Magma acoustics and time-varying melt properties at Arenal Volcano, Costa Rica

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Abstract. The similarity of acoustic and seismic spectra recorded during Strombolian activity of Arenal Volcano provides conclusive evidence that pressure waves are generated and propagated within the magma-gas mixture inside volcanic conduits. These pressure waves are sensitive to the flow velocity and to small changes in the gas content of the magma-gas mixture, and thus can provide useful indicators of the time-varying properties of the unsteady flow regime and the chemical composition of the melt. The dominant features of the observed explosion and tremor signals are attributed to the source excitation functions and the acoustic resonance of a magma-gas mixture inside the volcanic conduit. We postulate that explosions are triggered in the shallow parts of the magma conduit, where a drastic pressure drop with depth creates a region where violent degassing can occur. Tremor may be sustained by unsteady flow fluctuations at depth. Equilibrium degassing of the melt creates a stable, stratified magma column where the void fraction increases with decreasing depth. Disruption of this equilibrium stratification is thought to be responsible for observed variations in the seismic efficiency of explosions and enhanced acoustic transmission from the interior of the conduit to the atmosphere.

Introduction

Four distinct issues must be addressed in order to utilize acoustic and seismic waves to decipher the physics of volcanic processes. These are: (1) the identification of source processes that produce transient and sustained vibrations, (2) the propagation of pressure fluctuations in the fluid magma-gas or ash-gas mixture within the volcanic plumbing, (3) the propagation of acoustic waves from the volcanic vent to the pressure sensors, and (4) the propagation of seismic waves from the walls of the volcanic conduit to the seismometers. While the last two problems can be addressed through the classical methodologies of acoustics and seismology, a correct assessment and treatment of the first two is vital to our understanding of the physical and chemical processes within the volcanic interior. This manuscript focuses on volcanic explosion and harmonic tremor signals recorded simultaneously at Arenal Volcano by broadband seismic and acoustic sensors deployed to address these important problems.

Arenal Volcano is a young (~3,000 years old), 1.65 km high andesitic stratovolcano in Costa Rica [*Borgia et al.*, 1988], which was thought to be extinct prior to its violent Plinian eruption in 1968. Since 1984 Arenal has exhibited Strombolian activity characterized by frequent summit explosions and occasional extrusion of block lava. The details of Arenal's Strombolian eruptive activity and our continuous broadband seismic and geodetic monitoring over the past 2.5 years are presented in *Hagerty et al.* [1997]. During April and May, 1997, explosion and tremor signals were recorded by a linear array of coincident three-component seismometers and acoustic microphones deployed with 100 m spacing in a radial configuration approximately 2 km from the summit of Arenal. Both the microphones and the seismometers have a flat frequency response in the bandwidth of interest. Volcanic explosions produce transient acoustic and seismic waves with clear arrivals and broad spectra. Harmonic tremor is a sustained low-frequency ground vibration which exhibits evenly-spaced spectral peaks; harmonic tremor has been observed at many active volcanoes throughout the world [*McNutt*, 1989] and has been attributed to either reverberation within the solid volcanic strata or to the resonance of magmatic conduits [*Chouet*, 1996]. In between explosions, Arenal is primarily degassing, and we postulate that unsteady fluid flow sustained during the degassing process gives rise to pressure oscillations in the magma conduit and to observed tremor signals.

There exists a plethora of source mechanisms which can be invoked to excite the observed signals, but none of them can be accurately constrained until two essential problems have been carefully considered: What is the response of the magma-gas mixture to pressure

