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Complex behavior and source model of the tremor at Arenal volcano, Costa Rica

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Abstract

Typical records of volcanic tremor and explosion quakes at Arenal volcano are analyzed with a high-resolution time-frequency method. The main characteristics of these seismic signals are: (1) numerous regularly spaced spectral peaks including both odd and even overtones; (2) frequency gliding in the range [0.9–2] Hz of the fundamental peak; (3) frequency jumps with either positive or negative increments; (4) tremor episodes with two simultaneous systems of spectral peaks affected by independent frequency gliding; (5) progressive transitions between spasmodic tremor and harmonic tremor; (6) lack of clear and systematic relationship between the occurrence of explosions and tremor. Some examples of alternation between two states of oscillation characterized by different fundamental frequencies are also observed. Some tremor and explosion codas are characterized by acoustic and seismic waves with identical spectral content and frequency gliding, which suggests a common excitation process. We propose a source model for the tremor at Arenal in which intermittent gas flow through fractures produces repetitive pressure pulses. The repeating period of the pulses is stabilized by a feedback mechanism associated with standing or traveling waves in the magmatic conduit. The pressure pulses generate acoustic waves in the atmosphere and act as excitation of the interface waves in the conduit. When the repeating period of the pulses is stable enough, they produce regularly spaced spectral peaks by the Dirac comb effect and hence harmonic tremor. When the period stability is lost, because of failures in the feedback mechanism, the tremor becomes spasmodic. The proposed source model of tremor is similar to the sound emission process of a clarinet. Fractures in the solid or viscous layer capping the lava pool in the crater act as the clarinet reed, and the conduit filled with low velocity bubbly magma is equivalent to the pipe of the musical instrument. The frequency gliding is related to variations of the pressure in the conduit, which modify the gas fraction, the wave velocity and, possibly, the length of the resonator. Moreover, several observations suggest that two seismic sources, associated with two magmatic conduits, are active in Arenal volcano. They could explain in particular the apparent independence of tremor and explosions and the episodes of tremor displaying two simultaneous systems of spectral peaks.

Keywords: volcano seismology; volcanic tremor; explosion quake; source model; Arenal volcano

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1. Introduction

The large variety of seismic signals observed on active volcanoes is closely related to the diversity of processes involved at the sources and to the wide range of physical parameters that characterize the volcanic fluids and solid rocks. In order to constrain the volcano-seismic source models and to get information on the state of the volcanic systems, detailed observations and careful analysis of seismic signals are required.

Arenal volcano is a small (1670 m a.s.l., 15 km^3) stratovolcano located in north-western Costa Rica. Since the strong 1968 eruption, Arenal has experienced permanent activity characterized by constant lava extrusion at a present rate of about 9×10^6 m^3 per year (Wadge, 1983; Reagan et al., 1987; Wadge et al., 2006-this issue). Gas emission is produced both by passive degassing in rhythmic pulses along the edge of the crater, and by strombolian explosions (Williams-Jones et al., 2001). Since 1975 the effusive activity takes place in crater C (Fig. 1) which contains a lava pool composed of viscous basaltic andesite (Cigolini et al., 1984; Alvarado and Soto, 2002). The lava overflows the crater rim and produces an almost continuous flow on the north to southwest flanks of the volcano (Cigolini et al., 1984; Murillo and Ruiz, 2004). Sporadic pyroclastic flows are generated either by moderate column collapse from strombolian explosions, by small block avalanches from lava fronts (Alvarado and Arroyo, 2000) or by partial cone collapse and outpouring of the lava pool (Alvarado and Soto, 2002). During the last years, small lava domes progressively grew on the lava pool. The magma composition is almost constant since 1968 suggesting a steady basalt recharge of the magmatic chamber (Streck et al., 2002).

Seismic activity at Arenal is mainly composed of harmonic and spasmodic tremor, LP events and explosions quakes. Some of the events are accompanied by acoustic waves (Alvarado and Barquero, 1987; Barquero et al., 1992; Garcés et al., 1998; Hagerty et al., 2000). The origin of the seismic signals at Arenal is not yet well understood. Indeed, although several source models have been considered, none of these models can account for all the features of the seismic signals.

In this paper, we present a high-resolution spectral analysis of continuous records of tremor and explosions and we report a larger variety of behaviors than previously described. We discuss the implications of these observations and propose a source model that can explain most of the tremor properties.

