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Swarms of repeating long-period earthquakes at Shishaldin Volcano, Alaska, 2001–2004

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Abstract

During 2001–2004, a series of four periods of elevated long-period seismic activity, each lasting about 1–2 months, occurred at Shishaldin Volcano, Aleutian Islands, Alaska. The time periods are termed *swarms of repeating events*, reflecting an abundance of earthquakes with highly similar waveforms that indicate stable, non-destructive sources. These *swarms* are characterized by increased earthquake amplitudes, although the seismicity rate of one event every 0.5–5 min has remained more or less constant since Shishaldin last erupted in 1999. A method based on waveform cross-correlation is used to identify highly repetitive events, suggestive of spatially distinct source locations. The waveform analysis shows that several different families of similar events co-exist during a given swarm day, but generally only one large family dominates. A network of hydrothermal fractures may explain the events that do not belong to a dominant repeating event group, i.e. multiple sources at different locations exist next to a dominant source. The dominant waveforms exhibit systematic changes throughout each swarm, but some of these waveforms do reappear over the course of 4 years indicating repeatedly activated source locations. The choked flow model provides a plausible trigger mechanism for the repeating events observed at Shishaldin, explaining the gradual changes in waveforms over time by changes in pressure gradient across a constriction within the uppermost part of the conduit. The sustained generation of Shishaldin's long-period events may be attributed to complex dynamics of a multi-fractured hydrothermal system: the pressure gradient within the main conduit may be regulated by temporarily sealing and reopening of parallel flow pathways, by the amount of debris within the main conduit and/or by changing gas influx into the hydrothermal system. The observations suggest that Shishaldin's swarms of repeating events represent time periods during which a dominant source is activated.

Keywords: Shishaldin volcano; volcano seismology; long-period earthquakes; multiplets

1. Introduction

Low-frequency earthquakes associated with volcanic activity have been widely observed and are frequently associated with volcanic unrest and eruptions (Chouet, 1996). Low-frequency events can be classified into two event types according to the frequency content of their onsets: *long-period* (*LP*) events and *hybrid* events. The waveforms of LP events are characterized by emergent onsets and a low frequency content of 0.2–5 Hz with one or more sharply defined spectral peaks between 0.5 and 2.0 Hz followed by a superposition of simple decaying sinusoids. Hybrid events are very similar to LP events but are characterized by an additional high-frequency (> 5 Hz) component in their sometimes impulsive onsets (Neuberg et al., 2000); the amount of high-frequency energy

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reaching the seismic instruments is highly dependent on the effects of attenuation. Initial definitions of hybrid events require a variety of first motions resulting from brittle failure (Lahr et al., 1994). However, Neuberg et al. (2000) suggest that hybrid and LP events are part of a continuum of seismic waves that share common source processes but differ in the amount of high-frequency energy attenuated within their travel path.

A number of different theoretical models have been proposed for the generation of LP waveforms at volcanoes, mostly focused on the idea that the low-frequency energy is a manifestation of pressure-induced vibrations of fluid-filled resonators in magmatic and hydrothermal systems (Chouet, 1996). The low-frequency waveforms are generated by the radiation of energy trapped along the boundary of a fluid-filled container embedded in an elastic solid (Chouet, 1988; Neuberg et al., 2000). Various crack and conduit geometries have been proposed for the sources of LP events (e.g. Chouet, 1996; Neuberg et al., 2000). In order to create LP earthquakes an initial release of seismic energy is required within or close to the resonating body, such that energy can be trapped at the fluid–solid interface by the impedance contrast between the fluid and the surrounding solid (e.g., Chouet, 1986). The mechanism that triggers the oscillation of the conduit walls or fractures may be provided by pressure transients induced by the flux of hot volcanic gases from depth (e.g., Chouet et al., 1994). These oscillations, for example, can be driven by a hydrothermal system responding to enhanced degassing resulting from increased magma transport (Almendros et al., 2001; Nakano et al., 2003; Kumagai et al., 2005; Nakano and Kumagai, 2005). Resonance of a fracture can also be induced by the injection of ash-laden gas released from vesiculated magma (Gil Cruz and Chouet, 1997; Tuffen et al., 2003; Molina et al., 2004; Tuffen and Dingwell, 2005).

Alternative trigger mechanisms include small phreatomagmatic explosions at depth that result from magma–water interactions (Wohletz, 1986; Buttner and Zimanowski, 1998; Wohletz, 2002); a mechanism analogous to a pressure-cooker in which gas periodically escapes through fractures in a solid plug (Johnson and Lees, 2000); magma flow instabilities caused by conduit constrictions (Julian, 1994; Morrissey and Chouet, 1997); the sudden coalescence of foam into a single gas slug (Jaupart and Vergniolle, 1988, 1989); the oscillation of a gas slug at the top of the fluid prior to bursting (Vergniolle and Brandeis, 1994, 1996; Gil Cruz and Chouet, 1997; Vergniolle et al., 2004); and turbulent flow conditions that regularly form behind an obstacle, inducing conduit vibration (Hellweg, 2000).

Low-frequency events often occur in swarms, with typical durations of hours to months (Benoit and McNutt, 1996). At Redoubt Volcano, for example, the LP swarm that directly preceded the 1989–1990 eruption lasted 23 h at a rate of about one event every 20 s (Power et al., 1994). A high degree of similarity between low-frequency waveforms within swarms has been observed at many volcanoes; for example, Redoubt (Stephens and Chouet, 2001), Unzen (Umakoshi et al., 2003), Soufrière Hills (White et al., 1998) and Shishaldin (Petersen et al., 2006). These *repeating events* or *multiplets* represent seismic waves that have similar source processes and travel along an identical path to the seismometer indicating a common event source location. At Soufrière Hills Volcano multiplets that correlate with observed tilt signals associated with dome deformation cycles were observed indicating the pressurization and depressurization of the volcanic system (Neuberg et al., 2006). Neuberg et al. (2006) suggest that these events are the consequence of brittle failure of melt that activates resonators within the upper conduit. Mount St. Helens exhibited highly repetitive low-frequency events, termed *drumbeats*, which accompanied a lava-dome-building eruption; the events occur in about 30-second intervals and are thought to be caused by stick-slip motion between the upward moving dome and the surrounding rocks (Malone et al., 2005; W. Thelen, written communication, 2006). At Mt. Augustine a swarm of low-frequency multiplets that lasted ~90 min accompanied eruptive activity on January 12, 2006 (M. Gardine, written communication, 2006). Mt. Erebus has exhibited repeating low-frequency events produced by impulsive explosions of large gas bubbles from the surface of a long-lived, actively convecting lava lake (e.g., Grêt et al., 2005). At Mt. Redoubt, a slow evolution of repeating LP waveforms occurred within an 18-hour swarm preceding a major eruption, suggesting a migrating or physically changing source (Stephens and Chouet, 2001). Similar evolving waveforms were also observed at Mt. Unzen over a time period of 2 months of active dome growth (Umakoshi et al., 2003). Arciniega et al. (2005) observed repetitive LP events at Popocatepetl exhibiting changes in waveforms that correlate with changes in eruptive activity from degassing to lava-dome formation. At Galeras (Gil Cruz and Chouet, 1997) and Tungurahua (Molina et al., 2004) repetitive injections of ash-laden gas into a pre-existing crack within the conduit just above the magma system induces resonance of the crack that generates LP events. In case of these two volcanoes, the source processes are repeating, but the resulting seismic events are not highly similar due to changing acoustic properties within the conduit.

Repeating events often can be classified into waveform families or groups. Green and Neuberg (2006) analyzed a 6-day period of multiplets recorded at Soufrière Hills