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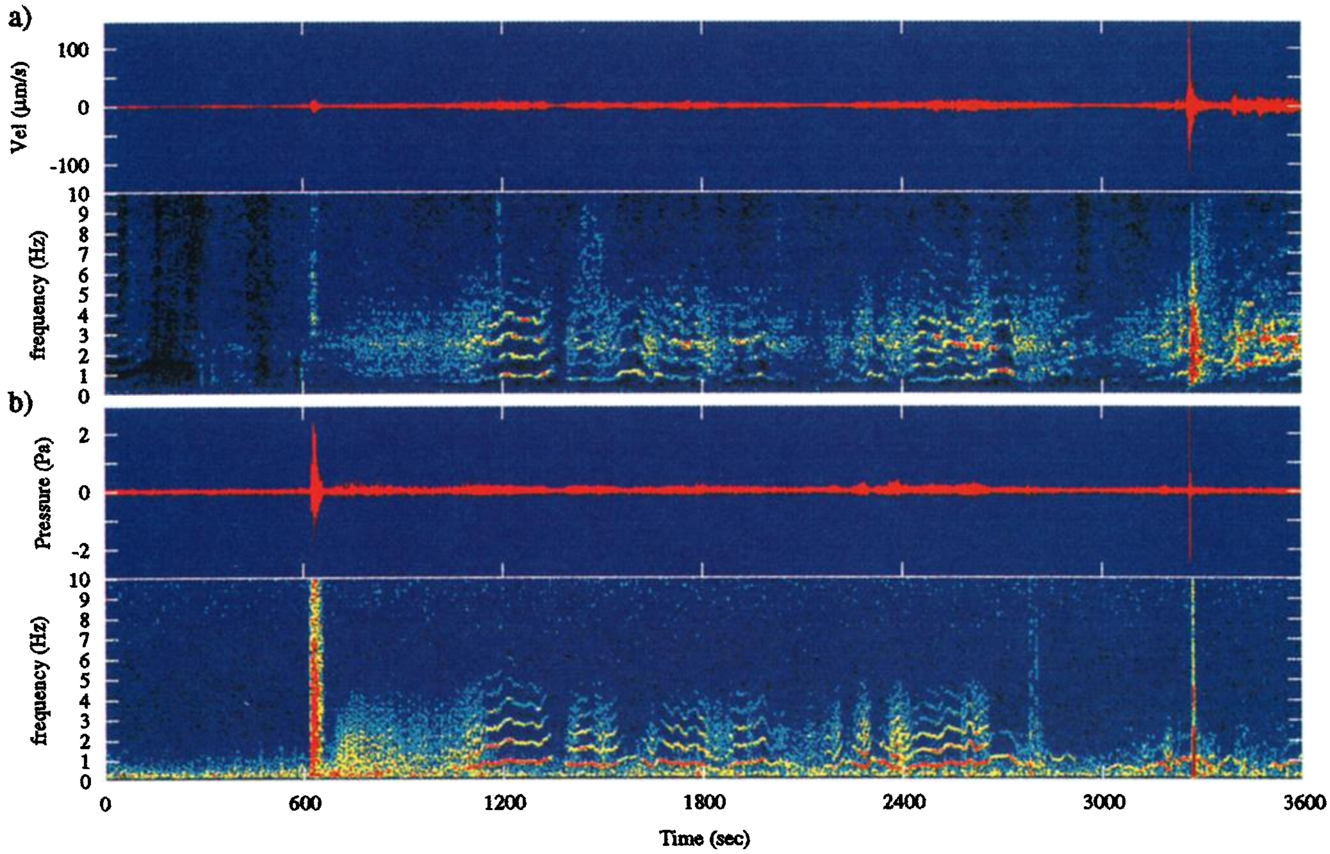

Figure 1. a) One hour of vertical ground velocity and the corresponding spectrogram, showing the normalized log of the power spectral density as a function of time. b) The airborne acoustic pressure recorded for the same time period, and its corresponding spectrogram .

and velocity excitations, and how does this mixture interact with the conduit walls and the overlying atmosphere? Aspects of these problems have been addressed in the theoretical acoustic models of *Garcés and McNutt* [1997], and *Garcés* [1997]. We draw heavily on these works, assume that source characteristics of explosions and tremor are held fixed, and explain the variable temporal and spectral structure of the Arenal signals by requiring only the acoustic properties and flow velocity of the melt to change with time. Specifically, we postulate that the vesicularity of the melt changes with varying fluid flow conditions, and the resulting changes in the density, viscosity, and sound speed of the magma affect the propagation of acoustic waves in the melt.

Theoretical Background

Changes in the acoustic properties of the melt are discussed in light of the fluid dynamics of the magma-gas mixture and the effect of the magma column's pressure gradient on the density, sound speed, and viscosity of the melt. As the ambient pressure decreases with reduced depth in the magma column, CO_2 and H_2O gas come out of solution, in that order. CO_2 is fairly insoluble, and may begin degassing at a few kilometers depth, but for a few percent mass fraction of dissolved H_2O, this component comes out of solution only in the upper few hundred meters. As the volume fraction of bubbles increases, the density of the mixture decreases. During low flow rates, passive magma degassing will create a stable density stratification in the conduit, with bubbly, less dense magma on top. However, by applying the equation of conservation of volume for magma flowing in a conduit of constant cross sectional area, the decrease in density means that the flow velocity of the magma-gas mixture must increase with reduced depth. Time scales characterizing bubble expansion range from 0.1 to 1000 seconds [*Toramaru*, 1995], hence it is quite possible to encounter time scales of depressurization which are smaller than those of bubble growth, so that equilibrium degassing and the static stratification of the magma column cannot be sustained [P. Papale, personal communication, 1998]. The time scale of depressurization will decrease with an increasing pressure gradient in the magma, or with an increased fluid acceleration. Thus we may associate an increasing flow rate, defined as the product of the fluid flow velocity times the conduit area, with the disruption of the equilibrium stratification. An additional consideration is the difference between magmatic and lithostatic pressure in the conduit. The magma conduit wall cannot withstand pressure differences much greater than 20 MPa without collapse [*Alidibirov and Dingwell*, 1996]; thus the magma pressure at depth should be quite close to lithostatic pressure. However, at shallower depths where gas has come out of solution, we expect a sharp pressure drop with reduced depth near the fragmentation level. The level at which this pressure drop occurs is likely to vary in time with flow conditions and gas content fluctuations in the melt [Papale and Dobran, 1994], and may provide an unstable zone below the fragmentation depth where shallow explosions can occur.

