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Degassing and Hydrothermal Activity at Mt. Spurr, Alaska During the Summer of 2004 Inferred from the Complex Frequencies of Long-Period Events

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Degassing and hydrothermal activity at Mt. Spurr, Alaska during the summer of 2004 inferred from the complex frequencies of long-period events

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[1] Results of analyses of unusual long-period earthquakes, recorded between July and September 2004 at Mt. Spurr, Alaska, are presented. The waveforms of these events are characterized by quasi-sinusoidal signatures of long duration (up to 40 sec) with slowly decaying amplitudes; bandwidths of 0.5–4.0 Hz are typical; amplitude spectra are marked by strong and sharp peaks, reflecting the quasi-monochromatic nature of the signal. The temporal variations of the complex frequencies are investigated by use of the Sompi method; the dominant mode is resolved and its Q factor estimated for each available event. Dominant frequencies are found in the band 0.8–2.2 Hz with Q varying between 25 and 100. The variations of the complex frequencies show an overall decline with time. The dynamic response of a shallow fracture filled with bubbly water to the flux of hot gases from depth, is proposed as a possible mechanism for the generation of the observed waveforms. **Citation:** De Angelis, S., and S. R. McNutt (2005), Degassing and hydrothermal activity at Mt. Spurr, Alaska during the summer of 2004 inferred from the complex frequencies of long-period events, *Geophys. Res. Lett.*, *32*, L12312, doi:10.1029/2005GL022618.

1. Introduction

[2] The observation and modeling of seismic waves provide a powerful tool to investigate magma and hydrothermal activity in volcanic environments. Long-period (LP) seismicity is of particular interest because it has been widely observed associated with volcanic activity [*Chouet*, 1996]. LP events at volcanoes all share similar features: a high frequency onset is usually followed by a harmonic wave train containing one or more dominant modes in the range 0.5–5 Hz; P-wave arrivals are often emergent and there is usually a lack of S-wave arrivals [*McNutt*, 2002].

[3] A number of theoretical models have been proposed to account for the generation of LP waveforms at volcanoes mostly relying on the resonance of fluid filled systems [*Aki et al.*, 1977; *Chouet*, 1988, 1996; *Commander and Prosperetti*, 1989; *Crosson and Bame*, 1985; *Fujita et al.*, 1995].

[4] While ordinary techniques used in seismology are frequently not applicable to the analysis of volcanic LP events, their study in the frequency domain provides useful constraints about the processes and fluid composition at the source [*Kumagai and Chouet*, 1999]. The Fast Fourier Transform (FFT) algorithm [*Cooley and Tukey*, 1965] has been largely used to investigate the frequency content of seismic waves; in more recent times, a parametric method for the spectral estimation of low frequency seismograms, the Sompi method, has been proposed and applied to LP seismic signals from different volcanoes [*Kumazawa et al.*, 1983; *Hori et al.*, 1989; *Kumazawa et al.*, 1990; *Nakano et al.*, 1998; *Kumagai et al.*, 2002]. The Sompi method is based on a homogeneous autoregressive (AR) equation and addresses the problem of resolving the decaying harmonic components of a time series corrupted by noise. The application of this technique is especially suitable for a particular type of LP earthquakes, whose waveforms are characterized by quasi-sinusoidal signatures and long durations. In this study, the Sompi method was applied to a suite of 35 LP events recorded at Mt. Spurr, Alaska, during the summer of 2004.

2. Recording of Data at Mt. Spurr

[5] Mt. Spurr is a snow and ice covered stratovolcano located on the northeastern end of the Aleutian arc approximately 130 Km west of Anchorage, Alaska, USA. Its activity in historical times is limited to two brief, explosive eruptions from Crater Peak, a flank vent located 3.5 Km south of the Mt. Spurr summit, in 1953 and 1992; the last eruption from the summit of Mt. Spurr is dated more than 5000 years ago. The volcano is monitored by the Alaska Volcano Observatory (AVO) with a network of 10 seismic stations (Figure 1). All stations have short-period (T = 1s), vertical component seismometers except station CRP, which has a three component, short-period (T = 1s) instrument.

[6] In summer 2004, an increase in earthquake activity beneath the summit of Mt. Spurr was detected as a notable departure from the background seismicity. The rate of activity was greater than any observed since the last eruptive period in 1992, averaging 20–30 events each day with magnitude less than 1.5 and, depths mostly between 0 and 6 km below sea level. A small number of deep (15–40 km) LP events were also observed. Most of the activity took place beneath the summit of Mt. Spurr while relatively few earthquakes were located beneath Crater Peak vent, the site of the 1953 and 1992 eruptions.