2. Seismicity of Arenal

The first seismological investigation at Arenal was carried out by Matumoto shortly after the 1968 eruption

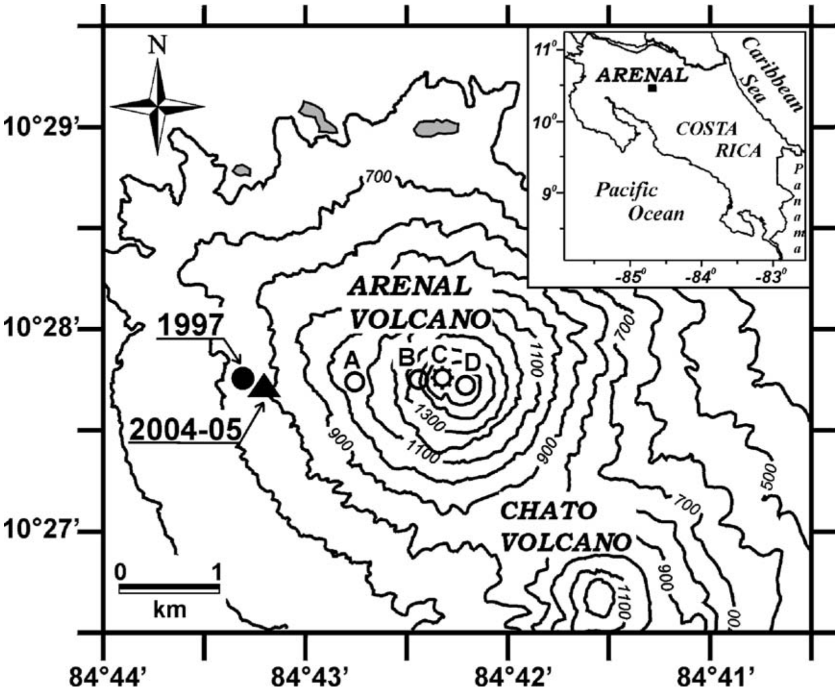

Fig. 1. Map of Arenal volcano with the location of the sensors set up in 1997 (close circle) and in 2004–2005 (triangle) and used in this study. Location of the old craters A, B and D and active crater C is indicated.

(Minakami et al., 1969). Continuous monitoring of the seismic activity started in 1974 with the deployment of a permanent network by the Instituto Costarricense de Electricidad (ICE). A station was also installed in 1984 by the Observatorio Sismológico y Vulcanológico de Costa Rica. In 1994, ICE created the Observatorio Sismológico y Vulcanológico de Arenal y Miravalles (OSIVAM) and deployed 12 digital seismic stations around Arenal and Miravalles geothermal field.

Seismic activity at Arenal volcano is characterized by a large variety of signals including harmonic and spasmodic tremor, explosion quakes, LP events, rockfall events and some volcano-tectonic (VT) swarms (Alvarado et al., 1997). Tremor is the most conspicuous signal at Arenal and lasts several hours per day. Spasmodic tremor is characterized by energy distributed in a wide frequency band, usually in the range [1–6] Hz, and its spectra have no dominant peaks. Harmonic tremor energy is concentrated in narrow frequency bands and its spectra contain several regularly spaced peaks. The overtone frequencies are integer multiples of the fundamental peak frequency which is generally in the range [0.9–2] Hz (Hagerty et al., 2000; Mora, 2003). Different estimations of the fundamental frequency given in previous studies (Minakami et al., 1969; Alvarado and Barquero, 1987; Morales et al., 1988; Melson, 1989; Barboza and Melson, 1990; Barquero et al., 1992; Métaxian et al., 1996) can be explained by the phenomenon of frequency gliding. Indeed, time-frequency analysis of continuous records reveals large variations (>50%) of the fundamental frequency in minutes or tens of minutes (Benoit and McNutt, 1997; Hagerty et al., 2000).

Strombolian activity started in 1984, producing 0.5–2 km high columns. The associated explosion quakes are low frequency, with most of the energy concentrated in several peaks between 1 and 3 Hz. Strong explosions are often accompanied by a large audible boom (Alvarado and Barquero, 1987; Garcés et al., 1998) which produces, several seconds after the P wave onset, high frequency seismic phase due to coupling between the acoustic waves and the ground. The explosion coda frequently becomes harmonic tremor (Barquero et al., 1992; Benoit and McNutt, 1997; Hagerty et al., 2000). LP events are very similar to explosions except that their records do not display acoustic phases. Hereafter LP events and explosion quakes will be considered as part of the same type of event, as there is probably no fundamental difference in their mechanism. Tens to hundreds of these events are observed each day (Mora, 2003). The seismic sources of tremor and discrete events are located below the active crater (Alvarado et al., 1997; Hagerty et al., 2000; Métaxian et al., 2002). Several volcano-tectonic swarms have been detected a few months before the major pyroclastic flows originated by crater wall collapses (Alvarado and Arroyo, 2000; Alvarado and Soto, 2002).

The level of explosions and tremor activity displays large variability on time scales of weeks to months. However a slight decrease of the number and amplitude of the explosions has been detected in the last 10 years (Mora, 2003; Taylor et al., 2004). Conversely, the main features of the seismic signals are almost permanent over at least the last decade. In particular, the records analyzed in the present study seem to be quite representative of the overall seismicity of Arenal.

