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Temporal structure of the global sequence of volcanic eruptions: Order clustering and intermittent discharge rate

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Abstract

To study the temporal organization of global volcanic activity over time scales from years to centuries, the following three event sequences were studied: two subsets of the regular catalog of eruptions after Siebert and Simkin [Siebert, L., Simkin, T., 2002. Volcanoes of the World. . . http://www.volcano.si.edu/gvp/world/], and the "ice core volcanic index" (IVI) sequence, based on the volcanic eruption record as acid layers in big glaciers (Robock, A., Free, M.P., 1996. The volcanic record in ice cores for the past 2000 years. In: Jones, P.D., Bradley, R.S., Jouzel, J. (Eds.), Climatic Variations and Forcing Mechanisms of the Last 2000 Years. Springer-Verlag, New York, pp. 533–546). To perform the statistical analysis in a meaningful way, data subsets were extracted from the original data, with size thresholds and time intervals carefully selected to make these subsets nearly homogeneous. The analysis has revealed, generally, the tendency to clustering, manifested in the following three forms: (1) The event rate is not uniform in time: event dates form active episodes ("common" clusters). (2) In the time-ordered, sequential list of sizes of eruptions, larger events do not appear purely randomly; instead, they form tight groups ("order clusters"). (3) The volcanic products discharge rate is significantly non-uniform, and shows episodic (intermittent or bursty) behavior. It was also found that for the volcanic sequences analyzed, the two types of clustering behavior mentioned in (1) and (2) are positively correlated: larger events are concentrated at the periods of higher event rate. Such a relationship is best demonstrated by the fact that there is clear negative correlation between the following two time series: (1) of the exponent b of the power law size–frequency distribution (the analog of b-value of the Gutenberg–Richter law for earthquakes) and (2) of the current event rate. Power spectra of the analyzed sequences mostly follow power laws, with negative exponent β. Thus, these sequences can be qualified as pulse flicker noises. In other words, they are fractal sequences with correlation dimension $D_c = \beta + 1 < 1$, and both their clustering and episodicity are of self-similar character. The revealed peculiarities of the global volcanic sequence suggest that some global-scale mechanism exists that is responsible for their origin. They are also or primary importance for understanding the impact of volcanism on climate.

Keywords: Volcanic eruption; Sequence; Global; Episodic; Fractal; Clustering; Size–frequency law

1. Introduction

The temporal structure of volcanic processes is interesting in itself, important at least for phenomenological description of observations. If established, the peculiarities of the temporal structure may elucidate mechanisms that are hidden under the observed variety of volcanic phenomena. Also, the probable impact of volcanism on climate can be significantly modified when volcanic aerosol formation is systematically organized in time. One more field where the understanding of the temporal structure may be useful is the study of volcanic hazard. In a number of studies it has been noted that that the temporal structure of volcanism is non-uniform, episodic in time for such processes as ocean ridge volcanism, hot spot volcanism, explosive volcanism in island arcs and trap volcanism (Kennett et al., 1977; Rea and Scheidegger, 1979; Makarenko, 1982; Cambray and Cadet, 1996; Sigurdsson, 2000; Prueher and Rea, 2001). However, these studies analyzed episodicity only in qualitative terms; no formal description for the episodic temporal structure of these volcanic processes was proposed. The described studies did not show specific time scales for episode durations. This may suggest that active episodes arise in time in a statistically self-similar manner. For historic timescales, statistically self-similar or fractal behavior of volcanic eruption sequences has been revealed by

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Dubois and Cheminee (1988, 1991), and Telesca et al. (2002). A detailed study of fractal space–time structure of intrusions was made by Pelletier (1999).

There are, however, other viewpoints and approaches in the analysis of volcanic eruption sequences. Some studies (e.g., Wickman, 1966; Ho et al., 1991; De la Cruz-Reina, 1991; Jones et al., 1999) either assume or prove that eruptions of a particular volcanic center or of an area behave purely randomly, as a Poisson process. There are also models of non-homogeneous Poisson processes, with variable (deterministic or random) event flux density (e.g., Ho, 1991; Connor and Hill, 1995; Jaquet and Carniel, 2001). Bebbington and Lai (1996) found that the Poission model is valid for one of the two volcanoes studied, but was rejected for another one that showed short-term eruption clustering (or, equivalently, correlation between events); neither of the two manifested long-term memory (and thus fractal behavior). Similarly, Godano and Civetta (1996) found that correlation of Vesuvius eruptions, although observable at short delays, practically disappears at long delays; and Jaquet and Carniel (2001), analyzing seismic activity at Stromboli, found that only short-term memory/correlation is present. Also, tendencies to periodicity of eruptions have been revealed, e.g., by Wickman (1966) who noted cyclic behavior of individual volcanoes, by Ammann and Naveau (2003) who found an expressed 76-year cycle in volcanic activity in tropical zone since 1400 using ice core data, and by Mason et al. (2004) who found a yearly cycle of eruptive activity.

