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John P. Benoit
University of Alaska Fairbanks

Stephen R. McNutt
Universtiy of Alaska Fairbanks, smcnutt@usf.edu

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New constraints on source processes of volcanic tremor at Arenal Volcano, Costa Rica, using broadband seismic data

John P. Benoit and Stephen R. McNutt

Alaska Volcano Observatory and the Geophysical Institute, University of Alaska Fairbanks

Abstract. Broadband seismic data recorded 2.3 km from the active vent of Arenal Volcano, Costa Rica, provide new constraints on tremor source processes. Arenal's tremor contains as many as seven harmonics, whose frequencies vary temporally by up to 75 percent, from initial values of 1.9 Hz for the first peak immediately following explosive eruptions to 3.2-3.5 Hz several minutes later. We infer that gas bubble concentration is variable within the conduit and also changes as a function of time, thereby changing the acoustic velocity. We infer that the source is a shallow, 200-660 m-long, vertically oriented 1-D resonator with matched boundary conditions, radiating seismic energy from a displacement antinode. Polarization analyses show that particle motion azimuths abruptly rotate, which may be explained by a decrease of the incidence angle. We suggest that energy is radiated predominantly from a displacement antinode that is changing position with time. Tremor consists mainly of transverse waves that travel at speeds of about 800 m/s. P waves in the magma conduit will couple very efficiently into S waves in the surrounding medium when there is virtually no impedance contrast between the two media for these two types of waves. The tremor at Arenal is similar to tremor at nine other volcanoes.

Introduction and Background

Volcanic tremor is a very common but poorly understood type of seismic signal produced by active volcanoes. Tremor has been documented at 160 volcanoes [McNutt, 1994], and a variety of source models have been proposed [Julian, 1994, Gordeev, 1993, and Chouet *et al.*, 1994 provide recent reviews]. Worldwide observations suggest that there are probably several source mechanisms.

We operated a broadband three-component seismometer (Guralp CMG-40T) at two sites 2.3 and 2.8 km from Arenal Volcano, Costa Rica (10N27.8', 84W42.3', elev. 1633m), for two weeks in April 1994 (Fig. 1). During this deployment we recorded high quality tremor data as well as other events characterized as whooshes, chugs and explosions (Fig. 2), complemented with visual and audio observations (W. Melson, writ. comm., 1994). Whooshes are small eruptions that sound like a jet plane, accompanied by emergent seismic events with durations 2-20 s. Whooshes are often accompanied by small ash plumes. Chugs are series of small events that sound like a steam locomotive with pulses 0.5-1.5 s apart accompanied by gas only. When chugs are audible at a distance of 2.8 km, strong volcanic tremor is usually recorded. Explosions are im-

pulsive seismic events with an audible acoustic wave and audible fallback of ejected material. A commonly observed temporal sequence is an explosion followed by a whoosh, then by loud chugs and strong tremor, then by weaker tremor [Melson, 1989]. A visit to the crater by one of us (SM) in 1983 showed that chugs are venting gas along the crater edge continuously, but with variable amplitudes. All these events occur at crater C near the summit (Fig. 1) from which lava flows are also emitted. Each of these eruptive phenomena is accompanied by a characteristic seismic signal (Fig. 2).

Arenal has had almost continuous effusion of lava since September 1968, following a series of powerful explosions in July 1968 [Melson and Saenz, 1973]. The volcano produces basaltic-andesite lavas with 54-56 % SiO₂ that initially contained an estimated 2-4 wt % H₂O [Reagan *et al.*, 1987; Melson, 1985]. Eruption rates have varied from 53 x 10⁶ m³ per year to the present rate of about 9 x 10⁶ m³ per year [Reagan *et al.*, 1987]. Barboza and Melson [1990] have examined correlations between seismic signals and eruption sounds.

Analyses and Results

We first analyzed spectra to determine how tremor frequencies changed as a function of time, and to illuminate source versus path effects. We found that tremor frequencies varied by as much as 75 % within minutes; a clear source effect. Second, polarization analyses were conducted to discriminate wave types and to determine the wave azimuths and incidence angles. We found that waves come from at least two different regions.

