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Reventador Volcano 2005: Eruptive activity inferred from seismo-acoustic observation

Jonathan M. Lees [a,*], Jeffrey B. Johnson [b], Mario Ruiz [a,c], Liliana Troncoso [c], Matt Welsh [d]

[a] Department Geological Sciences, University of North Carolina, Chapel Hill, United States
[b] Department of Earth and Environmental Science, New Mexico Tech., Socorro, NM, United States
[c] Instituto Geofisico, Escuela Politecnica Nacional, Quito, Ecuador
[d] School of Engineering and Applied Sciences, Harvard University, United States

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Abstract

Reventador Volcano entered an eruptive phase in 2005 which included a wide variety of seismic and infrasonic activity. These are described and illustrated: volcano-tectonic, harmonic tremor, drumbeats, chugging and spasmodic tremor, long period and very long period events. The recording of this simultaneous activity on an array of three broadband, seismo-acoustic instruments provides detailed information of the state of the conduit and vent during this phase of volcanic eruption. Quasi-periodic tremor at Reventador is similar to that observed at other volcanoes and may be used as an indicator of vent aperture. Variations in the vibration modes of the volcano, frequency fluctuations and rapid temporal fluctuations suggest the influx of new material, choking of the vent and possible modification of the conduit geometry during explosions and effusion over a period of six weeks.

Keywords: Reventador; volcano; Ecuador; infrasound; earthquakes; volcanic earthquakes; harmonic tremor; drumbeat earthquakes; volcano chugging

1. Volcan Reventador background

Reventador belongs to the easternmost of the four sub-parallel volcanic chains in the Ecuadorian Andes. It is situated ~100 km east of Quito, in the sub-Andean foothills at the boundary of the cordillera and Amazon basin (Fig. 1). The currently active cone reaches 3560 m with a vertical relief of about 1300 m and is growing within a 4×6 km collapse amphitheatre, open to the east, which dates from ~19,000 yr BP (INECEL, 1988). Eruptive products from the volcano, predominantly andesitic, are filling the caldera, including lahar deposits, lava flows and pyroclastic material (Samaniego et al., 2007 — this issue). Geochemical data suggest the presence of a small magma reservoir (30×10^6 m^3) with relatively low levels of basaltic magma recharge (INECEL, 1988). Additional geochemical studies of Reventador are highlighted in several additional papers in this volume (Ridolfi et al.; Samaniego et al., 2007 — this issue). Q1

Reventador is one of the most active volcanoes in Ecuador having the distinction of producing the largest volcanic explosion (3/11/2002) since Cotopaxi in 1877. Reventador has erupted on numerous occasions in historical times, producing both explosive activity and lava emissions. At least 16 of the recent eruptions were large enough to be observed from the Cordillera since 1541 (Hall et al., 2004), but only the most recent 1976 and 2002 eruptions were documented in detail. The climactic VEI 4 phase of the November 3rd 2002 eruption occurred with little precursory warning, in terms of seismic or eruptive activity (Hall et al., 2004). It awoke suddenly and produced a 17-km-high eruptive column, pyroclastic flows that rose up to 8 km, and, in subsequent weeks, two major lava flows emanating from the summit crater and from a flank vent (Samaniego et al., 2007 — this issue). After nearly a year of quiescence, new lava domes were extruded from November, 2004, through January, 2005, and again between March–June, 2005, forming several new lava flows. The most recent lava flow

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* Corresponding author.
E-mail address: jonathan_lees@unc.edu (J.M. Lees).

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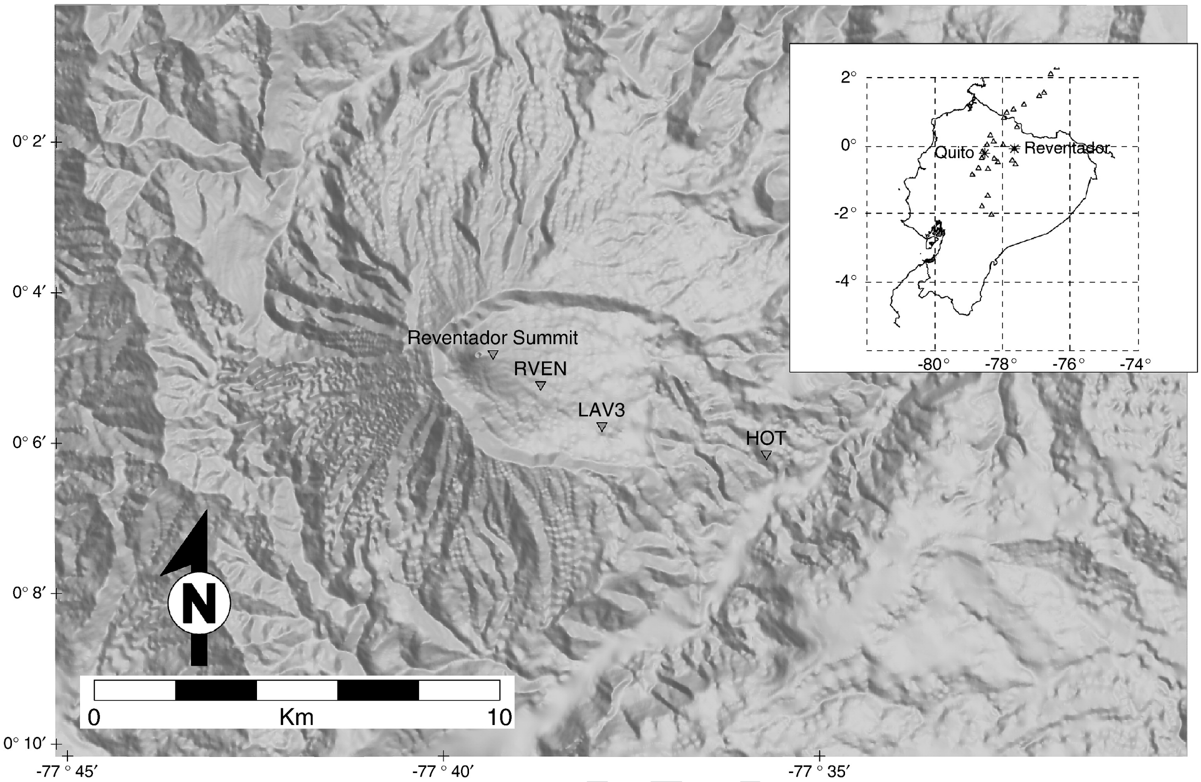

Fig. 1. Map of Reventador. Inset shows location of Reventador in Ecuador and its relation to the other volcanoes in the Northern Andes Cordilleras. Stations were located along a nearly linear array extending southeast from the vent. Station RVEN was located on the flanks of the erupting cone. Each station was equipped with a broadband 3-component seismometer and an infrasonic microphone.

erupted immediately prior to the deployment described in this paper and reached more than 4 km from its source in the breached 2002 cone.

An increase in explosive activity was observed prior to the cessation of vigorous lava flow activity in June 2005. This explosive period consisted of marked fluctuations in eruptive behavior, ranging from periods of quiescence lasting several days, to extended-duration Strombolian activity, with bombs ejected more than 500 m above the vent, to short-lived Vulcanian explosions, a few of which were responsible for small pyroclastic flows (e.g., an example is an event occurring on September 13th at 2:00 AM GMT). The renewed explosive activity during June–August, 2005, suggests a fresh injection of gas-rich magma (Samaniego et al., 2007 — this issue). However, the upturn in activity was relatively short-lived and by the end of 2005 there was little evidence for magmatic explosions.

