Gondwana Research 19 (2011) 1054–1061

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Explosive volcanic eruptions triggered by cosmic rays: Volcano as a bubble chamber

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ARTICLE INFO

Article history:
Received 25 September 2010
Received in revised form 3 November 2010
Accepted 10 November 2010
Available online 18 November 2010

Editor: M. Santosh

Keywords:
Volcanic eruption
Cosmic ray
Muon
Nucleation
Snowball Earth

ABSTRACT

Volcanoes with silica-rich and highly viscous magma tend to produce violent explosive eruptions that result in disasters in local communities and that strongly affect the global environment. We examined the timing of 11 eruptive events that produced silica-rich magma from four volcanoes in Japan (Mt. Fuji, Mt. Usu, Myojin-sho, and Satsuma-Iwo-jima) over the past 306 years (from AD 1700 to AD 2005). Nine of the 11 events occurred during inactive phases of solar magnetic activity (solar minimum), which is well indexed by the group sunspot number. This strong association between eruption timing and the solar minimum is statistically significant to a confidence level of 96.7%. This relationship is not observed for eruptions from volcanoes with relatively silica-poor magma, such as Izu-Ohshima. It is well known that the cosmic-ray flux is negatively correlated with solar magnetic activity, as the strong magnetic field in the solar wind repels charged particles such as galactic cosmic rays that originate from outside of the solar system. The strong negative correlation observed between the timing of silica-rich eruptions and solar activity can be explained by variations in cosmic-ray flux arising from solar modulation. Because silica-rich magma has relatively high surface tension (~0.1 Nm^{-1}), the homogeneous nucleation rate is so low that such magma exists in a highly supersaturated state without considerable exsolution, even when located relatively close to the surface, within the penetration range of cosmic-ray muons (1–10 GeV). These muons can contribute to nucleation in supersaturated magma, as documented by many authors studying a bubble chamber, via ionization loss. This radiation-induced nucleation can lead to the pre-eruptive exsolution of H_2O in the silica-rich magma. We note the possibility that the 1991 Mt. Pinatubo eruption was triggered by the same mechanism: an increase in cosmic-ray flux triggered by Typhoon Yunya, as a decrease in atmospheric pressure results in an increase in cosmic-ray flux. We also speculate that the snowball Earth event was triggered by successive large-scale volcanic eruptions triggered by increased cosmic-ray flux due to nearby supernova explosions.

1. Introduction

Explosive volcanic eruptions have the potential to result in major disasters, even in modern societies. Such eruptions affect the environmental at local and global scales: fallout of volcanic ash from eruption plumes can disrupt road and rail traffic, pollute water and air, and damage crops, thereby causing problems for local communities. The potential magnitude of the effects of explosive volcanism is greater than ever, as several mega-cities (Tokyo, Naples, and Mexico City) are located close to active volcanoes.

Large eruptions also strongly influence the global environment, especially the stratosphere. For example, the 1991 Pinatubo eruption in the Philippines emitted a large amount of fine particles and aerosols into the stratosphere (Deshler et al., 1993), where they remained for 3 years, absorbing 5% of the incoming sunlight (Minnis et al., 1993) and causing global cooling (0.5–0.6 °C) in the troposphere and corresponding warming in the stratosphere (Robock, 2002; Parker et al., 1996). These particles also accelerated the rate of damage to the ozone layer (Randel et al., 1995). The eruption also released 20 million tons of SO_2 to the stratosphere, which had a considerable impact on the SO_2 flux (Bluth et al., 1992).

Although the 1991 Pinatubo eruption was one of the largest of the 20th century, historical and geological records reveal that much larger eruptions occur on Earth at every hundreds of years. For example, the Laki eruption in Iceland in 1783 was one of the major eruption events in recent centuries, causing tremendous loss of life and having a pronounced effect on human activities worldwide, including widespread cooling throughout the Northern Hemisphere. In the same year, Mt. Asama in Japan erupted. The occurrence of several cold years, probably resulting from these two eruptions, gave rise to the Tenmei famine in Japan, which led to hundreds of thousands of deaths.

