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A statistical method linking geological and historical eruption time series for volcanic hazard estimations: Applications to active polygenetic volcanoes

Ana Teresa Mendoza-Rosas [a], Servando De la Cruz-Reyna [b,*]

[a] Universidad Nacional Autónoma de México, Posgrado en Ciencias de la Tierra, Instituto de Geofísica, Ciudad Universitaria, México 04510 D.F., Mexico
[b] Universidad Nacional Autónoma de México, Instituto de Geofísica, Ciudad Universitaria, México 04510 D.F., Mexico

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ABSTRACT

The probabilistic analysis of volcanic eruption time series is an essential step for the assessment of volcanic hazard and risk. Such series describe complex processes involving different types of eruptions over different time scales. A statistical method linking geological and historical eruption time series is proposed for calculating the probabilities of future eruptions. The first step of the analysis is to characterize the eruptions by their magnitudes. As is the case in most natural phenomena, lower magnitude events are more frequent, and the behavior of the eruption series may be biased by such events. On the other hand, eruptive series are commonly studied using conventional statistics and treated as homogeneous Poisson processes. However, time-dependent series, or sequences including rare or extreme events, represented by very few data of large eruptions require special methods of analysis, such as the extreme-value theory applied to non-homogeneous Poisson processes. Here we propose a general methodology for analyzing such processes attempting to obtain better estimates of the volcanic hazard. This is done in three steps: Firstly, the historical eruptive series is complemented with the available geological eruption data. The linking of these series is done assuming an inverse relationship between the eruption magnitudes and the occurrence rate of each magnitude class. Secondly, we perform a Weibull analysis of the distribution of repose time between successive eruptions. Thirdly, the linked eruption series are analyzed as a non-homogeneous Poisson process with a generalized Pareto distribution as intensity function. As an application, the method is tested on the eruption series of five active polygenetic Mexican volcanoes: Colima, Citlaltépetl, Nevado de Toluca, Popocatépetl and El Chichón, to obtain hazard estimates.

1. Introduction

Volcanic activity usually results from the interaction of many independent physical and geological processes acting over different time scales. The occurrence of volcanic eruptions may depend on the unknown nature of magma feeding from deeper sources, as well as the conditions of a previously resident magma, the nature of the magma mixing processes, the regional stresses, the local crustal composition and structure, the fluid distribution and composition under the volcano, the degree of fracturing, and even on some meteorological agents. These and other factors interact in complex ways introducing a random behavior on the time series of volcanic eruption occurrences.

On the other hand, volcanic eruptions may represent a serious threat on the people dwelling near a volcano, particularly when their perception of risk is negatively influenced by a large repose time, or by the lack of clear evidences of major past activity. Volcanic risk was first formally defined in UNDRO (1979) as a measure of the expected number of lives lost, persons injured, damage to property and disruption of economic activity as a result of a particular volcanic event. It was defined as the product of volcanic hazard, vulnerability and elements at risk (Fournier d'Albe, 1979). The volcanic hazard is consistently defined as the probability that a specific type of volcanic eruption occurs in a given area, within a given interval of time (De la Cruz-Reyna and Tilling, 2008) The volcanic risk is thus the probability of losing a certain percent of the value of a given exposed region over a given time interval caused by the possible occurrence of a particular volcanic eruption. Therefore, knowing the hazard allows designing adequate measures to reduce the risk through specific actions of vulnerability reduction.

Under the assumption that the past history of a volcano should reflect at least some relevant features of its expected future behavior, a careful analysis of the time series of past eruptions, that accounts for the scarcity of precise past eruption data, is essential to assess the hazard. The behavior of volcanic eruption time series of individual volcanoes shows a wide spectrum of possibilities. Some volcanoes show stationary patterns of activity, while others show time-dependent eruption rates. Nevertheless, combining the eruptions of large groups of volcanoes generates a definite homogeneous Poissonian behavior, as is the case of the overall global eruptive activity (De la Cruz-Reyna, 1991).

Early studies of volcanic time series were done by Wickman (1965, 1976) and Reyment (1969) used stochastic principles for the study of eruption patterns on specific volcanoes. However, the models presented

* Corresponding author.
E-mail address: sdelacrr@geofisica.unam.mx (S. De la Cruz-Reyna).

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by Wickman did not distinguish among eruption of different types, and as he stated in his 1976 paper, such models were not tested against observed records. Other studies, analyzed specific volcanic eruption series, as was the case of the Hawaiian volcanoes (Klein, 1982) or Colima (De la Cruz-Reyna, 1993; Solow, 2001). Bebbington and Lai (1996a,b) examined whether the Weibull renewal model was adequate to describe the patterns of two New Zealand volcanoes.

Subsequent studies became increasingly sophisticated including for instance transition probabilities of Markov chains (Carta et al., 1981; Aspinall et al., 2006; Bebbington, 2007), change-point detection techniques (Mulargia et al., 1987; Burt et al., 1994), Rank-order statistics (Pyle, 1998), Bayesian analysis of volcanic activity (Ho, 1990; Solow, 2001; Newhall and Hoblitt, 2002; Ho et al., 2006; Marzocchi et al., 2008), non-homogeneous models (Ho, 1991a; Bebbington and Lai, 1996b), a mixture of Weibull distributions (Turner et al., 2007), and geostatistical hazard-estimation methods (Jaquet et al., 2000; Jaquet and Carniel, 2006).

