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Temporal scaling of volcanic eruptions

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ABSTRACT

Volcanoes are a manifestation of the planet's past and present internal dynamics and are also a major natural hazard. Statistical analysis of volcanic eruptions is important in evaluating the risk they pose. Several stochastic models were suggested to describe the temporal sequences of eruptions. However, comprehensive understanding of the physical mechanisms responsible for eruptions remains elusive. In this work, we propose a scaling law to quantify the distribution of interevent times between eruptions for volcanoes that have the largest eruptive history as well as groups of volcanoes on Earth. We found that probability density functions have a similar functional form when they are rescaled with the corresponding sample averages. The obtained scaling law for interevent times can be modeled using the log-normal distribution and signifies that the dynamics of volcanic eruptions on Earth is similar and quite independent of the type of volcanism and the geographical location of volcanoes. The phenomenon of triggering volcanic eruptions operates in a similar way for all volcano types, which emphasizes the importance of studying volcanism as a universal process.

1. Introduction

Volcanic eruptions are outcomes of complex processes that operate in the upper mantle and crust when magma reaches the surface of the Earth. They constitute a major natural hazard on Earth especially in the areas with significant population density. Therefore, understanding the processes taking place in the magma chamber and surrounding crust that lead to an eruption is of fundamental importance. A typical approach to studying volcanoes involves examination of their structures, tectonic settings and associated eruptive activities. In contrast, statistical analysis is a powerful tool that can be used to identify patterns and correlations in the occurrence of volcanic eruptions. The first statistical analyses of eruption time series were performed on individual volcanoes in Hawaii and groups of volcanoes in Japan (Wickman, 1966; Klein, 1982). Since then, stochastic models and various distributions have been proposed on selected volcanoes such as homogeneous and non-homogeneous Poisson models (De la Cruz-Reyna, 1991; Ho, 1991; Salvi et al., 2006), Weibull renewal model for volcanoes in New Zealand (Bebbington and Lai, 1996), or a mixture of exponential distributions (Mendoza-Rosas and De la Cruz-Reyna, 2009). Rank-ordering power-law statistics was used to predict the repose time of extreme volcanic eruptions and the method was applied to the Taupo volcano (Pyle, 1998). The frequency-magnitude statistics of historical recurrence rates of large explosive eruptions was analyzed using extreme value theory (Deligne et al., 2010). The temporal structure of global sequences of explosive eruptions in Kamchatka was analyzed and self-similar clustering and episodicity were observed (Gusev et al., 2003). Clustering was also observed on the onsets of volcanic eruptions and their statistical behavior was modeled using a trend renewal process (Bebbington, 2010).

A promising approach to study volcanism is to look at the phenomenon as a whole in order to develop a general framework applicable to all the volcanoes, independent of the volcano's type and geographical location. This type of statistical analysis has been successfully applied to other natural processes and several scaling laws, implying that the triggering mechanism operates the same way at broad spatial and temporal scales, have been proposed in studies of seismicity (Corral, 2003), forest fires (Corral et al., 2008), solar flares (Baiesi et al., 2006), tropical cyclones (Corral et al., 2010), and in the occurrence of rock fracturing (Åström et al., 2006; Davidsen et al., 2007). Similar to the aforementioned processes, volcanism operates through nonlinear threshold dynamics. Despite this complexity, one can consider volcanic eruptions as a point process in space and time. In addition, the distribution of magnitudes and/or Volcanic Explosivity Index (VEI) of volcanic eruptions, displays scale-invariant characteristics (Newhall and Self, 1982; De la Cruz-Reyna, 1991; Simkin, 1993; Gusev et al., 2003). The cumulative distribution of the annual amount of tephra produced by eruptions also exhibits power-law behavior (Turcotte, 1997). A few statistical analyses have been performed on global data sets of volcanic eruptions. Gusev (2008) observed self-similar clustering in time and size for eruptions. It was also observed that large eruptions tend to occur during the most volcanically active periods. These characteristics of global volcanic activity lead to the conclusion that a global mechanism was responsible for the time/size

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clustering. Marzocchi and Zaccarelli (2006) observed two different regimes concerning interevent times: short times are clustered and can be explained by an open conduit system while long interevent times show random behavior, that can be characterized by a Poisson process and explained by a closed conduit system. These two regimes were also associated with different rhythms in magmatic intrusions (Dubois and Cheminee, 1991).

