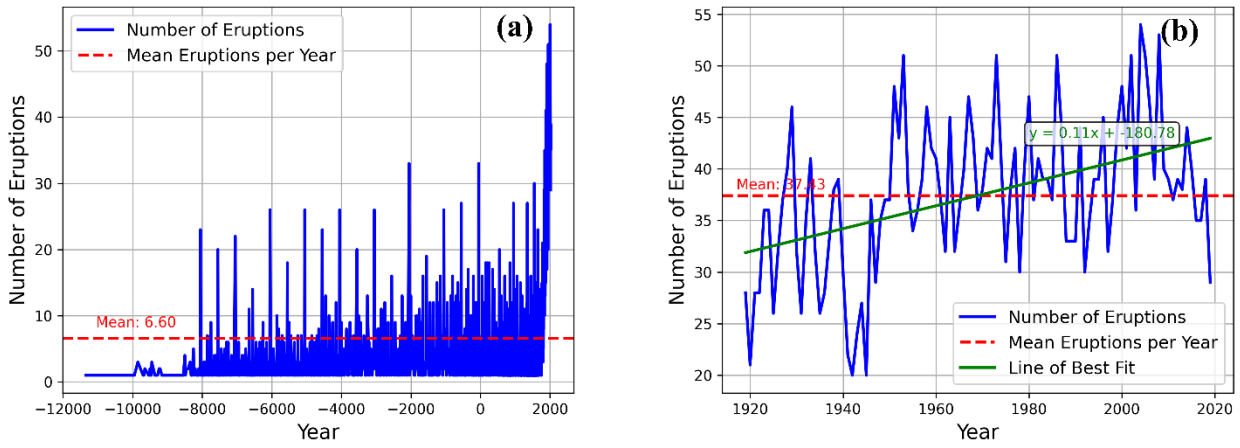


Figure 2. Volcanic Eruptions by Year. (a) Annual count from 11000 BCE to 2019 CE; (b) Annual count from 1919 to 2019 CE.

As shown in Fig. 2(b), the number of volcanic eruptions is increasing at a rate of 0.11 per year. In fact, according to Li et al.'s research, the past 600 years have been a period of global volcanic eruption growth [20], with the frequency of volcanic activity continuing to increase.

4.3. Impacts of volcanic eruptions

The Earth has entered a new phase of volcanic activity, with the impact of volcanic eruptions on the environment becoming increasingly prolonged and severe. For example, after the eruptions of Indonesia's Agung volcano in 1963, Mexico's El Chichon volcano in 1982, and the Philippines' Pinatubo volcano in 1991, the climate exhibited abnormal phenomena that lasted for about 1-3 years and even more [20]. The effects of a volcanic eruption can range from local damage to not only global environmental changes but also human's society. Here are some of the impacts of volcanic eruptions:

4.3.1. Temperature

Volcanic eruptions impact significantly on ocean and land temperatures, especially in areas close to the eruption. Underwater volcanoes can heat up the water, which can have detrimental effects on marine life. Similarly, volcanoes on land can cause the cooling of the environment. Ash and sulfur dioxide released into the atmosphere can block the sun's rays and lower the temperature. For instance, the eruption of Mount Pinatubo in the Philippines in 1991 resulted in a global temperature decrease of about 0.5 degrees Celsius for several years.

4.3.2. Climate

Volcanic eruptions can have a considerable impact on the Earth's climate system through the emission of substantial quantities of sulfur dioxide into the atmosphere. The released sulfur dioxide reacts with atmospheric water vapor to produce sulfuric acid aerosols that can scatter solar radiation, resulting in a net cooling effect on the planet's surface. This cooling effect is primarily attributable to the increased atmospheric albedo, which causes a reduction in the amount of incoming solar radiation absorbed by the Earth's surface. However, the duration of the cooling effect is often limited in time, lasting from several months to a few years, due to the rapid removal of the aerosols from the atmosphere through precipitation or other deposition mechanisms. Furthermore, the magnitude of the volcanic climate impact can vary significantly depending on the eruption's size, duration, and altitude, as well as the geographical location and prevailing atmospheric conditions.

4.3.3. Plants

Volcanic eruptions can result in substantial and diverse impacts on plant life and vegetation. The ash, tephra, and other pyroclastic materials discharged from a volcano can blanket extensive areas of

land, causing substantial damage and destruction to plant species. The loss of plant life can trigger a multitude of ecological repercussions and disturbances, including altered nutrient cycling, disrupted food webs, and habitat loss for various fauna that depend on these plants for their survival. Such impacts may persist over the long term, exerting cascading effects that can be challenging to reverse or mitigate, particularly in fragile ecosystems.

4.3.4. Human society

Volcanic eruptions can also have an impact on transportation and infrastructure. Ash can cause damage to engines, buildings, roads, and other infrastructure. The eruptions also significantly impact human health, which can cause respiratory problems and other health issues, particularly for vulnerable populations such as children and the elderly. In addition, volcanic eruptions can lead to displacement and disruption of communities, causing social and economic impacts. In the meantime, they can affect air and water quality, which are important to human lives as well.

4.3.5. Polar regions

Large volcanic eruptions, such as the eruption of Tonga volcano, can have global impacts through the air and ocean, including in Polar Regions [6]. They can trigger extremely high waves or even tsunamis that propagate to the Polar Regions, stirring up sea ice and icebergs, eroding glaciers, ice shelves, ice caps, and ice sheets, causing glacial melt and ice shelf collapse [7]. These impacts can potentially have irreversible effects on Polar Regions, not only affecting the polar ecosystem and glacial mass balance, but also potentially impacting the global ecological environment. The effects of volcanic eruptions on Polar Regions are of particular concern, as these regions are already experiencing rapid climate change and warming. In addition, Polar Regions play a crucial role in regulating the Earth's climate system, and their disruption could have far-reaching consequences for global climate. Therefore, it is essential to conduct further research on the potential impacts of volcanic eruptions in Polar Regions, in order to understand better and mitigate the potential risks associated with such events.

5. Conclusion

Volcanic eruptions represent a manifestation of the release of energy from within the Earth, a process that has been ongoing for over 4.6 billion years of Earth's history. Throughout this long history, volcanic activity has persisted almost without cessation, and its impacts on both natural ecosystems and human societies have been catastrophic, threatening the very environment upon which humanity depends for survival. The article ranked the 20 existing types of volcanoes based on their frequency of occurrence, with stratovolcanoes, shield volcanoes, and volcanic fields being the top three. After discussing multiple types of volcanic eruptions such as Plinian, Strombolian, Hawaiian, and Vulcanian, this article examined and summarized available data records. It first assessed the recording methods and found that in recent years, measurement tools gradually improved, more and more volcanic eruptions could be statistically observed using instruments. Based on this, it is concluded that volcanic eruptions have been on the rise over the last century (from 1919 to 2019). Finally, the article comprehensively summarized the long-term impacts of volcanic eruptions on the natural environment, such as temperature, climate, and vegetation, as well as their effects on human property and health, and the potential impacts on Polar Regions. With more observational data, future research can provide more detailed analyses of volcanic eruption events. This article provides a reference and support for subsequent research on volcanic eruptions and changes in polar material balance.

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