Explosive volcanic eruptions are driven by the exsolution of volatiles (mainly H_2O and to a lesser degree CO_2 and other gases) that are initially dissolved in molten magma, which is usually rich in

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doi:10.1016/j.gr.2010.11.004

volatile components, as the melting temperature of silicate compounds shows a dramatic decrease in the presence of volatile components, especially H_2O (e.g., Suzuki et al., 2007). During an inactive phase within a volcano, super-saturation of the magma in the conduit and the magma chamber occurs via magma ascent, which leads to decompression or fractional crystallization, resulting in turn in an increase in the concentration of remaining volatiles. This process results in bubble nucleation and growth, causing an increase in magma volume and the consequent arrival of the system at a critical stage for the eruption of bubbly magma. Given an appropriate trigger (e.g., earthquake shock or ascension of new magma), explosive foaming initiates in the magma conduit, thereby removing overlying rocks located near the surface of the volcanic edifice. A rarefaction wave, resulting from a sudden decrease in external pressure, travels down through the conduit and excites the nucleation and growth of bubbles in underling magma. This explosive increase in pressure and decrease in density in the magma chamber leads to the subsequent ascent of magma to produce a series of volcanic eruptions. The likely trigger mechanism of volcanic eruption remains poorly understood. Proposals to date include earthquake shock, the effects of a strong storm system, ascension of new magma and a sudden increase in super-saturation pressure due to crystallization (Gilbert and Sparks, 1998).

High-energy quanta, like cosmic-ray particles, has a possibility to mediate phase-transition of a supercritical media because of the high density of deposited energy by them, even though their averaged energy flux is negligibly low. It is well known that the cosmic-ray flux is modulated by the solar magnetic activity. We, therefore, examined the relationship between solar magnetic activity and 11 explosive eruptions from silicate-rich volcanoes in Japan over the past 306 years. Nine of the eruptions occurred during the inactive phase of solar activity (solar minimum), raising the possibility of an extraterrestrial control on explosive eruptions from silica-rich volcanoes. To explain this correlation, we propose a model in which eruptions are triggered by bubble nucleation induced by cosmic-ray muons. Unlike other channels of particles and electromagnetic waves (e.g., UV and visible light), muons with an energy of 1–10 GeV can penetrate about 10 m into porous volcanic rocks (which have an effective mean density as low as 1300–2000 kg m^{-3}). Such muons are produced by collisions in the atmosphere between nuclei and energetic cosmic-ray particles (mainly protons). It is well known that the cosmic-ray flux is modulated by solar magnetic activity: the flux is about 10–20% higher during the solar minimum. The proposed trigger mechanism applies to magma located within 10 m of the surface, not deep in the magma chamber located several kilometers below the surface, which is the area most commonly considered in terms of eruption triggers.

In a silica-rich magma, the nucleation rate of bubbles by thermal fluctuation is negligibly small because the surface tension of such bubbles is as high as 0.1 Nm^{-1}. In such magma, the net change in the Helmholtz free energy upon the formation of a spherical gas bubble ($\sim 10^{20}$ J) is higher than the thermal energy ($kT \sim 10^{18}$ J) in the magma (1000–2000 K); consequently, the ascending magma in the conduit remains in a supersaturated state without significant exsolution. In contrast, high-energy radiation, which has a much higher energy than thermal energy, can create embryo nuclei of bubbles in such supersaturated magma; in fact, a bubble chamber makes use of supersaturated liquid such as H_2 or propane (C_3H_8) to detect charged particles (Glaser, 1954; Glaser et al., 1956).