In this work, we analyzed the scaling properties of volcanic eruptions on Earth. For this purpose, we considered eruptive histories of the 26 most active volcanoes as well as eruptions of 163 less active volcanoes around the world. The volcanoes were also analyzed by grouping them into 9 geographical regions as well as grouping into 4 volcano types: calderas, complex volcanoes, shield volcanoes, and stratovolcanoes. We computed the distributions of interevent times between successive eruptions for all the eruption data sets considered. The scaling analysis was performed to quantify their universal properties. This was accomplished by using the corresponding mean interevent time of each data set as a scaling factor. A collapse of all the distributions into a single functional form for interevent times lead us to conclude that the processes responsible for volcanic eruptions on Earth were similar and quite independent of the type of volcanism and geographical location.

2. Volcanic eruption data

A time interval between two successive volcanic eruptions, or an interevent time, is an important characteristic of volcano dynamics (Marzocchi and Zaccarelli, 2006; Deligne et al., 2010). When one studies the distribution of interevent times it is crucial to define what constitutes the onset of an eruption. Here, we consider the onset as the time of the arrival of volcanic products at the Earth's surface. This includes explosive ejection of fragmental material or effusion of previously liquid lava. To analyze the interevent time distributions of eruptions, we extracted eruptive histories of volcanoes on Earth from the Smithsonian Institution global eruption catalog (Siebert and Simkin, 2002) and assembled them into separate data sets. For each individual volcano data set, we computed the time intervals Δt between successive eruptions as $\Delta t_i = t_i - t_{i-1}$, with t_i being the time onset of the ith eruption. For the analysis, we ignored the eruption duration but instead measured the interevent time between the onset of one eruption and the onset of the subsequent eruption.

The incompleteness of the catalogs is an important issue that had to be addressed in our analysis. Indeed, the number of reported volcanic eruptions has dramatically increased in the past 500 years (Simkin, 1993). This is mainly due to the development of modern tools and methods for monitoring and detection of volcanic activities. Previous studies of individual and combined volcanic catalogs have addressed the problem of incompleteness with some success (Marzocchi and Zaccarelli, 2006; Bebbington, 2010; Deligne et al., 2010). To ensure that the catalogs considered in our analysis were complete and that our estimates of the interevent times were not biased by incompleteness, we introduced a cutoff date for older eruptions for each of the considered eruption sequences. The cutoff date was determined specific to each volcano sequence considered. For this type of data, as stated before, the older the eruption date, the less reliable it was. We chose the cutoff date for each volcano by detecting when the data became less reliable based on the number of uncertain dates and changes in the mean rate of eruptions. This method might not fully account for uncertain or missing eruption dates, but at present, there is no truly reliable technique to validate the completeness of the volcanic eruption catalogs to ensure sufficient data for the analysis. In comparison, when studying earthquake interevent times, one often introduces a lower magnitude cutoff in the catalogs to address their incompleteness. In our case, we were dealing with the eruptive history of individual volcanoes, and even small eruptions represent the outcome of complex processes occurring in the magma chamber and could not be ignored in our analysis. In addition, the Volcanic Explosivity Index (VEI) (Newhall and Self, 1982) used as an estimate of the eruption's magnitude only takes into account the explosive component of an eruption and ignores the volume of lava produced by effusive eruptions. However, to analyze the scaling of interevent times with respect to the lower magnitude cutoff we also considered different VEI cutoffs in our study.