3. Data

The data set analyzed in this study was mostly recorded in February 1997 by a temporary broadband station (Guralp CMG 40T) located 1.8 km west from the active crater (Fig. 1). It was complemented by seismic and acoustic recordings obtained at almost the same place by a STS2 broadband seismograph set up in March 2004 and a L4-C seismometer and a Setra-270 pressure sensor in February 2005. The time-frequency analysis was generally carried out using the

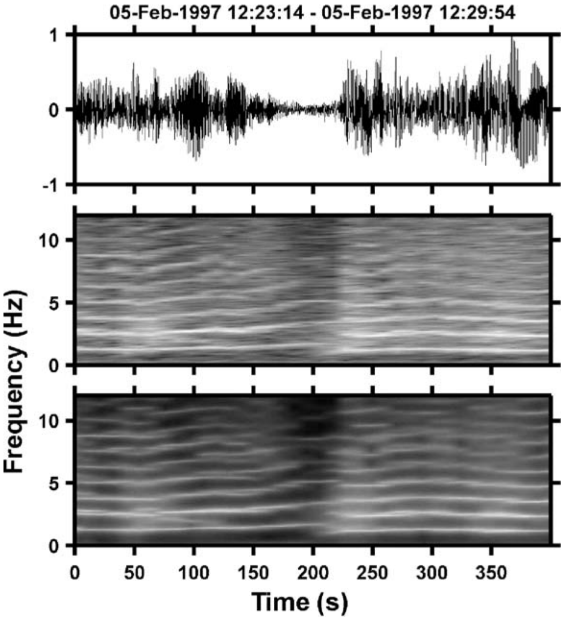

Fig. 2. Time-frequency representations of a tremor record. (a) Velocity seismogram, (b) short-term Fourier transform in logarithmic scale, (c) power spectrum in logarithmic scale estimated with the Burg method (Marple, 1987). The latter method has been used for the next figures. In this record, a frequency gliding to higher values is followed by a sudden decrease of the peaks' frequencies.

Burg method (Marple, 1987), which provides the highest spectral and temporal resolutions for this kind of signal among several methods that have been compared (Fig. 2). All the signals presented in this paper were recorded by the vertical velocity component of the seismometer. The signals from horizontal components display very similar features. Inspections of data from the permanent monitoring network of OSIVAM since 1999 show that the features of the seismic signals obtained from our data set are representative of their long-term behavior.

4. Characteristics and behavior of the tremor and explosion quakes

Fig. 3a displays a 2-h-long typical sequence of harmonic tremor and the corresponding time-frequency representation. The tremor spectra generally contain several (up to 10) regularly spaced peaks always with both odd and even overtones. The fundamental frequency is in the range [0.9–2] Hz and displays large temporal variations with two distinct behaviors. First, episodes of progressive gliding, that last tens to hundreds of seconds, are generally associated to frequency increases of about 1 Hz (hereafter called positive gliding). In some cases frequency decreases are also observed. Second, sudden jumps of frequency that generally correspond to a decrease of the frequency following a positive gliding (Fig. 2). Sometimes the tremor spectrum shows alternations with abrupt transitions between two states characterized by different fundamental frequencies (Fig. 3b). Note that in this case the highest frequency is generally not an integer multiple of the lowest one. Sporadically, the two states of oscillation seem to coexist during short periods. In both states, even and odd overtones are observed. However, no period doubling in continuous records has been observed in our data.