1.1. Seismicity and other geophysics

The paroxysmal eruption of November 3rd 2002 was preceded by limited seismic warning. Regional seismometers and local felt reports indicate that elevated earthquake activity began no earlier than 24 h prior to the VEI 4 event (e.g., Hall et al., 2004). Subsequent eruptive activity was slightly better predicted due in part to enhanced local monitoring seismic network deployed by the Instituto Geofisico of the Escuela Politecnica Nacional (IG-EPN). For example, the October 2004 lava extrusion was preceded by a large swarm of volcano-tectonic events, and accompanied by an increase of hybrid events (Troncoso et al., 2006). Following this the spring 2005 lava flows appear to have been preceded and accompanied by an increase of long-period events and harmonic tremor. Strong tremor signals and spasmodic tremor (drumbeats) were recorded in June 2005 at the same time that Strombolian activity was first observed from the crater. Earthquake catalogues from the IG-EPN show fluctuating episodes of activity with varying numbers of different kinds of seismic events including volcano–tectonic (VT), long period (LP), hybrid (HB) harmonic tremor (TR) and spasmodic tremor (SP) (Fig. 2). During the period of the broad-band deployment (Julian days 214–256), large numbers of LP, HB, and TR events were catalogued.

In an earlier paper, analysis of the infrasound signals at Reventador recorded during the 2005 broadband deployment showed that low frequency acoustic waves from three sources were correlated across the array (Johnson et al., 2006). Naturally, the volcano was one source of infrasound, although two non-volcanic sources were observed. Here we concentrate on seismic recordings and use the infrasound mainly to establish whether seismic events are associated with shallow, explosive activity or represent deeper foci of stress release.

2. Instrumentation and deployment

The deployment at Reventador in 2005 included three seismo-acoustic stations similar to deployments made at

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Stromboli and Tungurahua (McGreger and Lees, 2004; Ruiz et al., 2005). Two stations were equipped with 30 second Guralp CMG40T sensors (RVEN, LAV3) and one station (HOT) had a 120 s Guralp CMG3T. All three stations recorded three components. Each station included a Larsen–Davis low frequency microphone with a measured low frequency corner at 0.27 Hz (Johnson et al., 2006). Our stations were recorded continuously with a sample rate of 125 sample/s and 24 bit resolution. RVEN, LAV3, and HOT were oriented along a radial trajectory ranging from 2 to 8 km from the active vent (Fig. 1). This three-element network overlapped with one of the IG-EPN short-period telemetered stations and an experimental 16 station short-period seismo-acoustic wireless "mote" array based on the Moteiv TMote Sky wireless sensor platform (Werner-Allen et al., 2006). Data from these other arrays is not included in the analysis presented in this paper.

3. Data

3.1. General description

Activity at Reventador included a wide variety of signals similar to those observed at numerous volcanoes worldwide. The Reventador seismicity that we recorded between Julian day 214 and 256 (August 2nd to September 13th, 2005) is remarkable because it is so diverse and because it varied so considerably during the course of the six week seismic deployment. Fluctuations in volcanic activity were reflected in the seismicity, which was relatively mild at the onset of our installation period. Starting on day 215, however, explosion levels picked up and several episodes of high explosivity were observed. An example of 24 h of seismic activity on day 217 is presented in Fig. 3 which shows the extreme heterogeneity of seismic amplitudes and character. During periods of heightened seismicity, incandescence at the cone was often seen (when visibility was clear) and explosions were audible during the more energetic eruptive periods. Thousands of small earthquakes were recorded during this time period, many with accompanying infrasonic signals. Since the temporary deployment included broad-band sensors the seismic records encompass a wide range of wave types including: teleseismic waves, regional tectonic earthquakes, local earthquakes, volcano-tectonic (VT), long period (LP) events, very long period events (VLP), harmonic tremor, volcanic chugging and drumbeat sequences. These event types are described briefly in the following summary of volcanic activity.

While more than 623 large events were recorded world-wide over the span of the August–September deployment, 12 teleseismic arrivals were clearly recorded on the broadband stations established at Reventador. The teleseismic arrivals

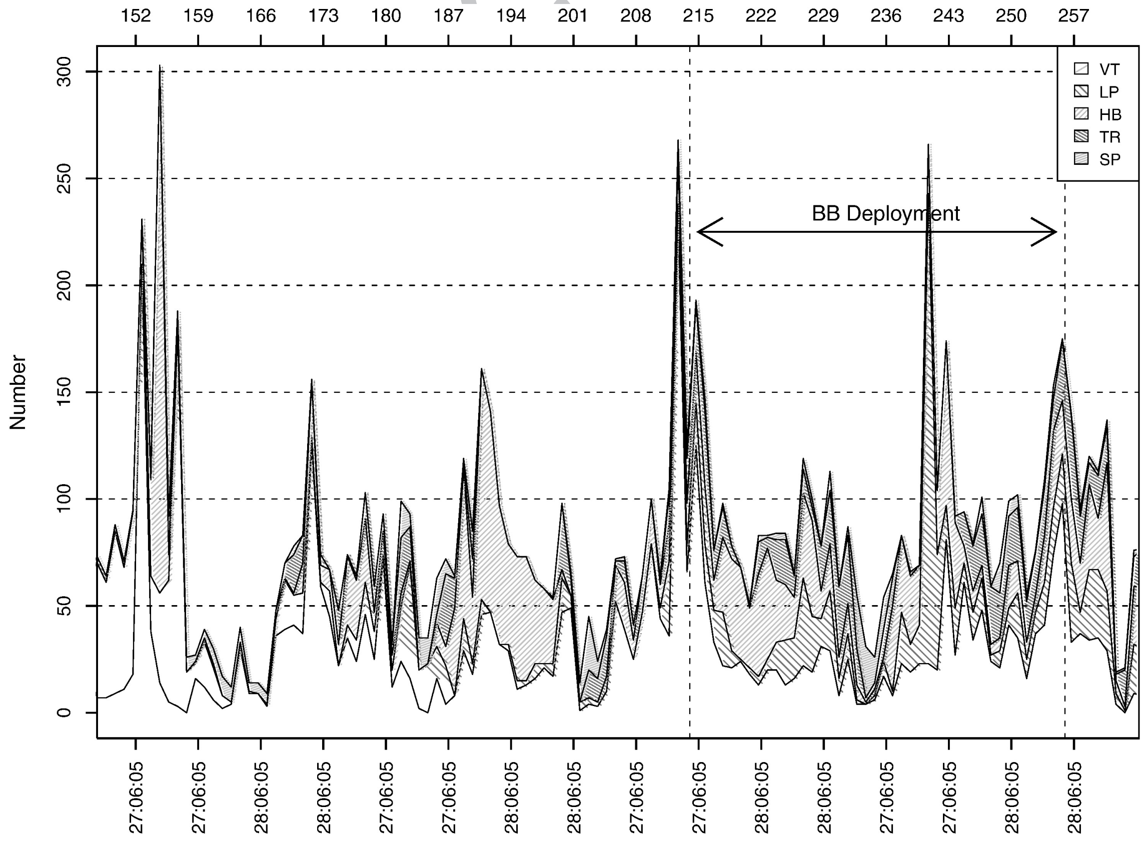

Fig. 2. Numbers of event types over a 108 day period in 2005. Event counts are determined from recordings made on the national Ecuadorian network by IG-EPN. Since this network is primarily short period and had only sparse deployment in the Reventador region, the counts are subject to considerable noise as compared to recordings made by the broadband instruments installed in August–September. The gray shaded regions shows the overlap with the broadband deployment.