3. Long-Period Events

[7] While several types of seismic events were observed at Mt. Spurr, the emphasis in this study is on low-frequency earthquakes that likely reflect the involvement of a fluid phase in the source mechanism. A set of 35 LP events has been selected for analyses. The waveforms are characterized

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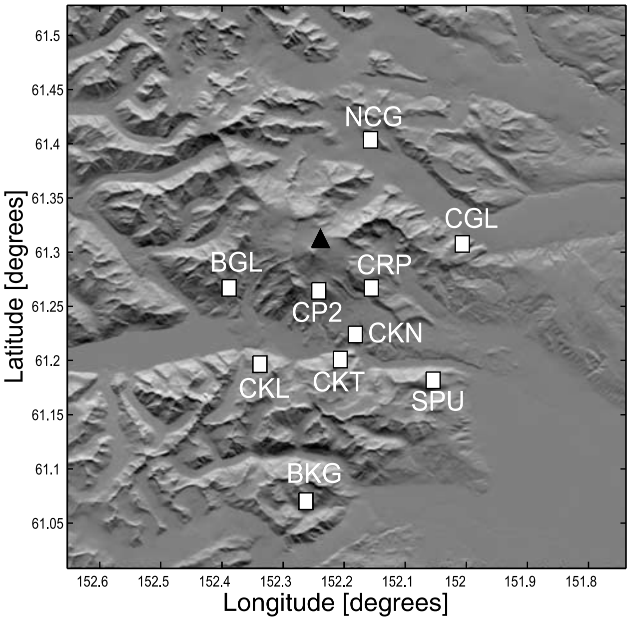

Figure 1. Seismic network at Mt. Spurr (white squares). Summit of volcano is marked with a black triangle. Crater Peak vent is located adjacent to station CP2.

by long duration (up to 40 s) and slowly decaying amplitudes; a low frequency, quasi-sinusoidal signature dominates the signal except for a brief time at the event onset, when higher frequencies are present. The onset is generally emergent and, the absence of clear P and S phases, makes locations difficult to determine. All the selected events are well recorded at stations CRP, CP2 and, in turn, at NCG, CGL, BGL; at the other stations the signal to noise ratio is poor. The amplitude spectra at CRP and CP2 are similar, characterized by narrow bandwidths (0.5–4.0 Hz) sharply peaked between 0.8 and 2.2 Hz. The substantial lack of high frequencies in the seismic signals may be indicative of a source located at shallow depths. Figure 2 shows the seismograms and amplitude spectra for three events recorded at CRP and CP2; the spectral energy, for individual events, is peaked at the same frequencies, reflecting a source effect. The other stations in the network exhibit spectra generally more complicated; however, the same peaks observed at CRP and CP2, although less pronounced, can be seen. Assuming a source located at shallow depths, the distribution of the seismic amplitudes suggests the summit area of Mt. Spurr as a preferred epicentral location for the long-period events.

4. Data Analysis and Results

[8] The temporal variations of the characteristic frequencies for the selected long-period events, are investigated by use of the Sompi method [*Hori et al.*, 1989; *Kumazawa et al.*, 1990; *Nakano et al.*, 1998]. The analyses are performed on waveforms recorded at stations CRP and CP2 between July and August 2004; the complex frequencies for the dominant modes of the available waveforms are estimated, then averaged for each event. According to *Kumagai et al.* [2002] the initial high frequency part of the waveforms is removed and, the AR model fitted to the remaining part of the signals; the complex frequencies are estimated for AR orders from 4 to 60 (Figure 3).

[9] The analyses resolved spectral peaks between 0.8 and 2.2 Hz; the Q factor, estimated for each peak, varies from 25 to 105. The temporal variations of the dominant frequencies can be considered in three time periods according to the occurrence of the events: 1) July 12–30, 2) August 13–31 and, 3) September 25–30, 2004. Figure 4 (top) shows the variations with time of the dominant frequencies; an overall declining trend is well delineated although some scatter is present; spectral peaks are found to decrease from 1.6–2.2 Hz, to 0.8–1.1 Hz with intermediate values in the band 1.2–1.6 Hz. The quality factors, vary from mean values of 75 during July, to 62 in August, and to 45 for the September events (Figure 4 (bottom)). It is worth noting that data are affected by a certain degree of scattering and, the temporal decrease could be less marked than indicated by average values of *Q*. In particular, the fluctuations observed during July and August do not show a well delineated decline while, the data of September tend to group together, highlighting a more effective decrease of *Q*.