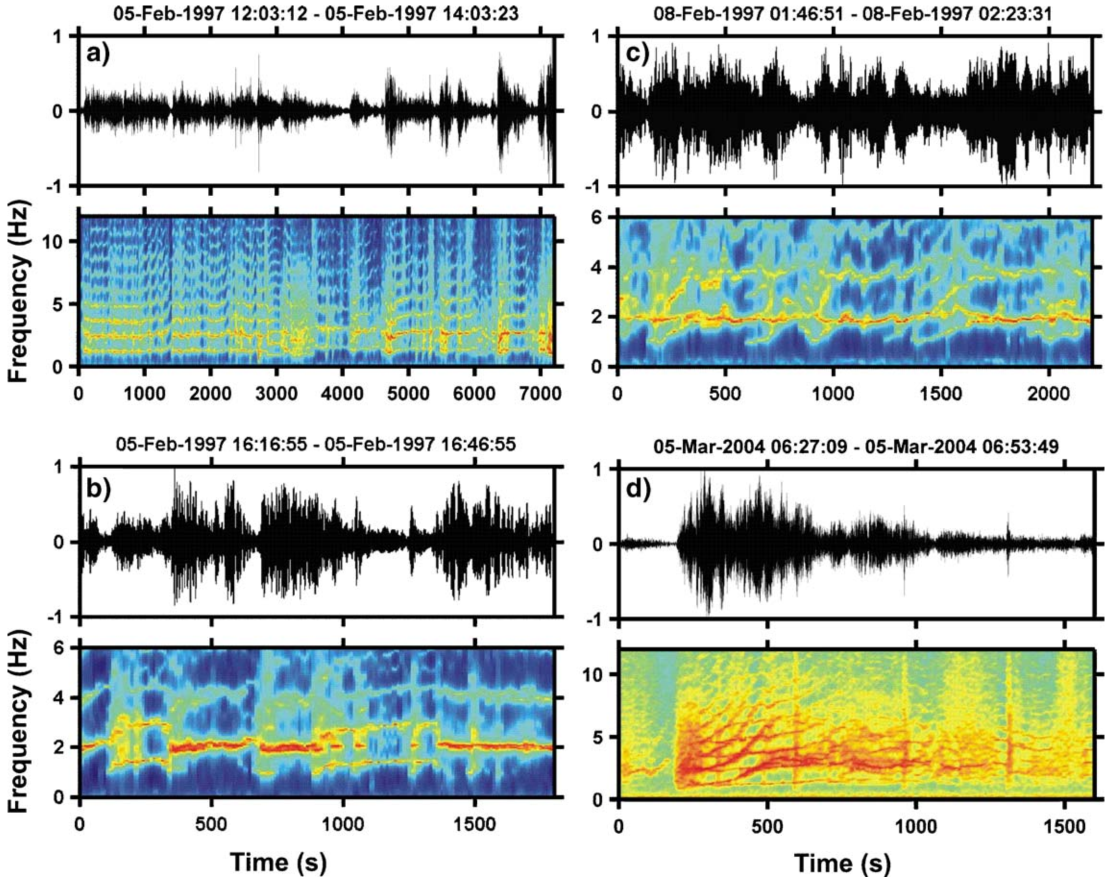

Fig. 3. Several records of volcanic tremor and corresponding time-frequency representation. Vertical velocity component, in arbitrary units. Note that different time and frequency scales are used. (a) Two hours of harmonic tremor. (b) Tremor showing sharp transitions between two states characterized by fundamental frequencies of about 1.5 and 2 Hz, respectively. (c, d) Examples of tremor showing two sets of spectral peaks with independent gliding behaviors.

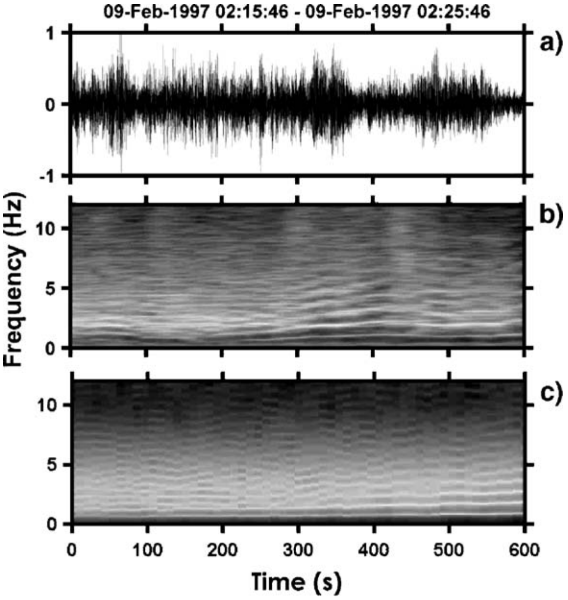

Fig. 4. (a) Transition between spasmodic and harmonic tremor and (b) corresponding time-frequency representation. At the beginning of this record, the spectral peaks are not well marked, characterizing spasmodic tremor. The peaks become clearer and clearer in a few minutes indicating that the tremor progressively turns harmonic. (c) Time-frequency representation of a numerical simulation (see text).

Some sequences of tremor involve two simultaneous systems of spectral peaks. Both systems are characterized by regularly spaced harmonic peaks with distinct fundamental frequency and independent frequency gliding with different characteristic times (Fig. 3c and d). Spasmodic tremor is characterized by a broader spectra with energy concentrated in the band [1–6] Hz and no regularly spaced and marked spectral peaks. Actually, there is no clear difference between spasmodic and harmonic tremor. Spasmodic tremor may contain low amplitude spectral lines and sometimes progressively evolves into harmonic tremor (Fig. 4a and b). The inverse process is also observed.

No clear systematic relationship between the occurrence of explosions and the tremor behavior could be found (Mora, 2003). The explosions can be preceded, or not, and can be followed, or not, by tremor episodes (Fig. 5a–c). A kind of event, called whoosh (Benoit and McNutt, 1997), is followed by a long tremor-like coda with fundamental frequency gliding from about 2 to 3 Hz (Fig. 5d). It is generally accompanied by audible exhalations similar to a locomotive chug.

5. Interpretative source model

One of the main challenges in volcano seismology is to infer the physical processes involved at the source of the volcano-seismic events. Detailed observations and data analysis may provide important clues to identify the source processes. For Arenal volcano, three types of model have been considered so far to account for the features of seismic signals.