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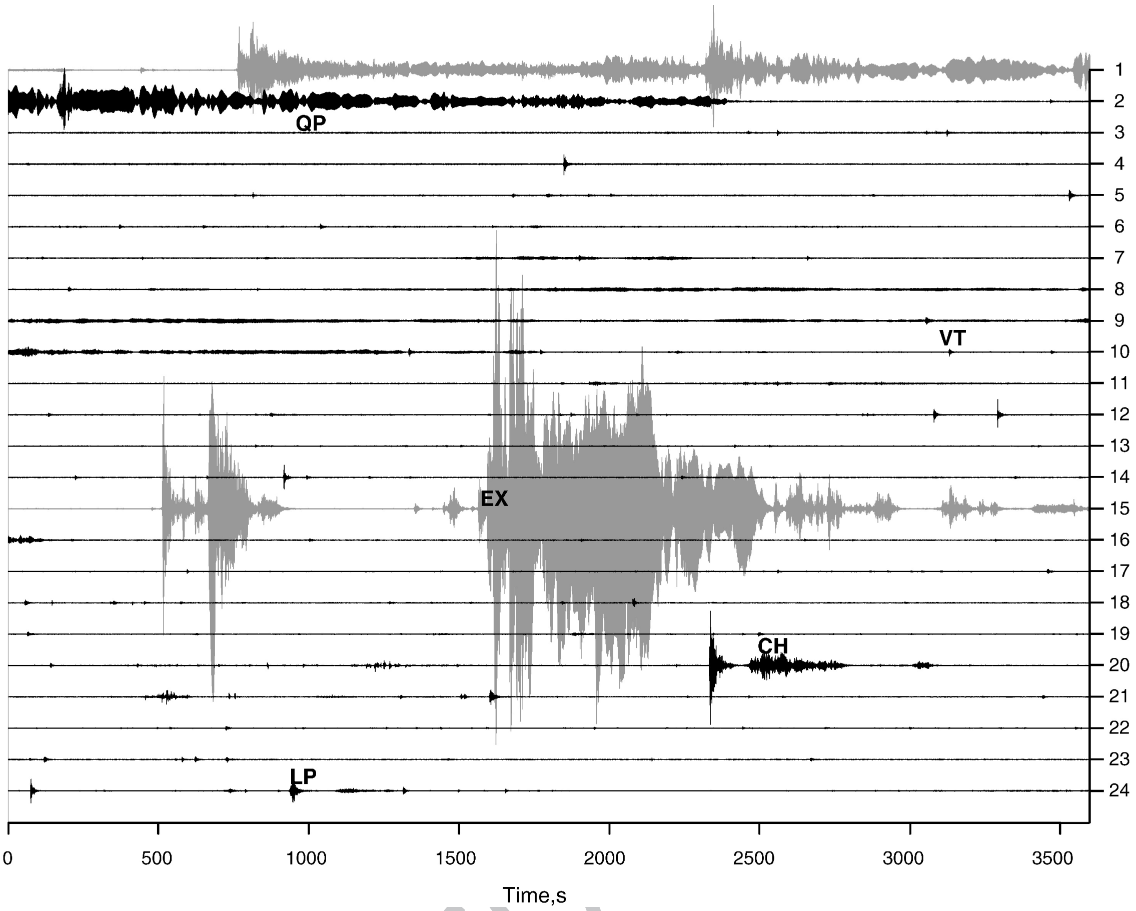

Fig. 3. Snapshot of seismic activity for day 217 at station RVEN. Quasi-periodic oscillations (QP), explosions (EX), small VT and LP events can be seen along with large explosions (EX) and chugging (CH). Explosions and larger events were accompanied by infrasonic waves but most of the quasi-periodic oscillation had nearly no corresponding acoustic signature. Amplitudes are scaled relative to the largest deviation.

show clear P and S-wave trains as well as surface waves with periods greater than 20 s. Since these events were clearly designated teleseismic they were excluded in the analysis of other long period signals and harmonic tremor described below.

During the 2005 deployment 597 regional events were reported on the Ecuadorian national seismic network catalogue. Among these regional events arrival times for at least 33 events were observed on each of the broad band stations at Reventador. Those events recorded on all three stations with clear arrivals were isolated and examined for travel time anomalies and are a focus of a subsequent study. In this paper we concentrate instead on waveforms and the descriptive character of explosions during this period of intense activity.

To illustrate the evolution of activity during the broadband deployment the mean squared amplitude (MSA) of the vertical component of two stations is presented in Fig. 4. Stations LAV3 and RVEN were low-pass filtered below 0.2 Hz and one hour blocks were extracted, squared and summed. It is important to note that fluctuations in seismic energy are observed on both RVEN and LAV3 indicating source variations in seismic energy radiation. The bottom panel of Fig. 4 shows the MSA of station RVEN sampled at 10 min intervals with no filtering, showing that both short term and longer term variations track each other closely, and that the temporal patterns do not depend on the smoothing window length. It is clear that levels of volcanic activity can be monitored by fluctuations in MSA. Times when the volcano appears to have lower productivity include a short stretch late in Julian day 219 through day 221 and a longer stretch between days 237–248. Variations of activity thus recorded may represent pulses of new magmatic material entering the conduit system leading to elevated explosivity over a short period. After a period of high level degassing, explosivity decreases with a corresponding lowering of seismic activity.

3.2. Long period (LP) events

On volcanoes LP events are characterized by narrow band spectra ranging from 2–6 Hz (McNutt, 2002). Thousands of events recorded at Reventador having LP characteristics were isolated and characterized as distinct from explosion earthquakes, based on the observation that they did not simultaneously radiate significant acoustic signals. These signals are generally emergent and occasionally have apparent S-wave arrivals later in the time series. The LP events ranged considerably in size and were less apparent during periods of

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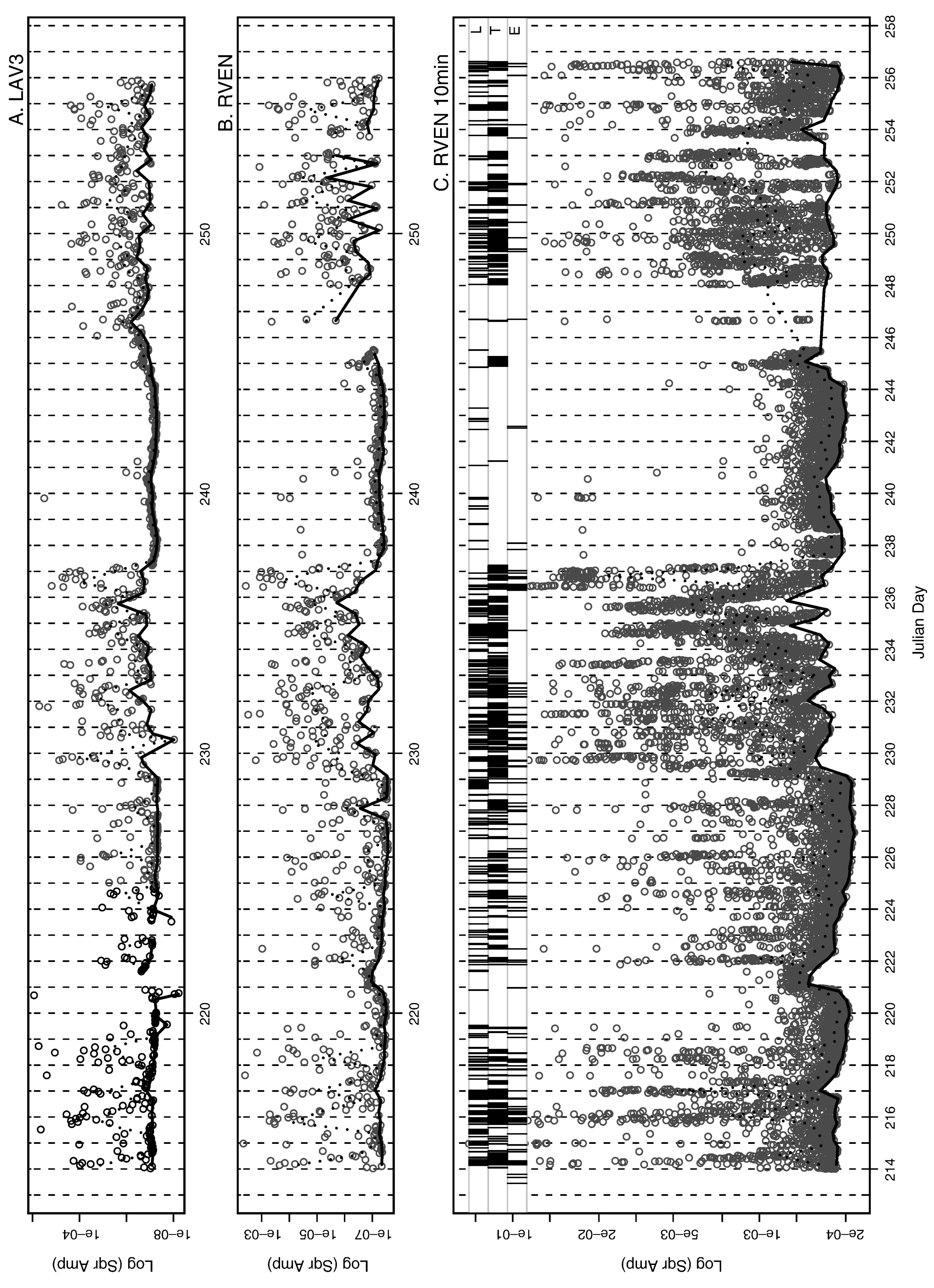