5. Discussion and Concluding Remarks

[10] The various LP events recorded at active volcanoes have been frequently interpreted as a consequence of the resonance of fluid filled systems triggered by pressure transients. The mechanism proposed for the generation of the LP events at Mt. Spurr, is the dynamic response of a fluid filled fracture to pressure changes induced by the flux of hot volcanic gases from depth. When the gas comes in discrete and strong pulses, the rapid pressurization of the system may act as a trigger for the long period oscillations of the resonator. On the other hand, if the gas flux is continuous, the build up of pressure in the fracture will be gradual; after a pressure threshold is reached the fluids are eventually discharged and their withdrawal results in a disturbance able to start vibrations at the source. Previous studies showed that the complex frequencies of LP earthquakes may be related to the particular type of fluids present at the source [*Kumagai and Chouet*, 1999]: a hydrothermal source filled with bubbly water may account for the

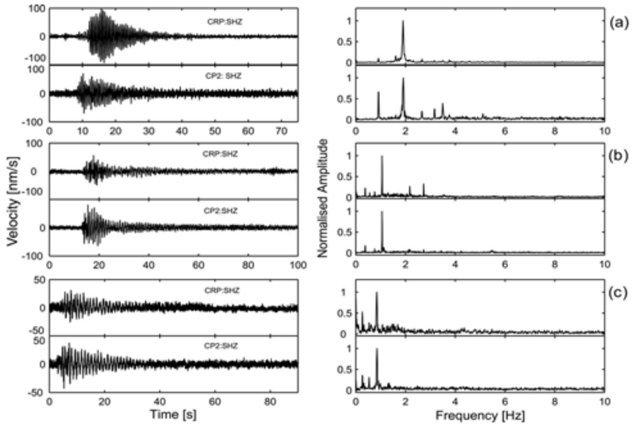

Figure 2. Waveforms and spectra of 3 LP events recorded at stations CRP and CP2. (a) 2004 July 18, 11:21:33 (UT); (b) 2004 August 14, 07:19:21 (UT); (c) 2004 September 25, 07:15:01 (UT).

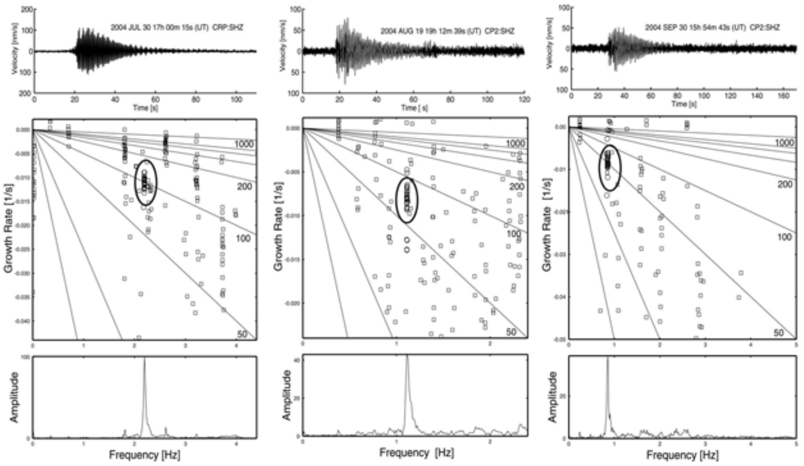

Figure 3. (top) Seismograms, (middle) *f-g* diagrams, and (bottom) spectra for three LP events at Mt. Spurr (from left to right events recorded on: 30 July 2004, 17:00:15 UT; 19 August 2004, 19:12:39 UT; 30 September 2004, 15:54:43 UT). The complex frequency is defined as *f-ig*, where *f* is the frequency, *g* is the growth rate and, $i = \sqrt{-1}$. Clusters of points (encircled with solid ellipses) on the *f-g* diagrams indicate a resolved dominant mode, scattered points represent noise. Solid lines are equi-*Q* lines. *Q* is defined in terms of the complex frequencies as the ratio $-(f/2g)$. Note different scales on the plots.

characteristic frequencies and *Q* observed at Mt. Spurr. This is consistent with observation of a 100 m diameter melt pit partially filled with water at the summit of Mt. Spurr. For a crack of constant geometry and size, a decrease in the dominant frequency can be explained by an increase of the gas volume fraction in the hydrothermal mixture; increasing the volatile content is known to decrease the acoustic velocity of a fluid and to increase its impedance contrast with the surrounding rock. Measurements of surface degassing at Mt. Spurr on August 7–8 and September 15, 2004, revealed a CO_2 output of 760 and 2300 tons/day, respectively; this provides evidence for an increase in the amount of gas at shallow depths beneath the volcano. On the other hand, changes of the crack length under fixed acoustic properties of the hydrothermal fluid, could also account for a decrease in frequency.