(1) A one-dimensional fluid-filled resonator (organ pipe) can explain the evenly spaced spectral peaks of the harmonic tremor (Alvarado et al., 1997; Benoit and McNutt, 1997; Garcés et al., 1998). In these models, the bottom end of the resonator is generally the bubble nucleation level, which represents a closed boundary because of the strong impedance contrast between magma without gas and bubbly magma. When the spectra contain both odd and even overtones, the resonator must be a closed–closed system with pressure anti-nodes at each end. This implies that there is a solid enough plug at the top of the magmatic conduit. Anyway the wave velocity must be low in order to avoid unrealistic estimations of the resonator length. This condition is fulfilled when the low velocity of either a tube wave (Ferrazzini and Aki, 1987), or a gas–magma mixture (Benoit and McNutt, 1997; Garcés et al., 1998) are taken into account. In both cases, small variations of the gas content produce strong velocity changes that can explain the observed frequency fluctuations. The excitation process of the resonance is generally not included in these models.

(2) A model based on the non-linear excitation of an irregular viscoelastic channel by fluid flow (Julian, 1994) has also been considered (Hagerty et al., 2000; Julian, 2000). These authors argue that a non-linear system can produce the phenomenon of period doubling, in relation to fluid flow modifications that could account for some of their observations. Nevertheless, this model is based on some assumptions, such as high flow velocity through a conduit constriction. Using a value of a few meters for the conduit diameter and considering the low effusive rate of about [0.3–0.6] m^3 s^{-1} (Wadge, 1983; Soto, 1998; Soto and Arias, 1998; Wadge et al., 2006-this issue), the resulting magma flow velocity is of the order of a few millimeters per second yielding a Mach number much smaller than unity. Therefore the physical conditions that could produce the non-linear excitation are not fulfilled for Arenal.

(3) A repetitive pressure transient can generate evenly spaced spectral peaks by Dirac comb effect as well. This mechanism was proposed to explain the numerous spectral lines of the tremor at Semeru volcano (Schlindwein et al., 1995). In the case of Arenal, it is consistent with acoustic measurements the spectrograms of which can display many regularly spaced spectral peaks (Hagerty et al., 2000). However the period of

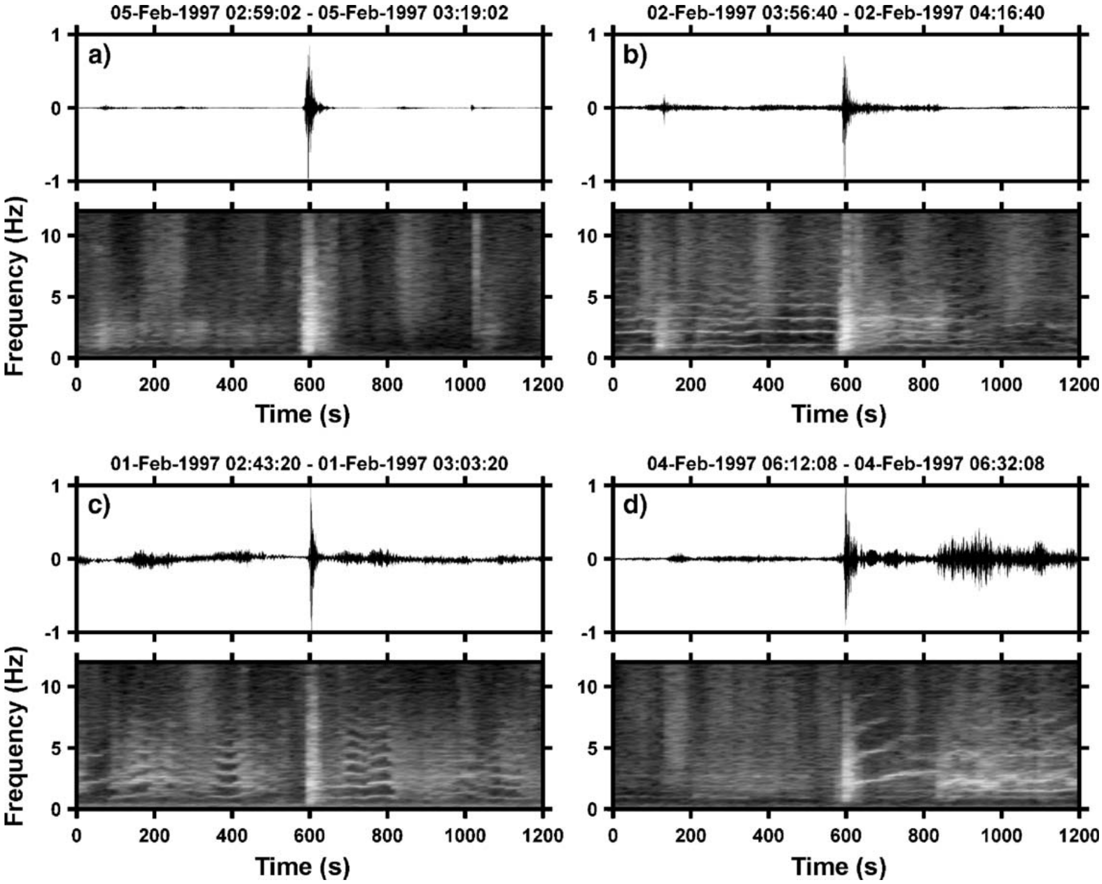

Fig. 5. Seismograms and corresponding time-frequency representations of explosions and whooshes. (a) Explosion not preceded nor followed by tremor. (b) Tremor perturbated by an explosion. (c) The tremor stops before the explosion, then appears again after the event. (d) Whoosh producing harmonic tremor in its coda with positive frequency gliding.