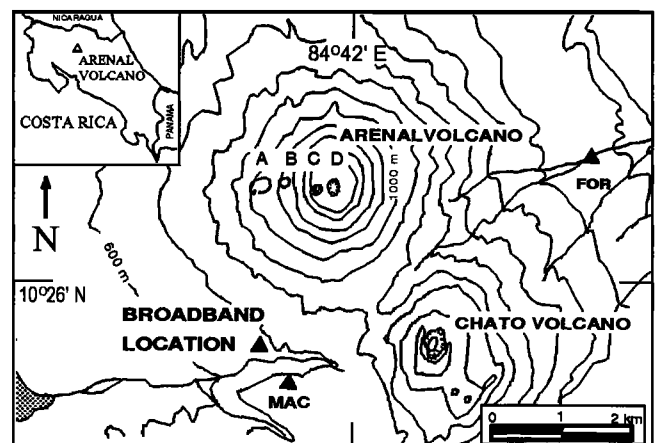


Figure 1. Map of Arenal Volcano, Costa Rica. The currently active crater is Crater C. The temporary broadband deployment was 2.3 km south-southeast of Crater C. The permanent seismometer (MAC) is located 2.8 km south of Crater C.

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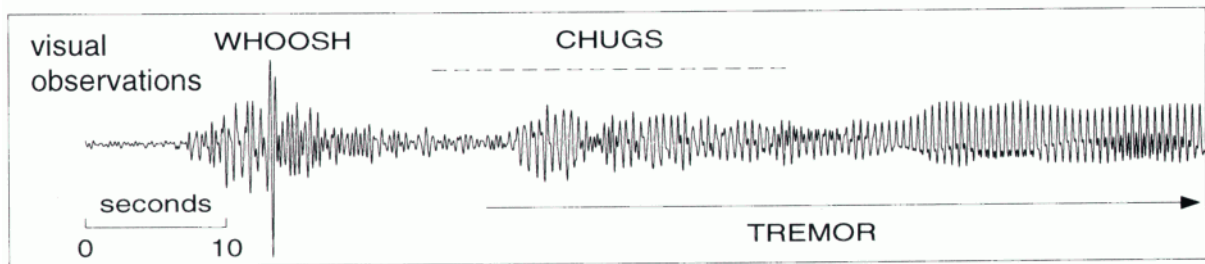


Figure 2. An example seismogram (radial component) of a small eruption (whoosh) followed by rhythmic degassing (chugs). Visual and audio observations show this eruption ejecting ash to ~500 m above the crater and the following chugs were audible at 2.8 km for ~25 s. Harmonic tremor begins during the chugs and continues for several minutes.

Velocity spectrograms were produced using a standard method of averaging periodograms. Figure 3 shows a typical example of the broadband seismic data. Three small eruptions (whooshes), each ejecting ash to ~500 m above the crater, occurred during this 50-min interval. Each whoosh lasted 10 - 20 s and was followed by a series of rhythmic gas emissions, or chugs, audible at a distance of 2.8 km for approximately 30 s and continuously near the vent. Note the close association between strong tremor and these two gas release processes. We found that the whoosh is expressed as a relatively broadband seismic signal with energy from 0.5 to 7 Hz. The seismic signals associated with the chugs and the following tremor are dominated by narrow spectral peaks at regular intervals (1.9, 3.8, 5.7, 7.6, ... Hz). Tremor stops abruptly when the frequency of the first peak reaches about 3.2-3.5 Hz (e.g. "A" in Fig. 3). The strongest tremor occurs immediately following whooshes and chugs. The tremor amplitude shows a systematic decrease as frequencies increase. The temporal sequence of a whoosh followed by loud chugs and strong tremor is repeated many times (e.g. Fig. 3).

To obtain information about wave velocities, we examined 3-component data for several explosions. The explosions

are assumed to be, to first order, point sources originating at shallow depths near the summit of the volcano. The first waves observed are weak, with particle motions longitudinal to the vent, and are inferred to be P waves. Larger amplitude waves are next observed showing particle motions transverse to the vent and are inferred to be S waves. The estimated S-wave velocity is 800 m/s using the arrival of the acoustic wave to fix the origin time. The largest amplitude waves with elliptical particle motion appear shortly after the S waves. We infer that these are surface waves. Both the S waves and surface waves may be produced by P waves impinging upon a low-velocity layer or layers near the source. This effect has recently been observed at Old Faithful geyser by *Kedar et al.* [1996].

