Available online at www.sciencedirect.com
ScienceDirect
Journal of Volcanology and Geothermal Research 173 (2008) 15 – 25
Journal of volcanology and geothermal research
www.elsevier.com/locate/jvolgeores

Empirical recurrence rate time series for volcanism: Application to Avachinsky volcano, Russia

Chih-Hsiang Ho

Department of Mathematical Sciences, University of Nevada, Las Vegas, NV 89154-4020, USA

Received 1 July 2007; accepted 7 December 2007
Available online 23 December 2007

Abstract

The volcanic activity of Avachinsky is assumed to follow a Poisson process and is fingerprinted with a sequence of empirical recurrence rate time series. The last 5 time series are used as a prediction set to check the predictive ability of the candidate model produced by time series modeling techniques. The model is used to forecast future recurrence rates that, in turn, are used to develop the mean function of the volcanic process, which is required to evaluate the probability of future eruptions. At the model validation stage, the candidate model forecasts a mean number of 2.31 eruptions for the prediction set that are close to the actual number of events, which are 2 eruptions. For a full scaled forecast, the model concludes a total of 2.37 new events for the next 25 years for the Avachinsky volcano.

Keywords: ARIMA models; ERR plot; intensity function; Poisson process; power-law process; volcanic hazard and risk

1. Introduction

A homogeneous Poisson process (HPP) has been commonly used to evaluate the recurrence rates of volcanoes (e.g. Wickman, 1966, 1976; Crowe et al., 1982; Scandone et al., 1993) until power-law process coupled with Bayesian analysis were proposed in a number of studies related to the volcanic hazard assessment of the Yucca Mountain high-level nuclear waste repository site (Ho, 1990, 1991, 1995). Volcanic probability models have advanced along related paths over the last two decades (e.g. De La Cruz-Reyna, 1993; Connor and Hill, 1995; Bebbington and Lai, 1996; Ho and Smith, 1997, 1998; Connor et al., 2000; Jaquet and Carniel, 2001; Ho et al., 2006; Christiansen et al., 2007). A vital parameter for volcanic hazard and risk assessments is the recurrence rate. This motivated us to develop a discrete time series based on the empirical recurrence rates (ERRs), computed sequentially at equidistant time intervals during an observation period. We demonstrated that the time-plot of the ERRs, referred to as the "fingerprint" or the "ERR plot," offers the possibility of further insight into the data and provides a technical basis for model developments for Avachinsky. In short, this article presents three main ideas: (1) convert Poisson processes to ERR time series, (2) study the time series using ARIMA approach (to be defined later), and (3) develop methods to retrieve the counterparts of the predicted ERRs. The first and the last main ideas are new and original contributions. Regarding the second point, the ARIMA models are well-known and time series computer packages/guides (e.g. Brockwell and Davis, 2002; Shumway and Stoffer, 2006) are available. Thus, we will not propose new developments in that area. However, we do provide detailed help to the intended audience of volcanologists throughout the entire paper to explain the practicalities of how one develops an ARIMA model. The interaction between point processes and time series created in this article provides additional opportunities for the application of time series methods to volcanic hazard and risk assessment studies.

The article is organized as follows. Section 2 presents the ERR formulation. Section 3 provides the background information of the Avachinsky volcano. Section 4 visualizes the aggregate behavior of the recurrence rate of Avachinsky using ERR plots. Section 5 reviews the basic modeling theory of ARIMA. Sections 6, 7, and 8 present the main results of the article, and Section 9 concludes.

E-mail address: chho@unlv.nevada.edu (C.-H. Ho).

0377-0273/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2007.12.003

2. Empirical recurrence rate

Let $t_1, \ldots, t_n$ be the time of n ordered eruption onsets during an observation period $(t_0,0)$ from oldest to youngest. Then, a discrete time series $\{z_\ell\}$ is generated sequentially at equidistant time intervals $t_0+h, t_0+2h, \ldots, t_0+\ell h, \ldots, t_0+Nh$ (=0 = present time or the end of an observation period). If t_0 is adopted as the time-origin and h as the time-step, then z_ℓ can be regarded as the observation at time $t=t_0+\ell h$, for the volcanism to be modeled. A vital parameter, desirable to the modelers of volcanic hazard and risk assessments, is the recurrence rate of targeted volcanism worldwide. Therefore, a time series of the empirical recurrence rates is proposed and defined as follows:

$$z_\ell = n_\ell / \ell h \quad (1)$$
$$= \text{total number of eruptions in}(t_0, t_0 + l)/l,$$

where $\ell = 1, 2, \ldots, N$. Note that z_ℓ evolves over time, and is simply the maximum likelihood estimator (MLE) of the mean unit rate, λ, if the underlying process observed in $(t_0, t_0+\ell h)$ is a simple Poisson process. In an asymptotic sense, the ERRs also track the intensity of the volcanic activities, if the events occur over time in a non-stationary fashion.