repetition must be quite stable to produce numerous spectral peaks (Hagerty et al., 2000; Powell and Neuberg, 2003). At Stromboli, gas bubble bursting produced the pressure transients. However, the delay time distribution between successive bursts is not stable enough to generate many spectral peaks by comb effect (Ripepe and Gordeev, 1999). In a study of Karymsky and Sangay volcanoes, Johnson and Lees (2000) proposed a mechanism analog to a pressure-cooker in which gas periodically escapes through fractures in a solid plug. Yet in this model, no mechanism stabilizing the repetition period is proposed.

Actually, none of the previous models can account alone for the different behaviors displayed by the seismic signals of Arenal volcano. We proposed a slightly more complex process involving various aspects of the previous models. The system considered here (Fig. 6) includes a conduit filled with bubbly magma. The crater, and possibly the upper part of the conduit, are filled by solid or very viscous volatile

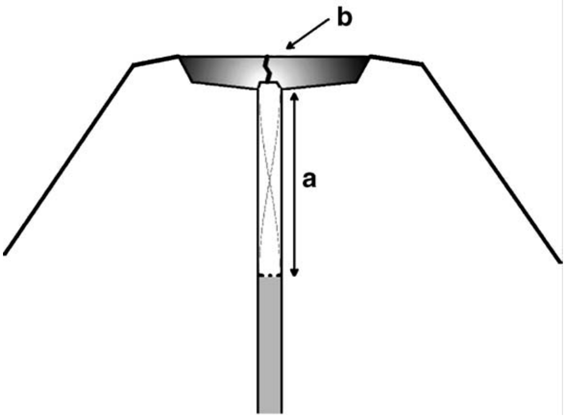

Fig. 6. The model of magmatic clarinet. It is composed by a conduit filled with bubbly magma (a) and closed at its upper part by a fractured plug (b). Standing (thin lines) or traveling interface waves in the conduit produce a pressure anti-node below the plug. Like a clarinet sound, the harmonic tremor is produced by intermittent gas flow through the fracture (the reed) with repeat period stabilized by the resonance of the conduit (the pipe).

depleted lava, and act as a plug of the conduit and a barrier for rising gas. The plug possesses one or several fractures through which gas can escape intermittently. We postulate that the tremor is produced by repetitive pressure pulses, with repeating period stabilized by a feedback mechanism linked to the resonance of the conduit. Because the waves in the conduit are mainly interface waves, the lower part of the resonating cavity is determined by a sharp variation of the stiffness factor of the conduit $C = \frac{bL}{\mu d}$, where b is the bulk modulus of the fluid, μ is the rigidity of the solid wall, L and d are the length and width of the conduit, respectively (Aki et al., 1977). This variation can be related to either a conduit constriction or widening, a geological layer with different rigidity, an exsolution level or a bubble layer. In the case of Arenal, however, the high water content of the magma (~4 wt.%, Wade et al., 2004) yields an exsolution level at depth of several thousands of meters. Thus the lower end of the resonator would not correspond to the bubble nucleation level. At the top end of the magmatic system, the elastic coefficients are much greater in the cold plug than in the bubbly hot magma. Therefore the plug behaves as a closed end of the pipe that reflects the elastic waves. Thus there is a pressure anti-node at least at the top end and the amplitude of the pressure oscillations, associated either to standing or traveling waves in the conduit, is maximum below the upper plug.

Under those conditions, the pressure may reach periodically a threshold, which depends on the plug properties that allow the fracture to open and part of the gas accumulated there to escape. Then, the pressure lowers and the fracture closes until the next pressure increase. The intermittent gas leaks produce negative pressure pulses in the conduit that can maintain the resonance if the pulse duration is of the order of half an oscillation period. This process is similar to that of a clarinet (Fletcher and Rossing, 1998), in which the standing waves in the pipe control the reed oscillations generating an intermittent air flow which in turn produces the excitation of the waves. For both, magmatic system and musical instrument, the long-lived vibrations result from a feedback between the waves in the pipe and the valve movements. The spectra of the radiated waves are characterized in both cases by regularly spaced peaks. The main difference comes from the process of wave emission. While the sound of a clarinet is radiated by the bell or the holes, the seismic waves are mainly produced as surface waves at the top of the conduit (Jousset et al., 2003). Moreover, the elastic waves in the volcanic resonator are interface waves, which are slower that acoustic waves (Ferrazzini and Aki, 1987; Jousset et al., 2003) and their attenuation level in the bubbly magma is relatively high. These features imply that the resonator has probably a length of no more than a few hundreds of meters (Collier et al., 2006).