Fig. 4. Mean squared amplitudes over the full span of the deployment. A,B) Recoded at station RVEN and LAV3 the top two panels show the mean square amplitudes averaged over 1 h. The dotted lines represent median smoothed averages and bold lines are minimum levels. C) Mean square average over periods of 10 minutes at station RVEN. This shows the basic same pattern as in A) and B) with more detail. Bar codes in C represent periods of LP events (L), periods of extended tremor (T) and individual explosions (E) recorded on seismic and acoustic sensors. The lull in activity between day 238 and 248 is significant.

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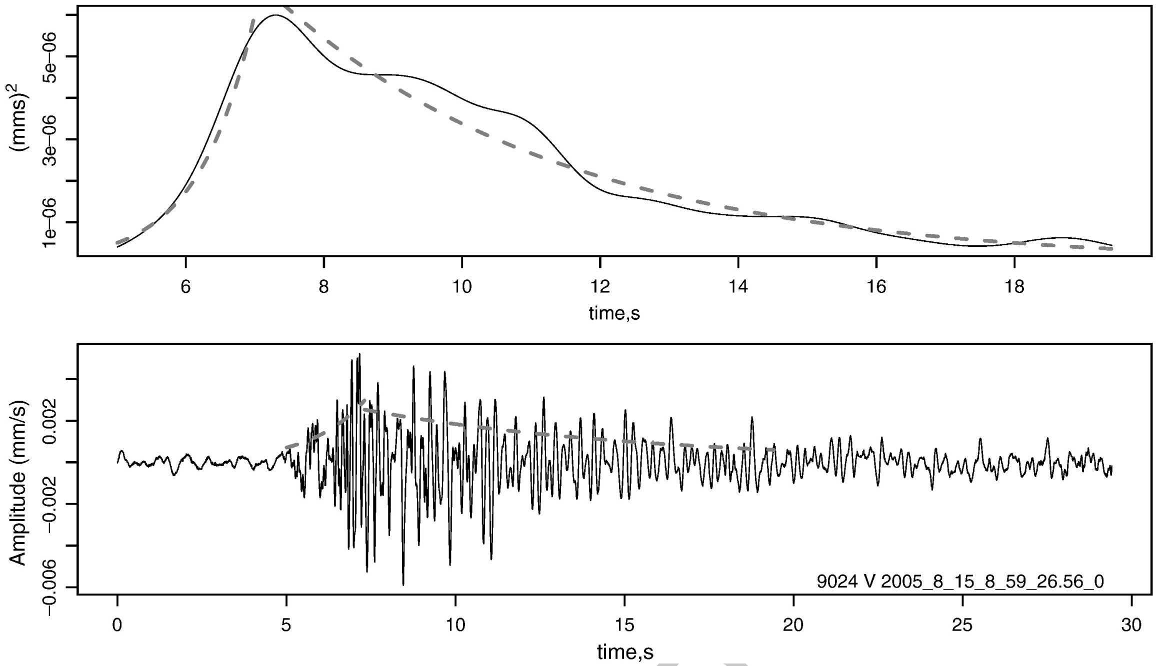

Fig. 5. Example of LP event and associated analysis of emergence and decay of amplitudes. Squared amplitudes are modeled with an exponential function prior to and following the peak of the smoothed energy. Parameters for these events are accumulated and compared for statistical analysis. The rise time slope values for this event are K1 = 1.24 for the emergent left hand curve and K2 = −0.23 for the decaying right hand side respectively.

continuous harmonic tremor. Extracting only signals with very high signal-to-noise ratio (>20) from this data subset we reduced the number of events recorded at both stations (RVEN and LAV3) to 130 clean signals which could be associated and compared (the furthest station from the vent, HOT, rarely recorded these events).

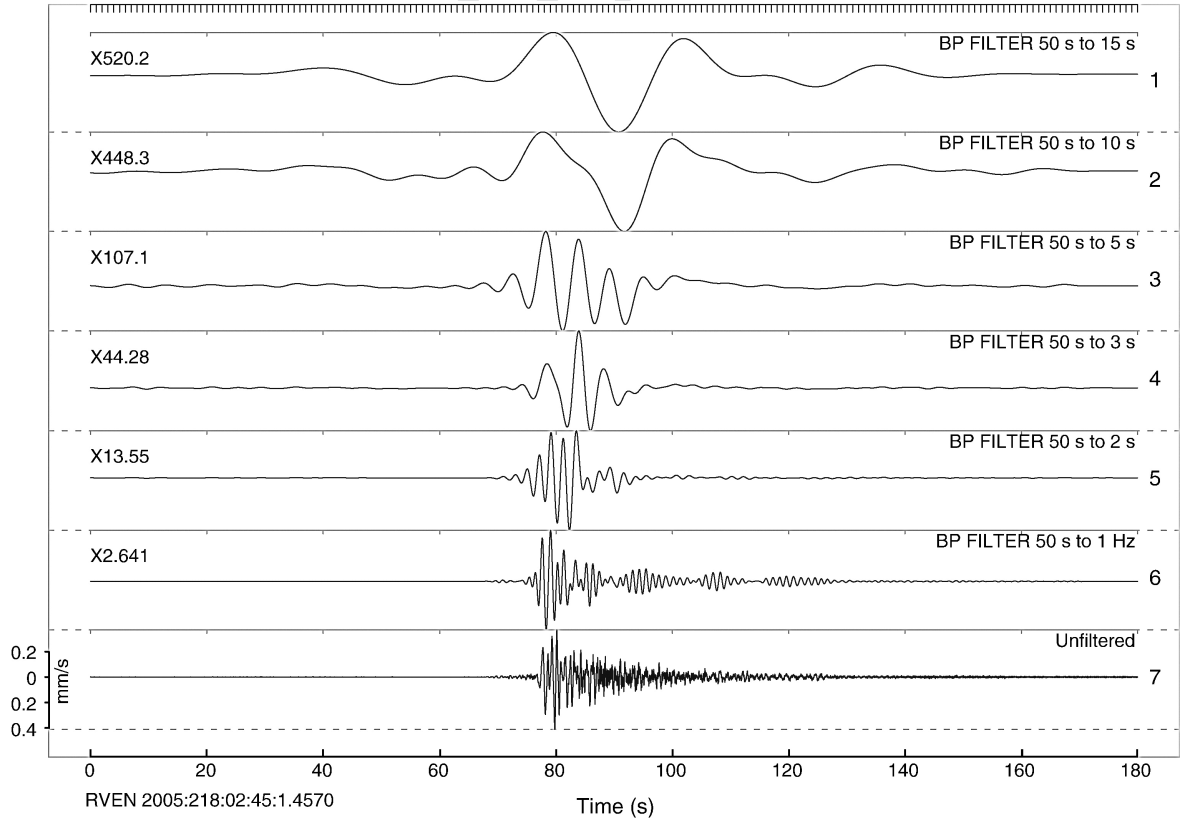

Fig. 6. Example of a VLP event. Vertical component of VLP event recorded at station RVEN is show with a spread of band-pass filters. High signal-noise ratio signals persist at very low frequency, (>15 s periods, top panel).