A charged particle loses energy via the ionization of molecules. There are two sources of radiation dose in magma: high-energy muons (1–10 GeV) produced by energetic cosmic rays in the atmosphere, and the decay of radioactive isotopes (mainly ^{40}K) in magma. The former effect varies over time by several percent depending on solar magnetic activity and atmospheric pressure, whereas the latter is stable for millions of years (the half-life of ^{40}K is 1.277×10^9 years). According to the theory of a bubble chamber (Seitz, 1957), molecules damaged by the ionization of passing charged particles have the potential to act as heterogeneous nucleation sites; such molecules include positive and negative ions, and temporal deficits. These nucleation sites are rapidly quenched or de-excited by the recombination of ions or redistribution of atoms in the liquid, and do not lead to actual bubble formation; however, a slight increase in radiation dose would exceed the maximum quenching capability of the magma, resulting in bubble formation and explosive exsolution of the magma (i.e., volcanic eruption).

The remainder of the present paper is organized as follows. In Section 2, we present the results of a correlation analysis of cosmic-ray flux and eruptive events from volcanoes with silica-rich magma. In Section 3, we propose an explanation of the obtained correlation, involving bubble nucleation induced by cosmic rays. Finally, a discussion, including implications for future work, is provided in Section 4.

2. Correlation between volcanic activity and muon flux

2.1. Selection of volcanoes

In our analysis, we focus on volcanoes with silica-rich magma (SiO_2 content >63%, corresponding to compositions ranging from dacite from ryolite). In such silica-rich magma, there occurs only negligible thermal nucleation of bubbles, meaning that excitation by cosmic rays is relatively important. There are 29 volcanoes in Japan with silicate-rich magma (8 rhyolitic, 11 dacitic to rhyolitic, and 10 dacitic) (Geological Survey of Japan, 2006). Of these, four (Mt. Fuji, Mt. Usu, Myojin-sho, and Satsuma-Iwo-jima; Fig. 1) have erupted 11 times between them over the past 306 years (between AD 1700 and AD 2005), the period for which a historical record of sunspot numbers is available and from which modulation of the cosmic-ray flux by the solar wind can be ready reconstructed. There have been no eruptions over the past 1000 years involving a rhyolitic magma source (e.g., Kozushima volcano). Among the volcanoes that produce dacitic to rhyolitic magma, only Mt. Usu in Hokkaido has erupted repeatedly during the past 306 years. Mt. Usu has erupted seven times since AD 1700: in AD 1769, AD 1822, AD 1853, AD 1910, AD 1944, AD 1977, and 2000 AD (Geological Survey of Japan, 2006). Among the other dacitic to rhyolitic volcanoes, only four eruption events are known: Mt. Fuji in AD 1707, Satsuma-Iwo-jima in AD 1934, and Myojin-sho in AD 1952

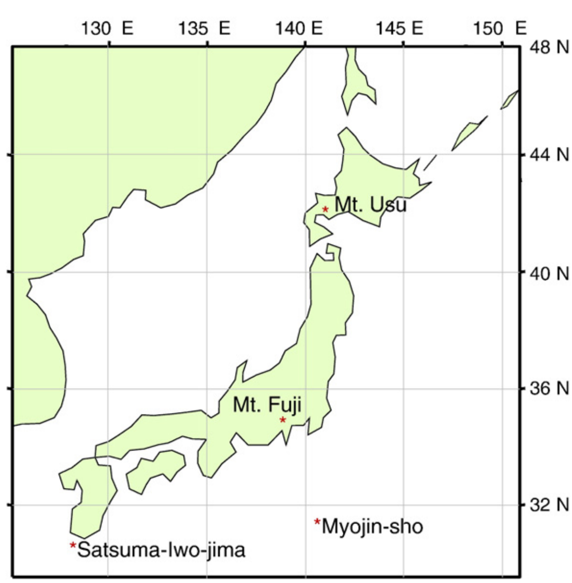

Fig. 1. Locations of the four volcanoes with silicate-rich magma that have erupted in Japan over the past 306 years.