In Fig. 7, we display the records of an explosion obtained in 2005 with a pressure sensor and a seismometer located at the same place. The frequencies of the fundamental peak estimated using AR modeling (Lesage et al., 2002) for the acoustic and the seismic waves are almost equal and they show simultaneous glidings from 2 Hz to 3 Hz in about 60 s (Fig. 7c). This observation corroborates the idea that the pressure pulses associated to the intermittent gas flow produces acoustic waves in the atmosphere and are also the excitation mechanism of the tremor source.

The behavior of the system is closely related to the lava plug properties which are continuously changing. This evolution results from a combination of processes: (1) extrusion of fresh magma in the lava pool, (2) cooling, increase of viscosity and solidification of the capping crust, and (3) partial destruction by explosion, fracturing and collapse. The short-term modifications of the plug are probably the origin of several features of the seismic signals. The fractures that open and close can be more or less choked by rubble which can strongly

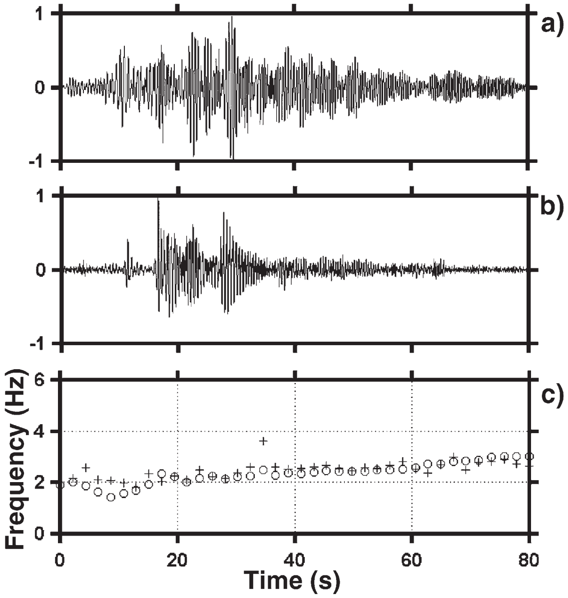

Fig. 7. Vertical ground velocity (a) and acoustic pressure (b) for an explosion recorded on February 14, 2005. (c) The frequencies of the fundamental spectral peaks, obtained by auto-regressive modeling, for the seismic (circle) and acoustic (cross) records are shown for comparison. The close values and similar variations of the frequencies suggest a common origin for the two types of waves.

modify its response to pressure variations. This can produce varying delays of the valve opening and closure yielding, for moments, loss of synchronization with the feedback mechanism and thus irregular pressure pulses generating spasmodic tremor. When the rubble is progressively expelled out of the fractures, the valve behavior becomes well synchronized with the pressure oscillations, allowing the spasmodic tremor to turn into harmonic tremor (Fig. 4a and b). To illustrate this process, we simulated the transition between spasmodic and harmonic tremor. A synthetic signal is obtained by repeating a short pulse. The mean repeating period varies linearly with time from 1.6 to 0.8 s, while the standard deviation of the period fluctuations decreases from 0.40 to 0 s. The corresponding time-frequency representation (Fig. 4c) displays spectral peaks that progressively emerge from the wide band spectra of the spasmodic tremor. This mechanism suggests that there is no fundamental difference between the sources of the two types of tremor at Arenal.

On the other hand, the state of the plug also controls the pressure of the magmatic conduit, the variations of which are closely related to the frequency gliding of the tremor. The period of the repetitive pressure pulses is equal to the period of the fundamental mode of the resonator. It depends on the velocity of the interface waves propagating in the conduit and on the length of the resonator. A pressure decrease induces, in the bubbly magma, an increase of the gas fraction and a decrease of its bulk modulus and acoustic velocity, lowering the tremor frequency. Furthermore, a pressure decrease also produces an increase of the nucleation depth (Sturton and Neuberg, 2003), yielding frequency decrease if the lower end of the resonating pipe is determined by the exsolution level. When the valve is well sealed, the pressure increases and a positive frequency gliding is produced. On the contrary, when the plug tightness is damaged and the gas can escape continuously, the pressure progressively lowers leading frequency decrease and negative gliding. The gliding toward higher frequency observed after some explosions (Fig. 5) would correspond thus to a pressurization of the system in relation to the cooling of the superficial lava and the sealing of the upper end of the conduit. When the vent closes, the waves in the conduit are no longer excited and the tremor stops while its frequency is high. In any case, the evenly spaced spectral peaks are produced by the Dirac comb effect. Numerical simulations show that the comb effect is still effective even when strong frequency gliding occurs (Fig. 8).