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Since LP arrivals at Reventador were invariably emergent it was difficult to characterize the signals and reduce the large data set to a manageable descriptive subset of parameters that may be compared spatially and temporally. Furthermore, we seek a quantitative method to compare these events to similar signals observed on volcanoes elsewhere. To this end, we propose to approximate rise and decay rates by modeling the squared amplitude signals with exponential functions. Squared vertical-component velocity amplitudes were smoothed and fit with two exponential functions of the form $y=Ae^{(Kt)}$. The first coefficient was calculated from the onset of the signal to the maximum smoothed square amplitude and the second from the maximum to the point where the signal reached 10% of the pre-event noise level. An example is presented in Fig. 5. Overall rise and decay rates (K) range from 0.6 to 1.07 s^{-1} and -0.24 to -0.17 s^{-1} respectively. The typical coda durations of Reventador LP events were 20–28 s. Rise rates were considerably higher than decay rates, on average, indicating a front loaded mechanism for LP events and suggesting that attenuation (both intrinsic and scattering) may play a role in the slower decay of these seismic signals. Because LP events were not accompanied by obvious acoustic signals they are assumed to occur away from the active surface vent, most likely deeper in the conduit or plumbing system of Reventador. Since these events are small they are not typically located by IG-EPN networks.

3.3. Very long period events

Very long period (VLP) events in August 2005 at Reventador were ubiquitous. Examining the data through a series of bandpass filters, shows that many signals had high signal to noise ratio at pass bands below 10 s (Fig. 6). Over 431 VLP events were extracted from the data set and 103 of these had elevated (>4) signal-noise ratio. The VLP events are similar to those observed at Stromboli (Chouet et al., 2001, 2003; McGreger and Lees, 2004) where signals in the 2–50 s pass band were analyzed for moment tensor inversion. With only three stations recording in the broadband range we cannot conduct an inversion for the source of these events. Based upon its largely open-vent geometry we speculate that it would plausible for Reventador to exhibit a physical mechanism similar to that of Stromboli, i.e. a slug or bubble rising through the conduit, deforming the cone, at very long wavelength. To determine the details of the conduit geometry at Reventador will require additional monitoring and considerable more broadband stations than the three we deployed.

3.4. Spasmodic/harmonic tremor

Over the course of the 40-day deployment several sequences of quasi-periodic tremor were recorded on seismic and acoustic

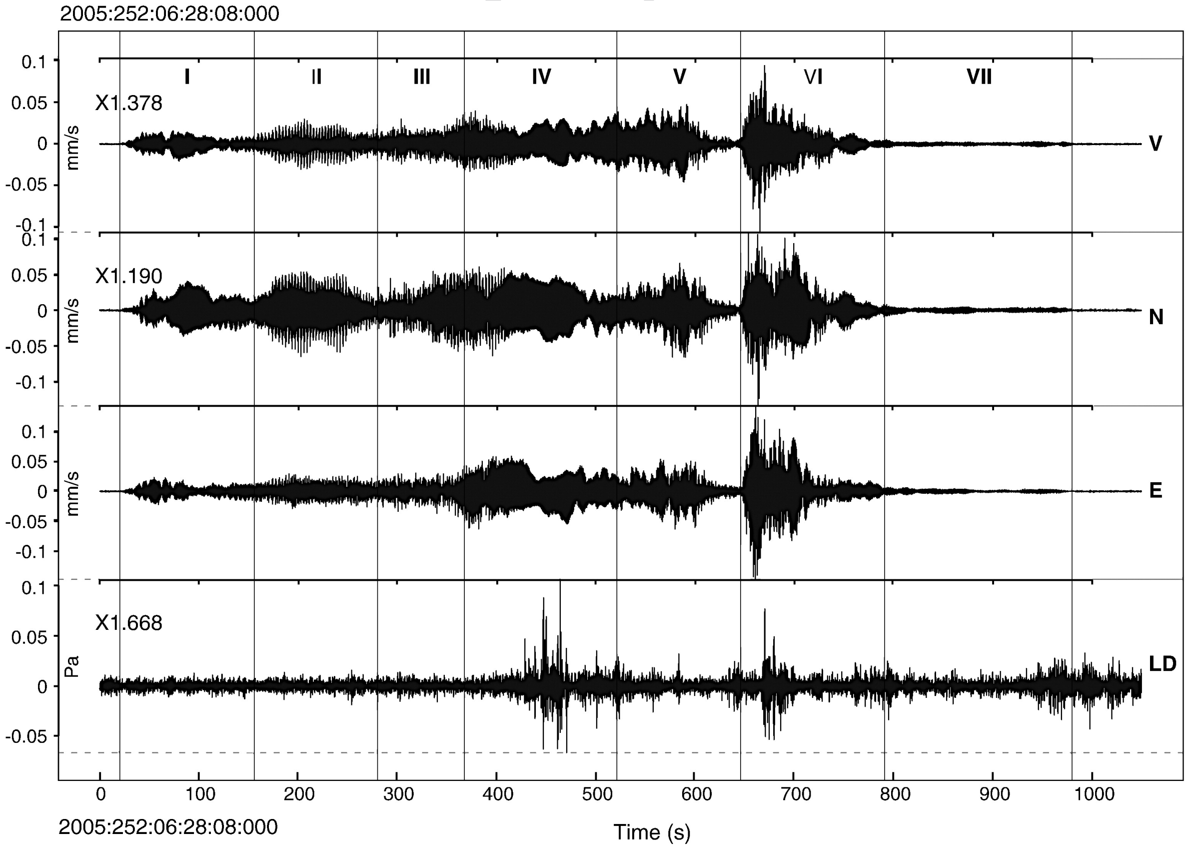

Fig. 7. Example of complex tremor. Infrasound (LD) and three components of seismic data are presented showing the rapidly changing nature of explosion tremor at station RVEN. The sequence is broken down into 7 stages, discussed in detail in the text. The infrasound (LD) is presented to show that there is not a strong correlation between acoustic and seismic signals during this sequence, in contrast to other sequences where strong correlations indicate vent activity (Fig. 10).