For our analysis, we considered the individual eruption sequences of 26 prominent volcanoes around the world (Table 1). We selected these individual volcanoes because their eruptive histories were long enough to be considered in a statistical analysis and the events were relatively recent and therefore the dates were reasonably reliable. We also studied other volcanoes from the volcanically active regions around the world. Their eruption sequences were usually not very long so the construction of statistical distributions for interevent times was problematic. To increase statistics by assuming that volcanoes located in the same region and surrounded by similar tectonic settings produce statistically similar eruption sequences (Rodado et al., 2011), we subdivided the Earth into nine volcanically active regions: Alaska (3 volcanoes considered, 72 eruptions), Aleutians (14 volcanoes, 142 eruptions), Central America (22 volcanoes, 403 eruptions), Iceland (7 volcanoes, 100 eruptions),Indonesia (37 volcanoes, 768 eruptions), Japan (21 volcanoes, 502 eruptions), Kamchatka (11 volcanoes, 289 eruptions), New Zealand (4 volcanoes, 175 eruptions), and South America (36 volcanoes, 522 eruptions) (the detailed information for each volcano considered is given in Tables S1, S3–S11 in the on-line supplementary material). We also considered these volcanoes by classifying them into 4 groups according to their type: caldera, complex, shield, and stratovolcano (Tables S2 and S12). For each of the catalogs considered, when the day of the event was not specified, we assigned it as being the first day of the month. When both the day and the month were missing, we assigned the date to the first of July. This was done following the methodology suggested by Gusev (2008).

The individual volcanoes or groups of volcanoes produce interevent distributions over comparable length scales. In order to model

Table 1
Summary of the eruption data used for the interevent time analysis of 26 prominent volcanoes. The second column provides the number of eruptions for each volcano. The third column gives the time span of the eruption history considered for each volcano. τ_n is the mean interevent time between eruptions computed for each data set with uncertainties reported as standard errors.

Volcano (region)	#eruptions	Time span	τ_n [days]
Ambrym (Vanuatu)	46	1888–2008	976 ± 160
Asama (Japan)	110	1595–2009	1386 ± 247
Aso (Japan)	129	1434–2008	1637 ± 232
Bezymianny (Kamchatka)	53	1955–2010	387 ± 54
Colima (Mexico)	51	1519–1997	3495 ± 709
Cotopaxi (Ecuador)	58	1532–1940	2612 ± 1108
Etna (Italy)	155	1381–2010	1492 ± 217
Grimsvotn (Iceland)	44	1610–2011	3405 ± 403
Kilauea (Hawaii)	64	1790–1983	1116 ± 272
Kirishima (Japan)	55	1524–2010	3285 ± 613
Kliuchevskoi (Kamchatka)	99	1697–2009	1163 ± 156
Krakatau (Indonesia)	41	1883–2010	1164 ± 401
Llaima (Chile)	53	1640–2008	2584 ± 885
Marapi (Indonesia)	59	1770–2004	1474 ± 280
Mauna Loa (Hawaii)	38	1832–1984	1498 ± 267
Merapi (Indonesia)	56	1768–2010	1608 ± 185
Piton de al Fournaise (Reunion Island)	160	1721–2010	665 ± 61
Poas (Costa Rica)	44	1880–2009	1099 ± 163
Raung (Indonesia)	55	1815–2008	1302 ± 217
Ruapehu (New Zealand)	58	1861–2007	938 ± 206
Semeru (Indonesia)	58	1818–1967	954 ± 202
Slamet (Indonesia)	41	1772–2009	2161 ± 528
Taupo (New Zealand)	25	9460 BC–260 AD	147923 ± 47242
Tengger (Indonesia)	58	1804–2010	1322 ± 174
Tongariro (New Zealand)	68	1839–1977	755 ± 96
Villarrica (Chile)	66	1730–2009	1570 ± 173