[11] The interpretation of variations of the *Q* factor is more controversial. The quality factor can be written as $Q^{-1} = Q_i^{-1} + Q_r^{-1}$, in terms of the intrinsic attenuation of the fluid, Q_i^{-1}, and of the energy losses due to the radiation pattern, Q_r^{-1} [*Aki*, 1984]. Using the Van Wijngaarden-Papanicolaou model [*Commander and Prosperetti*, 1989], Q_i in a bubbly fluid can be modeled as a function of the gas bubbles radius, *r*, of the frequency of the traveling wave and of its gas volume fraction. As an example, for bubbly water at shallow depths (5 MPa, 537 K) with gas volume fraction between 2% and 10% and a traveling wave of 1 Hz, $r = 0.3$ mm, result in Q_i of the order of 10^2; Q_i, for $r = 1-3$ mm, is about 10–20. If the frequency of the traveling wave is increased in the range 1.6–2 Hz, bubble radii of 0.3 mm account for values of Q_i in the range 100–50. For the fundamental radial mode of a fluid filled sphere $Q_r^{-1} = S \cdot \ln[(Z + 1)/(Z - 1)]$, where *S* is a constant and *Z* the impedance contrast; in this case, the explicit dependence of Q_r on *Z*, implies a decrease in wave attenuation when the volatile content increases. *Nakano et al.* [1998] showed that for the fundamental mode of a sphere of constant size filled with bubbly water, changes of Q_r^{-1} can be neglected with respect to changes of Q_i^{-1}.

[12] In the case of a rectangular crack, Q_r depends on the resonance mode and on the geometry of the fracture as well as on the gas volume fraction of the fluid. *Kumagai and Chouet* [2001] show that for the mode 2W/3 of a fluid filled crack, Q_r may reach values as high as 70 for bubbly water with a gas volume fraction of 10%. A variable crack geometry may account for changes in Q_r; if the ratio of the fracture length, L, to its aperture, d, increases, Q_r is found to decrease. Values of Q_r in the range 70–40 result from L/d ratios between $5 \cdot 10^3$ and $5 \cdot 10^4$ for the mode 2W/3 of a rectangular crack filled with a fluid mixture with $\alpha/a = 10$ and $\rho_f/\rho_s = 0.2$ (α = compressional wave velocity of the host rock; a = sound velocity of the fluid; ρ_f and ρ_s, densities of the fluid and solid). In the case of bubbly water (gas volume fractions up to 10%) at shallow depths, Q_r^{-1} and Q_i^{-1} are generally comparable and neither one can be neglected.

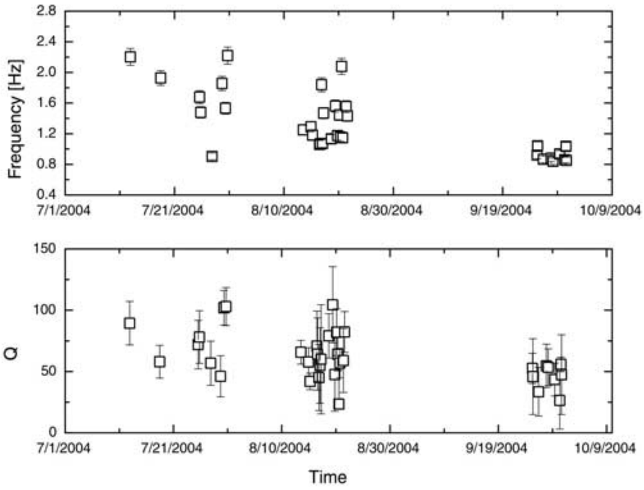

Figure 4. Temporal variations of peak frequencies and *Q* for LP events at Mt. Spurr (error bars = 1σ).

[13] The temporal variations in the complex frequencies of LP events at Mt. Spurr exhibit a pattern substantially different from other volcanoes where the same analyses have been performed. In most of documented cases, increase (decrease) in frequency is associated with decrease (increase) in Q, suggesting a process of heating and drying of the hydrothermal system (replenishment with new 'wet' material); at Mt. Spurr frequency and Q decrease simultaneously. The interactions between a flux of hot volcanic gases and a crack filled with bubbly water, may explain the generation of LP events at Mt. Spurr. We propose that the combined effects of variations in the properties of the bubbly fluid (increase in gas volume fraction and/or increase in bubbles size) and changes in the geometry of the crack (increase in L/d ratio) are responsible for the observed changes in the complex frequencies of LP events at Mt. Spurr.

[14] It is relevant, in terms of hazard reduction, to distinguish whether or not magmatic fluids are involved in the generation of seismic signals; the analyses of waveforms in the frequency domain, provides a powerful tool to infer the fluid composition at the source and to distinguish between magmagenic and hydrothermal signals. Based on present data and observations, we suggest that near future volcanic unrest at Mt Spurr may include episodes of phreatic activity from the summit.

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