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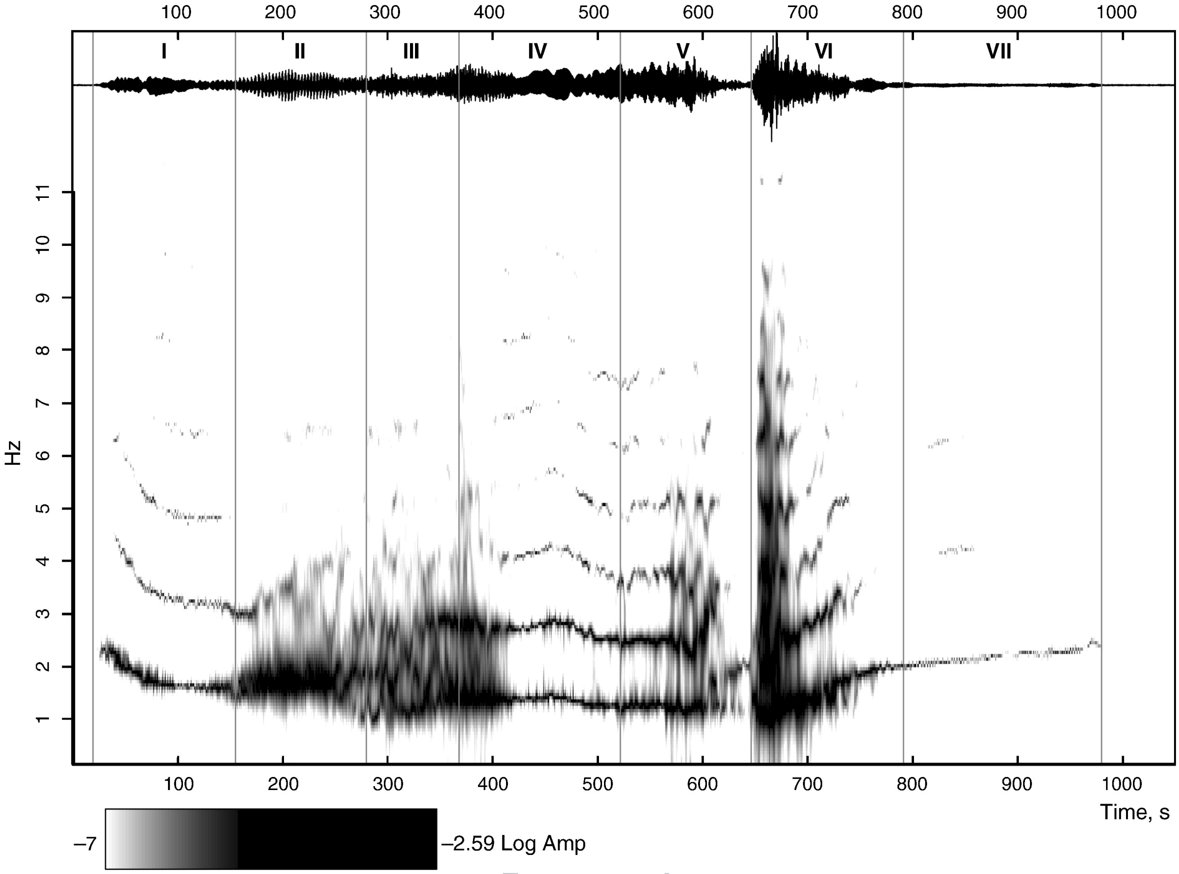

Fig. 8. Spectrogram of vertical component of signal presented in Fig. 7. Vertical axis is frequency and colors represent Fourier Transform amplitude levels for a moving 4-s sample window overlapping 3-s windows. Stages I–VII are shown and discussed in the text.

sensors. Quasi periodic signals are non-stationary waveforms that include several (<6), dominant, narrow band frequencies that may, gradually, vary over time (see Lees et al., 2004 for more examples; see Lees and Ruiz, 2007 — this issue). These recordings varied considerably, in pronounced contrast to periodic tremor seen at Karymsky or Sangay. Occasionally, tremor lasted only for the duration of a single, 30 s event. More commonly, however, extended quasi-harmonic tremor lasted tens of minutes to hours at a time. The dominant frequency was typically about 2 Hz and slight gliding was observed in some instances. We did not observe significant temporal variations in frequency content even when amplitudes fluctuated considerably. We did not experience any behavior similar to that recorded at Montserrat (Neuberg et al., 2000) or Miyakejima (Fujita et al., 2002) where discrete drumbeat-like events appear with heightened recurrence rates prior to larger explosions. Monochromatic harmonic tremor appeared intermittently with occasional abrupt starts and stops.

As an example, consider the 1000 s duration event illustrated in Fig. 7 (beginning on Julian day 252 at 6:28 GMT). This episode was well recorded at stations RVEN and LAV3, near the erupting cone. There were no apparent corresponding infrasonic signals accompanying this tremor, so we speculate that processes associated with these signals occurred well below the active vent. The wave train can be broken up into seven phases, illustrated in Fig. 7, labeled I–VII. A spectrogram of the vertical component (Fig. 8) shows that the frequency content and general character of the signals change rapidly and exhibit consistency over spans of 10’s to 100’s of seconds.

At the commencement of the tremor episode (Stage I) frequencies are relatively high (Fig. 8) and there is a 0.013 Hz/s glide trending towards a lower fundamental frequency at beginning of the trace sequence. The sequence then goes into a spasmodic mode with a dominant carrier frequency of around 1.6 Hz (Stage II). Arrivals of these dispersed wavelets are estimated using the Morlet wavelet transform to improve accuracy of timing estimates (Lees and Ruiz, 2007 — this issue) (Fig. 9). Bursts start with longer interval time and increase in frequency by about 0.018 pulses/s until they level out at ~3/s. This is opposite the trend observed at first when gliding was apparent. The isolated pulses begin with longer intervals and stabilize at a constant rate. The shortening of the pulse spacing along with the increase of amplitude may indicate a preparation stage, where an optimal resonance is attained, prior to a more stable oscillatory phase. This situation could arise if the aperture started to close down, raising the pitch of the oscillations until the chaotic elements are dominated by a more organized, polychromatic vibration. The gliding, on the other hand, starts out at higher frequency and stabilizes at the lower frequency. This suggests two opposing processes affecting the conduit. A process involving a decrease of frequency implies an opening up of constrictions as fluids pass through the conduit, as we see

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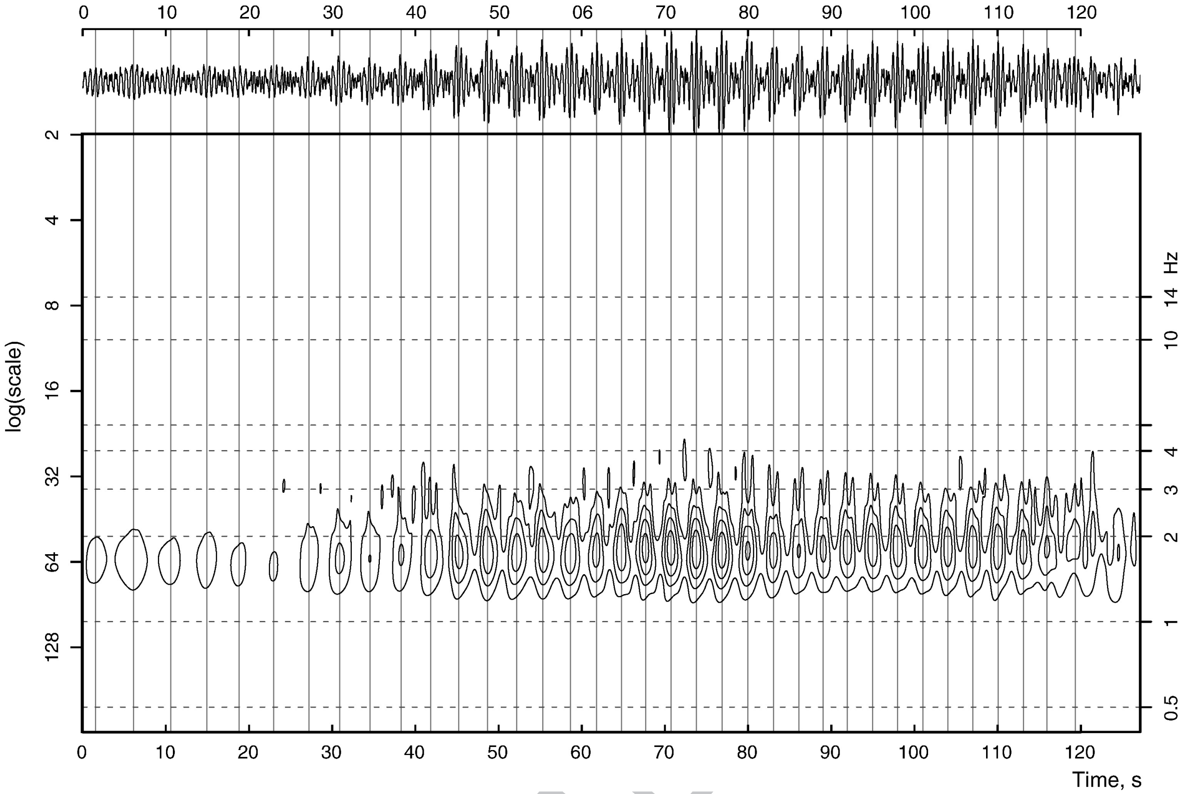