The sound speed of magma-gas mixtures is a nonlinear function of void fraction [*Miksis and Ting*, 1986], and may range from as low as 10 m/s for bubbly foam at shallow depths, to up to 2500 m/s for magma below the CO_2 nucleation depth. This depth dependence of the sound speed profile and the associated acoustic impedance of the melt (defined as the product of the melt density and sound speed) produces an acoustic decoupling between the shallow and deep sections of a stable, stratified magma column [*Garcés and Hansen*, 1998]. The viscosity of a magma-gas mixture may increase or decrease with increasing void fraction. Both the viscosity and sound speed of the melt affect the acoustic attenuation properties of the magma, and they may also affect whether brittle or ductile fragmentation occurs [*Garcés*, 1997]. Hence, significant variations in the acoustic response of magma may be encountered during different flow regimes. We use acoustic recordings of eruptive activity at Arenal to infer time-varying physical properties of the magma-gas mixture and relate these to unsteady flow conditions in the conduit.

Physical Interpretation of Recorded Seismoacoustic Signals

Figure 1 shows one hour of vertical ground velocity and airborne acoustic pressure recorded 2 km from the summit during our array experiment. The seismic and acoustic records in Figure 1 show a period of quiescence preceding the first explosion. For the first 600 s, it is reasonable to assume that Arenal is not erupting, that the magma has a stable density profile determined by equilibrium thermodynamics, and that a magma-gas mixture of low sound speed floats over less vesiculated magma with a higher sound speed. The first explosion at 600 seconds is barely visible in the seismic record, but is quite prominent in the acoustic record. This inverse partitioning of explosion energy between the seismic and acoustic wavefields - explosions either produce clear seismic phases or sharp ground-coupled air waves, but not both - has been observed in much of the data collected at Arenal [*Hagerty et al.*, 1997]. Assuming that the explosion occurred at shallow depth in the magma conduit, as suggested by seismic locations [*Hagerty et al.*, 1997] and acoustic waveform modeling, the energy partition of the first explosion can be attributed to the acoustic impedance profile in the magma column; an explosion detonated in a low sound speed, low density magma-gas mixture would preferentially couple into the low sound speed, low density atmosphere because there is a better acoustic impedance match between these two media than between the shallow magma, the deeper melt, and the rigid conduit walls.

Following the explosion, the acoustic channel shows the initiation of unsteady flow. The explosion amplitudes recorded on the acoustic and seismic channels and the fact that the flow initiation process is more marked in the acoustic channel than in the seismic channel, suggests that flow entrainment was initiated by a shallow explosion and that, following the initial transient overpressure, a decompression front propagated from the shallow regions into the deeper regions of the conduit. By 1200 s, the tremor signal is well defined on both the acoustic and seismic channels, and is characterized by a fundamental frequency of 1 Hz with harmonic overtones. Figure 1 is somewhat anomalous compared with other tremor episodes in that most of the time tremor signals were recorded by the seismometers but not by the pressure sensors.

We attribute the frequency content of the tremor and explosion signals to the longitudinal resonance of the magma-gas mixture within the conduit. The shallow, highly vesiculated explosion source region is estimated to have a vertical extent on the order of tens of meters, and presumed to be floating atop a tremor-sustaining region with a vertical extent on the order of hundreds of meters. The frequent lack of acoustic recordings of tremor is expected because of the acoustic decoupling between the deeper magma in the conduit and the shallow foam. Pressure signals originating at depth are strongly reflected by the low sound speed layers of the upper vesiculated magma, and the fraction of the acoustic energy transmitted to the atmosphere is heavily attenuated by the foam, so under equilibrium conditions the predicted pressure amplitudes radiating from the vent should be low. The fact that the tremor signals are intermittently observed in the acoustic records suggests two possible flow regimes: One where the flow rates are sufficiently low to permit a stable density stratification determined by equilibrium degassing, and a second regime where the equilibrium stratification may be disrupted, possibly due to higher flow rates, so that acoustic signals originating at depth may transmit into the atmosphere with greater ease.