3. Data

3.1. Decade Volcanoes

Decade Volcanoes are volcanoes identified by the International Association of Volcanology and Chemistry of the Earth's Interior, or IAVCEI (http://www.iavcei.org/). These volcanoes are being studied to achieve a better understanding of volcanoes to reduce the number of casualties in the event of a volcanic eruption, and to build a foundation of research on worldwide active volcanoes. A volcano can be designated as a Decade Volcano if it: (1) is a representative of more than one volcanic hazard, such as tephra falls, pyroclastic flows, lahars, silicic lava flows, lava dome collapses, volcanic edifice instabilities, etc.; (2) is located in a populated area; (3) is accessible both physically and politically for study and local support is available; and (4) has a recent geological activity.

3.2. Avachinsky volcano

Avachinsky, Kamchatka began to form 60–70,000 years ago in the far east of Russia. Avachinsky has a horseshoe-shaped caldera, which formed 30–40,000 years ago in a major landslide which covered an area of 500 km^2 south of the volcano. Together with neighboring Koryaksky volcano, it has been designated as a Decade Volcano, worthy of particular study in light of its history of explosive eruptions and proximity to populated areas. Scientists peered into volcanoes on the Kamchatka peninsula in Russia as part of an international symposium on geothermal energy resources. Readers interested in the volcanoes of southern Kamchatka are referred to the article published by Waltham (2001) and references therein. Additionally, fumarolic activity of Avachinsky from 1993 to 1994 was documented in Taran et al. (1997).

There are about 15 geothermal plants in the state of Nevada, USA (e.g. http://www.nevadageothermal.com/), which power about 73,000 homes (2% of the state's population). The state has committed to obtaining at least 20% of its energy from renewable sources by 2015. Knowledge gained in Russia about maximizing efficiency of geothermal power production will help the state reach the goal. Therefore, among the 16 Decade Volcanoes accepted by the IAVCEI Sub-Commission, we chose Avachinsky volcano to demonstrate the proposed method. The approach could readily be generalized to other volcanoes, following the lead taken in this article.

3.3. Data preparation

The recent (on a geological time scale) eruption history of Avachinsky volcano extends for at least 30,000 years since somma formation. However, not all dates obtained from a Global Volcanism Program (http://www.volcano.si.edu/) are present or reliable; some of the dates are missing the month, the day, or both, while some eruptive events are recorded as questionable. We are using the following guidelines: (1) only eruptive events with VEI ≥ 1 are extracted from the whole data set and put into an Excel spreadsheet for further treatment. (2) The eruption onsets with missing months and/or days are randomly regenerated (e.g. Guttorp and Thompson, 1991) from Minitab statistical software (http://www.minitab.com/). Unfortunately, these two data selection criteria left us with only a small part of Avachinsky's history — there are 19 historical eruptions that could be used for the analysis (Table 1). The aggregate volcanic eruptive episodes based on the said data are presented with a dot-plot (Fig. 1). Note that there are four eruption onsets in close succession that are included in Table 1: November 26, 1851, December 21, 1853, August 13, 1854, and May 28, 1855. These four events can be counted as one extended eruption and sensitivity analysis, reflecting the uncertainties in the underlying data, may be performed (e.g. Ho, 1995). Clearly, inclusion of this type of data might pose a serious violation of the fundamental model assumption if a homogeneous Poisson process (requires constant rate) or a power-law process (requires monotonic rate) is assumed. On the other hand, the proposed method relieves the restrictions and diagnoses of such assumptions.

4. Method — ERR plot

The choice of the time-origin for an ERR time series may appear problematic if the starting time of the study is not predetermined or if the observation period is not well-defined. For Avachinsky, an intuitive first choice of the time-origin would be the starting event, August 24, 1737 (Table 1). It will then inevitably yield a dull ERR time series in the beginning: starts with 7 zeroes and followed by a spike at time separation or lag 8 if a 5-year time-step is used, because the next event (November 20, 1772) occurred about 35 years later. An alternative approach is to extend and adjust the time-origin approximately one sample mean of the entire inter-event times beyond the first event so that the subsequent ERRs are not significantly altered and the entire observation period ends at present date, which is also divisible by