Generally, the multi-scaled clustered behavior is common but not universal tendency, and its presence for any particular data set needs separate analysis. In such an analysis, the problem of data completeness is specifically important. Although some approaches has been proposed for treatment of incomplete data (Guttorp and Thompson, 1991), really convincing results can only be obtained if one is provided with a homogeneous, consistent initial data set.

A few kinds of temporal structure of volcanic event sequences have been mentioned above. To discuss them, more accurate terminology is needed. Consider first the approach when the event size information is ignored. For such cases, we shall further call the tendency of event rate/density to form episodic maxima "common clustering". This term is needed in order to distinguish this kind of behavior from another mode of clustering that we call "order clustering". To observe this second kind of clustering, event sizes should be analyzed along with event times. Observing a sequence of events of various sizes, one can note a tendency of *large* eruptions to appear in clusters (Gusev et al., 2003). These clusters are seen in the time-ordered event list, *with accurate event times ignored*. It is important to realize that this "order clustering" phenomenon is completely independent of common clustering, when *sizes of events are ignored*, and should not be confused with the latter. Order clustering was first revealed in global and regional earthquake catalogs (Ogata and Abe, 1991; see also Gusev, 2005).

Both common and order clustering may be limited to short time/number delays (short-term clustering, with a certain limited correlation time), or to be manifested simultaneously for many time scales, including the longest among those observed. In this latter case we speak of long-term clustering, or long-term memory. In the simplest case, clustering behavior can be organized in a similar way on all analyzed time scales; then we speak of self-similar or fractal behavior (Mandelbrot, 1982). Sometimes, the analyzed range of scales can be divided into sub-ranges with different fractal behavior in each (Dubois and Cheminee, 1993); but data sets studied here are limited in volume and do not permit such a fine analysis.

Generally speaking, clusters of each of the two described kinds may arise independently. Alternatively, they can occur in some organized fashion, e.g., positively or negatively correlated. The actual mode of behavior is unknown, and its study might shed some light on the mechanisms that control the evolution of volcanism. It is difficult, however, to develop this line of study with data sets of the actual size (100–300 events). Therefore, an indirect approach was developed, based on the following observation. During the time segment occupied by an "order cluster", the fraction of large events (among all events) can be expected to be unusually high. This fact suggests that order clusters can affect the size distribution of events. For many kinds of natural (and social) phenomena, the event size distribution is near to power law (Pareto law), and this kind of distribution was also noted for eruption sizes (Turcotte, 1992; Simkin, 1993) as well as for earthquake energies/seismic moments. With respect to earthquake sequences, it is common to monitor size distribution variations through the study of the exponent of the mentioned power law, commonly denoted "the *b*-value". One can expect that this approach can be applied to volcanic sequences as well. This is done in the following, with an unexpectedly definite result: common clusters and order clusters show clear positive correlation.

Speaking abstractly, there is a multitude of modes of possible non-uniform behavior of a volcanic sequence. One of the simplest and often observed forms of such a multi-scaled behavior is the scale-invariant or self-similar behavior. Such processes are called fractal time sequences, or flicker noises (see e.g. Mandelbrot, 1999). The fractal behavior of natural and artificial phenomena attracted very wide attention recently in many fields of science; a number of studies were listed above that suggest that the formation of fractally organized clusters may be considered to be a reasonable initial hypothesis in the study a volcanic sequence. For this reason, in the following analysis the fractally clustered or intermittent behavior is considered as a main alternative to the uniform, non-clustered behavior. Recently, updated versions of two important data sets representing global volcanic activity has been kindly made available for me by their authors. In the following, these global data sets are used to achieve better understanding of the temporal behavior of global volcanism over time scales from months to hundreds of years.

When event dates and sizes are combined in a catalog of events, they define the temporal structure of the output of eruption products, further called volcanic discharge. Through the accumulation of volcanic material and thus formation of volcanic rock sequences, this output determines, to a large degree, the geological effect of volcanism. Its analysis is critical for