The polarization azimuth and incidence angle of the tremor waves were estimated using the covariance method described by *Montalbetti and Kanasevich* [1970]. The analyses were conducted by windowing each spectral peak in time and frequency. The covariance matrix is formed over the three orthogonal components of the seismogram and then diagonalized. The direction of the largest eigenvector is taken to be the polarization direction of the particle motion. Typical sample windows were 10 to 20 s in time and 3 Hz in frequency.

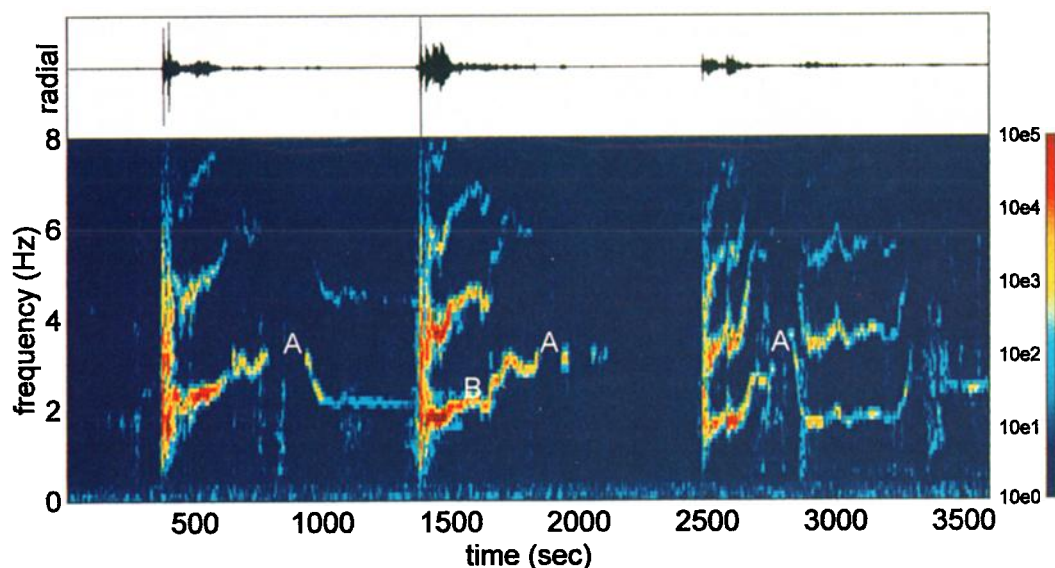


Figure 3. Velocity seismogram and spectrogram (radial component), beginning at 01:05 UT, April 25, 1994, showing three small eruptions. The beginning of the second event is shown in detail in figure 2. The spectra of the volcanic tremor are dominated by narrow peaks spaced regularly in frequency, each of which changes frequency systematically with time. The tremor stops abruptly when the frequency of the first peak reaches ~3.2 Hz (see point "A"). The spectrogram is constructed by stacking 10 s FFT spectra with 50% overlap. Scale bar (right) shows arbitrary units.

We chose the first spectral peak for detailed analysis. This peak (1.9-3.2 Hz) contains the longest wavelengths (~800 m) and is therefore least susceptible to path effects. This peak was linearly polarized (largest eigenvalue \gg intermediate eigenvalue) and the polarization angle was stable for up to 90 s. The tremor episodes began with linearly polarized particle motion (N40W azimuth; grazing incidence). Then, after 90 s the particle motion azimuth of the first spectral peak rapidly rotated clockwise 105° to N65E. The transition occurred within 12 s ("B" in Fig. 3). At the same time the apparent incidence angle steepened suggesting that the source had deepened. This shows that either the source wave type is changing, that waves began to follow two different paths, or that there are two spatially distinct sources. The frequency content did not change significantly during this transition, suggesting that the overall source dimensions had not changed. Figure 4 shows the horizontal particle motions for three 1 s windows around this transition. Figure 4 also shows theoretical particle motions for a plane shear wave, propagating at N34E azimuth, incident at three angles that span the critical angle of $\sim 36^\circ$ [after Nuttli, 1961]. The dramatic change in the surface particle motion shown in Figure 4 can be explained by an S-wave source that becomes deeper with time. If a spherical wave front is used the same behavior is observed but the critical angle is smaller [Booth and Crampin, 1985].

