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Seasonal seismicity at western United States volcanic centers

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Abstract

We examine 20-yr data sets of seismic activity from 10 volcanic areas in the western United States for annual periodic signals (seasonality), focusing on large calderas (Long Valley caldera and Yellowstone) and stratovolcanoes (Cascade Range). We apply several statistical methods to test for seasonality in the seismic catalogs. In 4 of the 10 regions, statistically significant seasonal modulation of seismicity (>90% probability) occurs, such that there is an increase in the monthly seismicity during a given portion of the year. In five regions, seasonal seismicity is significant in the upper 3 km of the crust. Peak seismicity occurs in the summer and autumn in Mt. St. Helens, Hebgen Lake/Madison Valley, Yellowstone Lake, and Mammoth Mountain. In the eastern south moat of Long Valley caldera (LVC) peak seismicity occurs in the winter and spring. We quantify the possible external forcing mechanisms that could modulate seasonal seismicity. Both snow unloading and groundwater recharge can generate large stress changes of >5 kPa at seismogenic depths and may thus contribute to seasonality.

Keywords: seasonality; earthquake triggering; pore-fluid pressure; seismic activity; volcano

1. Introduction

Considerable progress has been made during the past several decades toward better understanding of volcanic processes and mitigating volcano hazards. Much of this progress has been achieved by increasing the density and sophistication of seismic networks in active volcanic areas. Patterns of seismicity in the western United States following large and remote earthquakes suggest that triggered seismicity is more likely to occur in the relatively hot, weak crust of volcanic areas [1–3]. Several mechanisms have been proposed to explain this phenomenon including rectified diffusion [4], changes to the state of fault surfaces from dynamic stresses of mainshock events [5], changes to the state of magma bodies caused by dynamic stresses from a distant earthquake [6,7], and fluid pressure variations in pores and fractures as large seismic waves pass through a region [8–10]. Further, Gao et al. [11] found that in parts of California the timing of earthquakes was annually modulated for 5 yr following the magnitude 7.3 Landers earthquake, with more earthquakes occurring in the latter half of the year, especially in hydrothermal and volcanic areas. They concluded that the annual pattern is probably induced by an external stress, possibly barometric pressure variations.

Other studies have suggested that seismicity in both continental volcanoes and sub-seafloor hydrothermal systems can be modulated by daily Earth tides [12–

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14] and by climatic forces that have an annual period [15–18]. The suggestion that large-scale, global climatic forcing may influence seismic activity [19,20] is of particular interest because it suggests that volcano hazard assessment and monitoring efforts should take into consideration both seasonal and long-term climate variability.

In studies of volcanic areas where seasonal seismicity has been detected, the maxima in seismic activity appear to occur 1 to 6 months after the majority of snowmelt [15,17,18]. Based on this lag period, it has been proposed that the earthquake triggering mechanism is diffusion of pore pressure to the earthquake nucleation zone several kilometers beneath the volcano [17,18]. This mechanism is feasible under a narrow but plausible range of permeabilities, porosities, and water saturations. It has also been suggested that unloading of the snow pack is the mechanism for triggering earthquakes [15]. Since elastic rheology would imply that earthquakes should occur instantaneously following removal of the snow load, Heki [15] proposed that the lag time between snowmelt and seismicity represents the earthquake nucleation time, with larger delay periods expected for larger earthquakes.

In this study, we explore the extensive available data sets from active volcanic systems in the western United States, including stratovolcanoes of the Cascade Range and the large calderas at Yellowstone and Long Valley (Fig. 1). The regional tectonism in these areas provides the close-to-critical background stress necessary to allow seasonal triggering of seismicity. We apply a variety of statistical tests to the data sets to determine which systems (if any) have seasonal trends in seismicity, presumably modulated by external climatic forcing. We then discuss possible mechanisms to explain annual periodicity in seismic records.

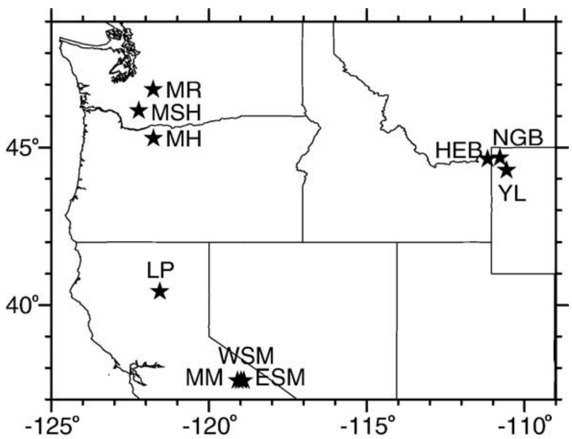

Fig. 1. Location map of study areas in the western USA: MR = Mt. Rainier, MSH = Mt. St. Helens, MH = Mt. Hood, LP = Lassen Peak, ESM = eastern south moat, WSM = western south moat, MM = Mammoth Mountain, HEB = Hebgen Lake/Madison Valley, NGB = Norris Geyser Basin, YL = Yellowstone Lake.

2. Study areas

We investigate 10 volcanic systems in the western United States characterized by frequent seismicity: four stratovolcanoes in the Cascade Range (Mt. St. Helens, Mt. Hood, Lassen Peak, and Mt Rainier) and six seismically active subareas at LVC and Yellowstone (Fig. 1). Each of the selected areas has at least 20 yr of available seismic records. In order to have meaningful statistical analyses, areas were only examined if there were at least 50 earthquakes with magnitudes greater than the minimum requirement for catalog completeness. Other volcanic areas such as Mt. Adams, Mt. Bachelor, Mt. Baker, Glacier Peak, and Mt. Shasta were excluded from the analysis because the seismic catalogs do not span long enough periods, are incomplete, or do not have a sufficient number of earthquakes during the 20-yr period of this study.

2.1. Cascade range

The Cascade Range extends approximately 1200 km from southern British Columbia to northern California. It is located on a tectonically active, convergent plate boundary between the North American and Juan de Fuca plates, and has been volcanically active for about 40 million yr. Several major Quaternary stratovolcanoes are in close proximity to populated regions, making it especially important to understand their seismic behavior.

We analyzed seismic patterns from four volcanoes that have sufficient data to support statistical analysis: Mt. St. Helens and Mt. Rainier in Washington, Mt. Hood in Oregon, and Lassen Peak in California (Fig. 1). Most seismic events in these four areas occur at relatively shallow depths. At Mt. St. Helens, most of the seismicity extends to depths of ~9 km below the mean station elevation, although there is a zone of concentrated seismicity that occurs at a depth of ~3 km [21]. At Mt. Rainier, most of the seismicity occurs in the upper 3 km of the crust [22]. The seismicity at Mt. Hood is more evenly distributed between the mean station elevation and a depth of 7 km [23]. At Lassen Peak, most of the seismicity occurs at depths of approximately 3–5 km [24]. Seismic records in Washington and Oregon are available through the Pacific Northwest Seismic Network (http://www.geophys.