Different parameters have been used as random variables to characterize the eruptive time series. Among them, the most frequently used are: the duration of eruptions, the interval between eruptions, the effusion rate; the volume or mass released, and the intensity of eruptions.

The probabilities of occurrence of future eruptions, and thus the volcanic hazard, may be estimated analyzing the sequence of past eruptions in a volcano, characterizing the eruptions by a measure of size that reflects their destructive potential, and assuming that the impact and effects of an eruption are proportional to both, the total mass or energy release (magnitude) and the rate of mass or energy release (intensity). The Volcanic Explosivity Index VEI is the quantity that characterizes eruptions based on those parameters (Newhall and Self, 1982). Frequently, an eruption has been defined ambiguously as a sudden, violent discharge of volcanic material, as well as a gentle, protracted pouring of lava or fumes. For our purpose we shall consider here only significant explosive eruptions, which usually are short-duration events when compared with the time between eruptions (also referred as repose time, even if minor or gentle effusive activity occurs). The volcanic eruption sequences of polygenetic volcanoes are thus considered here as point processes developing in the time axis, and the distribution of eruptions and the repose times between them are analyzed in different VEI categories or classes.

On the other hand, merging historical (usually describing more frequent smaller eruptions) and geological (usually describing larger, infrequent eruptions) eruptive data has been pointed as an important factor for a proper estimation of the likelihood of more damaging events (Marzocchi et al. 2004).

In this paper we propose a statistical methodology for estimating the volcanic hazard of future explosive eruptions using VEI — characterized sequences linking historical and geological records to obtain robust volcanic eruption time series. We first test the independence between successive eruptions to detect possible memory effects, and the stationarity, or time dependence of the explosive eruption sequences to find a possible non-homogeneity of the process. We then use a Weibull analysis to study the distribution of repose times between successive eruptions, and a non-homogeneous generalized Pareto–Poisson process (NHGPPP, as defined below) to obtain volcanic hazard estimations. We apply this method to Colima, Citlaltépetl, El Chichón, Nevado de Toluca and Popocatépetl volcanoes in México. Finally, the hazard estimates obtained with this and other methods are discussed and compared.

2. Methodology

The first step is testing the eruptive time series for independence between successive events and for the time dependence or stationarity of the process. The independence test is simply made by means of a serial correlation scatterplot (Cox and Lewis, 1966). The latter test is performed examining the repose period series for each VEI category and using a moving average test that reveals the possible existence of significantly different eruption rates, not attributable to the local rate changes expected in a stationary random process (Klein, 1982; De la Cruz-Reyna, 1996). These tests should be performed on a portion of the time series that satisfies a criterion of completeness, i.e. a portion in which no significant eruption data are missing, which in most cases is the historical eruption data set of intermediate-to-high VEI magnitudes.

A second step is the Weibull analysis of the repose periods between eruptions, which allows a quantitative description of both, stationary and non-stationary time series through the distribution shape parameter. The time-independence tests applied on the portions of the series assumed to be complete do not guarantee that the whole of the series has been stationary over its whole length. Therefore, the third step involving the link between the historical, usually complete, and the geological, probably incomplete eruptive series requires of a method that makes the estimation of hazard less sensitive to such condition. We propose here as the best estimate of the volcanic hazard

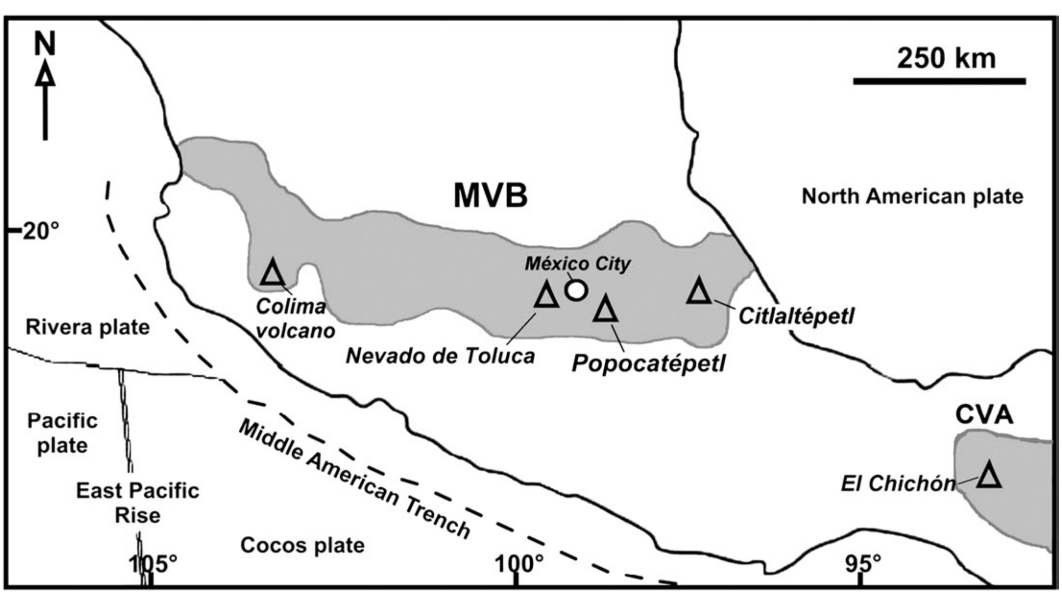

Fig. 1. Location of Colima, Nevado de Toluca, Popocatépetl, Citlaltépetl and El Chichón volcanoes.