Fig. 9. Wavelet transform of stage II from signals vertical component signals shown in Figs. 7–8. Wavelet transform is used to find the maxima of pulses when signals are diffuse and emergent. The associated maxima are the local peaks shown as the centers of contours and marked by vertical grey lines.

at the very beginning of the sequence. Two minutes later when the spasmodic mode begins, choking is accelerated, indicated by the decrease in time interval between pulses. We have adopted here a model akin to Julian (2000), however, other models have been proposed to explain the variations of frequency gliding, including variations in gas content (Garces et al., 1998; Powell and Neuberg, 2003; Sturton and Neuberg, 2003).

After the period of regular pulsations we enter a chaotic mode (Stage III) where specific harmonic behavior is absent, although the dominant overall frequency remains at around 1.6 Hz. Near the end of chaotic Stage III the waves become strongly bi-chromatic in Stage IV: two frequencies dominate, at the center of Stage IV the frequencies peak at 1.38 and 2.82 Hz. Later they glide down to 1.21 and 2.46 Hz towards the end of Stage IV and they remain fairly constant through the next Stage V where at 600 s vibrations diminish to the noise level. At time 645 s a second earthquake is registered (Stage VI) with broad band frequency content. Following the initiation of this event the frequency becomes more banded and glides upward from 1.15 Hz to 2 Hz at ~0.01 Hz/s. At around 800 s (Stage VII), low amplitude, monochromatic shaking is seen with slight gliding to higher frequencies. This stage is the apparent cessation of activity until the next activity is observed 500 s after the end of Stage VII.

While not all sequences of tremor at Reventador follow the details shown in this progression many had characteristics that were generally similar. Numerous episodes included varying forms described in sequences I–VII though not in the same order and not necessarily at the same intensity. Activity at Reventador during the six weeks of deployment was distinguished by this very heterogeneity of behavior fluctuations. Extreme variations in explosion levels, abrupt initiation and termination of monochromatic tremor, alternating chaotic and band limited sequences, all suggest that the volcano was in a state of dynamic flux. We surmise that during this period magma was injected into the edifice and associated gas flux was intense and erratic.

3.5. Chugging sequence

Volcanoes that exhibit quasi periodic harmonic tremor that is associated with infrasonic or acoustic signals have been observed at Arenal, Costa Rica (Benoit and McNutt, 1997), Karymsky, Russia (Lees et al., 2004), Sangay (Lees and Johnson, 1999) and Tungurahua (Ruiz et al., 2005), Ecuador. The chugging is named for volcanic sounds observed that resemble a passing steam locomotive (Benoit and McNutt, 1997). Chugging has been modeled as periodic harmonic tremor from conduit standing waves (Benoit and McNutt, 1997; Garces et al., 1998) or proposed as quasi-periodic discrete pulses associated with choked flow near the vent (Johnson et al., 1998; Johnson and Lees, 2000; Lees et al., 2004). An example of a chugging sequence at Reventador is shown in Fig. 10 with one acoustic and three seismic channels presented. This example is similar to chugging observed at Karymsky and Sangay because

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the chugging sequence appears to start after a delay time (151 s) following an initial explosion. The expanded view shown in the inset of Fig. 10 illustrates that the chugging has nearly the same character as has been observed at the other two volcanoes: emergent rise, pulses separated by about 1 s, and asymmetric amplitudes. Sequences of chugging have been analyzed in detail at Karymsky and Sangay where they have been shown to exhibit non-linear behavior suggesting feedback mechanisms that govern pressure fluctuations in the near surface vent. In the example present (Fig. 10, inset) the first 56 beats show a curious trend: The first 6 beats exhibit a strong positive correlation (12 Pa/s) between time interval and acoustic amplitude. After the amplitude/time-lapse relation reaches a peak, it levels off briefly and then decays in a somewhat linear trend (−5.7 Pa/s). The negative slope (longer lapse time for smaller amplitudes) is opposite the general trend seen at Karymsky (Lees et al., 2004) and Sangay (Lees and Ruiz, 2007 — this issue). Furthermore, within the chugging sequence, the time intervals follow the trend of gliding described above: short time-lapse (high frequency) early in the sequence trending to longer time-lapse later when the amplitudes decrease. The linear relationship between amplitude and time-lapse is suggestive of the non-linear dynamics inherent in the system. At this point we do not have a clear understanding why trends at Reventador differ from those cited at other volcanoes we have studied.

3.6. Drumbeats, day 241

On at least 6 occasions Reventador entered vibrational modes of semi-periodic multiple small seismic events, referred to as ‘drumbeats’ (Moran et al., in press). On day 241 we observed several sequences of multiple pulses separated by, on average, 32±6 s intervals (Figs. 11 and 12). These series of events are similar to ‘drumbeat’ events recorded at Mount St. Helens (MSH) during the 2004–2005 eruption episodes (Iverson et al., 2006) although during the drumbeat episodes we do not observe corresponding acoustic signals (Matoza et al., in press). At Mt. St. Helens drumbeats were recorded for long periods with time intervals fluctuating between 30–300 s. These were associated with the dome building events where evidence of stick–slip behavior of the whale back showed signs of spasmodic growth (Ozerov et al., 2003; Iverson et al., 2006). The drumbeat sequences at Reventador are not as vigorous (amplitudes are smaller than at MSH and interval times are consistently around 32 s) as those seen at Mt. St. Helens and they last only for a short period on days 241–242. Furthermore, due to the recessed nature of the vent at Reventador, we have no direct observations of vent extrusions. It would be premature to suggest that these events signal the onset of an intrusion and growth of a plug near the vent of Reventador, although it is noteworthy that these drumbeat episodes occur during a period