The phenomenon of "gliding", whereby the ensemble of spectral peaks change frequency as a function of time while maintaining their harmonic spacing, can be clearly seen in Figure 1. From 1100 to 1300 s the tremor spectral peaks oscillate about a central value. To a first approximation, the peak spacing is given by $c(1-M^2)/(2L)$ where c is the melt sound speed, L the effective length of the magma conduit, and M the Mach number of the flow, defined as the ratio of the mean flow velocity to the sound speed. Fluctuations in the effective length of the conduit are expected as the degassing episode progresses and the level of the upper magma surface, as well as the impedance contrast between this surface and the atmosphere, varies. Yet it is even more effective to alter the gas content of the melt, as small changes in the percentage of exsolved volatiles make large changes in the sound speed and Mach number of the magma-gas mixture. The frequency increase in the spectral bands shown in Figure 1 would then correspond to an increase in the melt sound speed, which is what would be expected as the exsolved gas is released and lost to the atmosphere [*Benoit and McNutt*, 1997]. Once enough gas has been released, a temporary state of equilibrium is reached where the flow either stops or becomes steady, and a brief period of acoustic quiescence is experienced ($t \approx 1400$ s in Figure 1). The metastable state of equilibrium is easily disrupted by small pressure fluctuations in the melt, which can be prompted by the release of gas pockets or the injection of new material, and before the system has time to fully equilibrate it is once again set into oscillation ($t > 1400$ s). This cycle repeats itself throughout the period shown in Figure 1, until at 3300 s, a second explosion takes place. This second explosion has a strong seismic signal as well as a marked acoustic arrival, thus reinforcing the idea that the equilibrium stratification of the magma column has been disrupted. As the impedance match between the upper and lower parts of the magma conduit is ameliorated, more of the explosion energy can propagate into the deeper parts of the magma, where the higher sound speed and density improve the acoustic coupling between the magma and the conduit walls.

Concluding Remarks

Simultaneous measurements of acoustic and seismic waves accompanying explosions of Arenal Volcano provide conclusive evidence that a magma-gas mixture can sustain propagating pressure waves. By introducing the boundaries of a magma conduit, acoustic resonance can be maintained by sustained unsteady flow. To explain the temporal and spectral variability of the recorded seismoacoustic signals, we introduce the concept of a time-varying void fraction profile in the magma column which is determined in part by the flow regime. During low flow rates, equilibrium magma degassing may determine the stable stratification of the magma column, causing an acoustic decoupling between the shallow and deep parts of the magma column, and suppressing acoustic energy transfer between the explosion and tremor source regions. At higher flow rates, the equilibrium stratification may be disrupted, leading to improved acoustic transmission through the magma column. This would augment radiation of tremor energy into the atmosphere and enhance the coupling of explosion energy into the ground.

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References

Alidibirov, M., and D. Dingwell, Magma fragmentation by rapid decompression, *Nature*, *380*, 146-148, 1996.

Benoit, J. P. and McNutt, S. R., New constraints on source processes of volcanic tremor at Arenal volcano, Costa Rica, using broadband seismic data, *Geophys. Res. Lett.*, *24*, 449-452, 1997.

Borgia, A., C. Poore, M. J. Carr, W. G. Melson and G. E. Alvarado, Structural, stratigraphic, and petrologic aspects of the Arenal-Chato volcanic system, Costa Rica: Evolution of a young stratovolcanic complex, *Bull. Volcanol.*, *50*, 86-105, 1988.

Chouet, B., Long period volcano seismicity: its source and use in eruption forecasting, *Nature*, *380*, 309-316, 1996.

Garcés, M. A. and R. A. Hansen, Waveform analysis of seismoacoustic signals radiated during the Fall 1996 eruption of Pavlof volcano, Alaska, *Geophys. Res. Lett.*, *25*, 1051-1054, 1998.

Garcés, M. A., On the volcanic waveguide, *J. Geophys. Res.*, *102*, 22,547-22,546, 1997.

Garcés, M. A. and S. R. McNutt, Theory of the sound field generated by a resonant magmatic conduit, *J. Volcanol. Geotherm. Res.*, *78*, 155-178, 1997.

Hagerty, M. T., S. Y. Schwartz, M. Protti, M. Garcés, T. Dixon, Observations at Costa Rican volcano offer clues to causes of eruptions, *Eos Trans. AGU*, *78*, p. 565,570-571, 1997.

McNutt, S. Volcanic tremor from around the world, *Bull. - New Mex. Bureau of Mines & Min. Res.*, *131*, 183, 1989.

Miksis, M. and L. Ting, Wave propagation in a bubbly liquid with finite-amplitude asymmetric bubble oscillations, *Phys. Fluids*, *29*, 603-618, 1986.

Papale, P. and F. Dobran, Magma flow along the volcanic conduit during the Plinian and pyroclastic flow phases of the May 18, 1980, Mount St. Helens eruption, *J. Geophys. Res.*, *99*, 4355-4377, 1994.

Toramaru, A., Numerical study of nucleation and growth of bubbles in viscous magmas, *J. Geophys. Res.*, *100*, 1913-1931, 1995.

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