Several features of the tremor and explosion quakes at Arenal strongly suggest that two seismic sources are active in the volcano. They would be located in the magmatic conduits connected to the two unsteady vents observed in the crater (Fig. 9). The episodes of tremor containing two systems of overtones with independent frequency glidings (Fig. 3c and d) could be interpreted by simultaneous oscillations of the two corresponding resonators and by different pressure variations in the conduits related to independent evolutions for their respective plug. Furthermore, some explosions could occur at the top of one of the conduits while harmonic tremor is generated, or not, in the other one. The apparent lack of relationship between explosions and tremor (Fig. 5) could thus be derived from the relative independence of the two vents. A double source could also give a speculative explanation to some sudden frequency jumps and especially to the alternations between two systems of harmonic spectral peaks (Fig. 3b). Indeed, if the two conduits are not linked, they form independent resonators. On the other hand, if their lower ends correspond to their branching, where the tube is wider and where some foam may accumulate, small modifications of this part of the system may produce an acoustic link between the conduits. This link would yield them to form a unique resonator with greater length and lower fundamental frequency (Fig. 10). The modifications could occur in a short time producing the

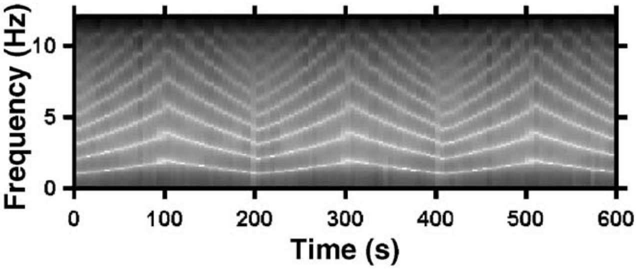

Fig. 8. Time-frequency representation of a synthetic signal that mimics frequency gliding. The signal is obtained by repeating a short pulse with a repeat frequency that varies in time according a saw tooth function. Although the repeat period strongly (but smoothly) varies, the comb effect still produces many spectral peaks provided the analyzing window is short enough compared with the characteristic time of the variations.

Fig. 9. View of Arenal volcano from the NW. The fumaroles indicate the existence of two vents in the active crater C. The old crater D stands on the background of the picture. Photo by L. Madrigal (February 2004).

observed frequency jumps. Further investigations are need to find a mechanism able to connect and disconnect the conduits.

6. Conclusion

The high-resolution spectral analysis carried out on the seismic signals of Arenal has revealed a large diversity of behaviors. This reflects the complexity of the magmatic system and of the physical processes involved. It is well known that fluids with two or three phases (gas + liquid + crystals) can display several flow regimes and that their physical properties are strongly dependent of the gas fraction. Moreover, the existence of a lava pool filling the crater may produce a large variety of phenomena due to the non-Newtonian behavior of the material, the strong dependence of the viscosity to temperature, the extrusion, cooling and superficial flows of magma, and to the formation, fracturing and destruction of the solid crust capping the top of the conduits.

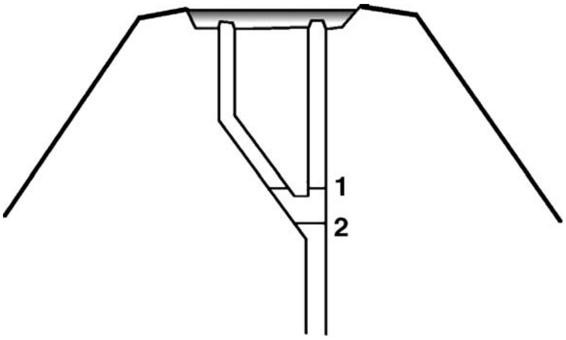

Fig. 10. Sketch of the two magmatic conduits connected to the vents. When their lower ends are at position 1, higher than the branching, the conduits form two independent resonators. When the ends are at the lower position 2, they are acoustically connected and behave as a single resonator with much lower frequencies than in the former case. Rapid modifications of this part of the conduits could thus explain the sudden frequency jumps displayed in Fig. 4. More investigation is required to understand this hypothetical process of intermittent link between the resonators.

The model proposed in this paper is relatively simple in its present state. It is similar to the pressure-cooker model proposed by Johnson and Lees (2000) for the source of tremor at Karymsky and Sangay volcanoes. However, our model includes a mechanism which makes the pressure pulses regular enough to produce the observed overtones by the Dirac comb effect even during frequency gliding episodes. It is consistent with most of the seismic signal features described, including the numerous regularly spaced spectral peaks, the frequency glidings, the double system of spectral peaks, the alternation between two states of oscillation, the transition between spasmodic and harmonic tremor, and the lack of clear correlation between explosion quakes and tremor. Furthermore, the mechanism involved for the excitation is almost non-destructive and can thus explain the long-lasting tremor of Arenal. Several features of the tremor and explosions are simply explained by a double source associated to two magmatic conduits. Photographic evidences and visual observations suggest that at least two vents exist since 1987, although they are not stable in time, space nor grade of activity.

Numerical simulations of the proposed model will be carried out in order to study the influence of its parameters on its efficiency in generating tremor. Improvements of this preliminary model should mainly address the effect of the pressure variations on the magma properties in the conduits and the interactions between the lava pool and the elastic waves in the conduit. The mechanism of the explosions should also be studied more precisely in order to build a source model that could account for all the observed seismic signals. Long-term continuous recordings of both seismic and acoustic waves generated by the volcano, together with visual or video observations of the active crater would help constrain a more quantitative model of this system.

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