Discussion and Conclusions

The tremor at Arenal is a uniform, regular signal with spectra showing as many as seven evenly spaced peaks, with the inter-peak frequency spacing the same as the zero-to-first-peak spacing. This type of spectral pattern has been attributed to both source and path effects. The non-stationarity of the

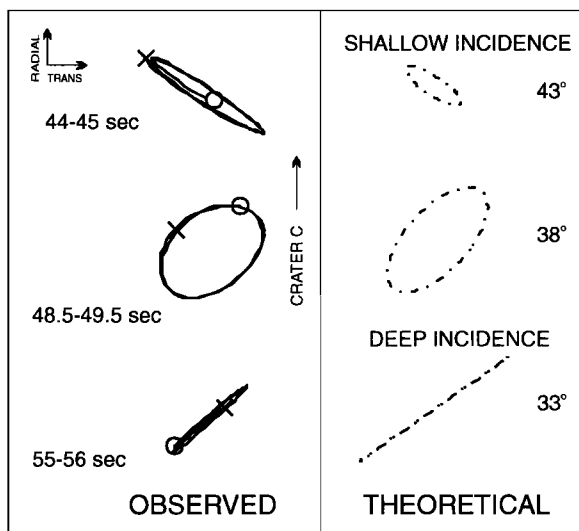


Figure 4. Observed and theoretical particle motions in the horizontal plane. The left column shows a 12 s sequence (0.5-3 Hz bandpass) taken from the second tremor episode ("B") in figure 3. An "x" marks the beginning and an "o" the end of each one-second trace. The particle motion azimuth abruptly rotates clockwise 105° . The right column shows theoretical particle motions on a horizontal free surface due to a shear wave (polarization angle $\epsilon = 20^\circ$, Poisson's ratio = 0.25) incident at three angles (measured from the vertical). The observed tremor particle motions may be explained by an apparent steepening of the incidence angle.

signal with time points strongly towards source effects. Several source models may be employed to explain these observations; including the non-linear excitation due to unsteady flow [Julian, 1994] and the resonance of a fluid-filled cavity with various geometries [e.g. McNutt, 1986; Chouet et al., 1994]. We prefer the resonance of a fluid-filled cavity model, because such signals have been produced naturally at hydroelectric dams by resonance in the outflow tunnels, e.g. as Tarbela dam, Pakistan; [McNutt, 1986], and have also been produced in the laboratory [Leet, 1988]. Furthermore the resonator model provides a spatially extended source. Using the lowest frequency observed, 1.9 Hz (Fig. 3), and the highest laboratory value for velocity of P waves in andesite melt, 2.5 km/s [Murase and McBirney, 1973], yields a maximum length of 658 m. The resonator is certainly shorter than this because it contains gas bubbles, which lower the acoustic velocity. If we use the value of 800 m/s, measured for S-waves in the wall rock, then the length would be 212 m. At 800 m/s we infer that the impedance contrast between the fluid and the wall rock is at a minimum, creating the most efficient generation and transmission of S waves from the interface.

We suggest that the source fluid is gas-charged magma for several reasons. First, incandescent lava is being emitted continuously from the same vent area that produces the whooshes and chugs. Second, the tremor is quite strong, of order 20 cm^2 reduced displacement. Tremor that has been observed in hydrothermal systems is weaker, $<5 \text{ cm}^2$ [McNutt, 1992], and theoretical modeling of energy available from bubble collapse in water shows values of $<10 \text{ cm}^2$ [Leet, 1988]. Third, a gas cavity or bubbly water column would have poor coupling with the wall rock because of the high impedance contrast between the fluid column and the wall rock.

We do not see evidence of 2-D modes as noted by Chouet et al. [1994] for rectangular cracks, although our instrument may be too far away to record high frequencies from such modes. Data recorded by us at five different sites 2-7 km from Arenal all show the same regular tremor with the same frequencies. Due to the lack of a second set of modes we choose a 1-D model. The matched boundary conditions, which are suggested by the spectra, may consist of two configurations, "open-open" or "closed-closed." The "open-open" system has pressure nodes and displacement antinodes at each end whereas for the "closed-closed" system the pressure and displacement nodes are switched. These boundaries or impedance discontinuities are controlled by either geometric or velocity contrasts within the conduit. Geometric boundaries may consist of the open vent on top and a flaring of the conduit diameter at the bottom, corresponding to an "open-open" system. Velocity-controlled boundaries may consist of a very slow, gas-bubble-rich layer overlain by relatively cool, fast, crust at the top of the conduit, and the bubble nucleation front at the bottom, corresponding to a "closed-closed" system.

We favor the "closed-closed" system for two reasons; first the "closed-closed" system has a pressure antinode at the top where degassing occurs as rhythmic pulses -- chugs -- that are coupled to the oscillating magma conduit and feed energy back into it. The frequency of chugs is similar to the fundamental mode of the tremor, about 2 Hz. The energy exchange may occur if each chug is triggered by a decompression wave; the gas release upward will cause a downward push or compression that is in phase with the reflected wave at the surface. Second, the "closed-closed" system has a transient lower boundary which provides an explanation for the abrupt loss of tremor, commonly observed (e.g. "A" in Fig. 3). As de-

gassing occurs, the bubble concentration will decrease and the bubble nucleation front will cease to act as a reflecting boundary sustaining strong resonance (strong tremor). The impedance contrast will be lost when the bubble concentrations are uniform across the former boundary. Complete degassing is not required: only enough to remove the impedance contrast.

All the spectral peaks remain evenly spaced while they shift upward in frequency by up to 75%. Frequencies are lowest right after the whoosh, when the conduit is most gas-rich (i.e. slowest velocities), then shift upward as gas presumably is lost and the acoustic velocity increases. Additionally, when the tremor returns (e.g. at 800 s in Fig. 3) it returns first with higher (gas poor) frequencies that gradually lower as gas content increases. The effect of bubbles on P-wave speeds in fluid has been shown by Leet, [1988] to agree with the observations here: a P-wave speed of 800 m/s in the magma implies a theoretical bubble concentration of 10^{-3} . We believe this value is too low, however, because of the shallow depths and because the magma contains abundant phenocrysts (up to 55%) so it may not behave as a theoretical two-phase fluid.

The polarization analyses show that both the particle motion incidence angle and the azimuth change systematically while the frequencies remain constant ("B" in Fig. 3). This shows that either the source wave type is changing, that waves began to follow two different paths or that there are two spatially distinct sources. Our temporary deployment did not collect sufficient data to definitively state which of the above hypotheses best explains this observation. We speculate that the depth of the source has changed, altering the path to the receiver. Small changes in incidence angle can cause dramatic changes in observed particle motion for waves incident near the critical angle. The change in the depth of the source would result from uneven bubble concentrations within the conduit. The position of a resonator's displacement antinode depends on the acoustic velocity profile within the conduit. As bubble concentrations change during degassing the position of the displacement antinode or strongest source of tremor will shift.

None of the new data presented here address the question of the energy source. We suggest that expanding gases provide most of the potential energy that drives the tremor and other events. The available power from 2 wt % water is about 6×10^6 J/s, whereas the strongest tremor has an energy release rate of about 8×10^5 J/s, for a seismic efficiency of 13 %.

These data provide compelling arguments for a simple model of the source of volcanic tremor at this volcano. However, our model may apply only to this one type of signal. Tremor strikingly similar to that at Arenal has been observed at nine other volcanoes, including Semeru [Schlindwein et al., 1995], Langila [Mori et al., 1989], Merapi, Krakatau (R. Schick, writ. comm., 1994), Sakurajima [Kamo et al. 1977], Ruapehu [Hurst, 1992], Fuego, Pacaya (D. Harlow, writ. comm. 1984), and Karymsky (Gordeev, writ. comm. 1996). Future work is needed to test the model with additional instruments. This will allow us to better constrain the source locations, to determine the velocity structure, and to understand the evolution of the tremor source with time.

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J. Benoit and S. McNutt, Geophysical Institute, University of Alaska Fairbanks, Fairbanks AK 99775-7320 e-mail: benoit@giseis.alaska.edu or steve@giseis.alaska.edu

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