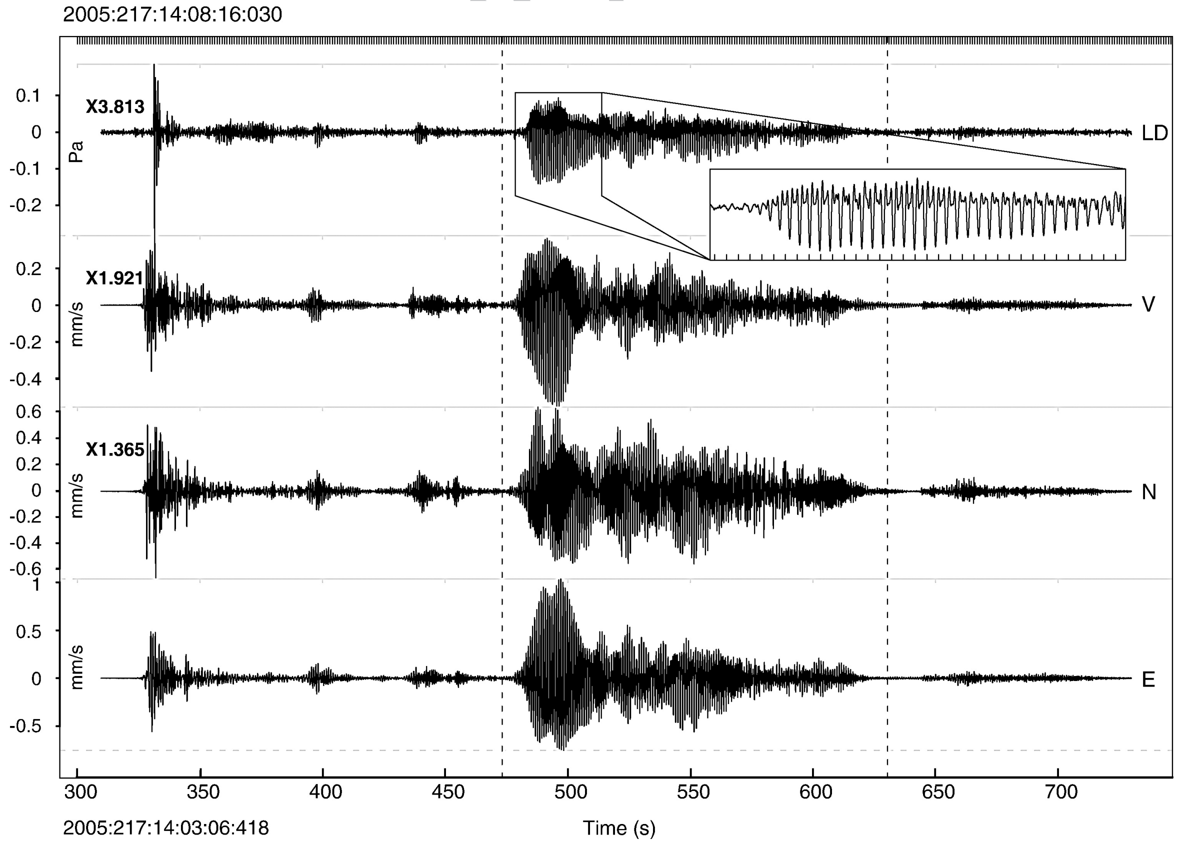

Fig. 10. Example of a chugging sequence on day 217. An initial explosion is followed by an extended series of pulsations called chugging and seen at Karymsky, Sangay and Arenal Volcanoes. These are observed on acoustic as well as seismic records. Inset shows a detail of the acoustic record.

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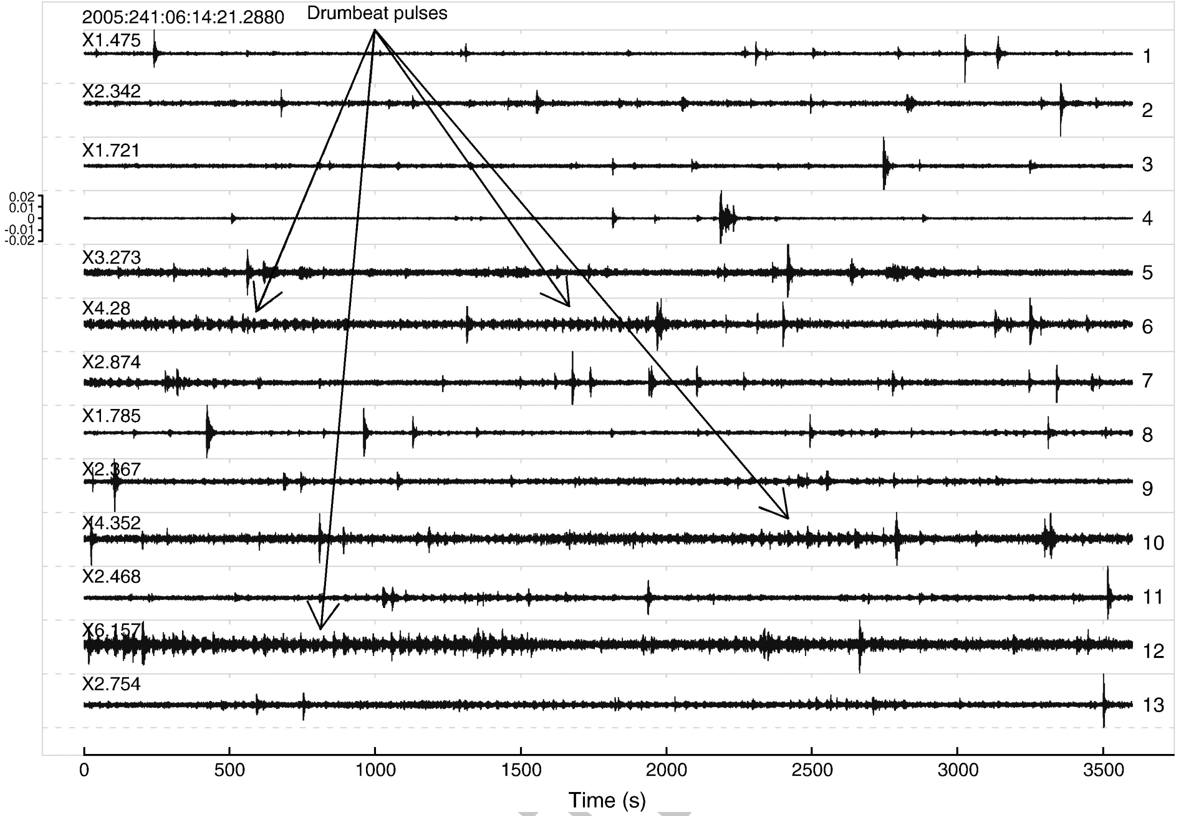

Fig. 11. Drumbeat example on days 241–242. In the middle of the quiet period extending from day 238 to 248 Reventador showed several periods of pulsating "drumbeats" with interval times of ~32 s. These are similar to drumbeats recorded during the dome building stages of the 2004–2005 eruption of Mt. St. Helens. Drumbeat sequence in hour 22 (lowest arrow in plot) is shown in detail on Fig. 11.

when the overall seismic energy is at an apparent low (Fig. 4). Explosion activity, LP, VLP, and quasi-periodic tremor are all diminished during the drumbeat periods. It is possible that the growth of a dome intrusion at the near surface vent is suppressing degassing by plugging the openings and thus diminishing seismo-acoustic release. Once the potential dome building events have ceased the volcano returns to a high level energy release (i.e., on Julian day 248). The source of Reventador drumbeats, however, is not yet known and may just as well result from sequences of LP events associated with deeper fluid processes. This interesting feature of the seismic record thus remains a matter of continuing speculation.

4. Discussion and conclusion

Seismo-acoustic recordings of Reventador Volcano in 2005 provide an effective means of remotely monitoring fluctuations in the state of the volcano during a stage of heightened explosive activity. One of the most striking features of this period is the extreme variability and character of explosion activity. It is clear from seismic records that the modulating energy release at the vent provides a means to describe the physical state of the vent and the nature of magma flux in the conduit over temporal spans of seconds to days. At least two periods (day 220 and 238–241) of reduced seismic energy release indicate a change in the volcano state, potentially preparatory periods when pressures build up prior to energetic explosion phases that follow. The repose episode on days 241–242 includes drumbeat sessions, which may indicate emplacement of a viscous plug.

The variety of quasi-periodic oscillatory behavior dispersed throughout the recording period is an indicator of the physical state of the conduit and vent. Because of the wide variability of the observed signals it is apparent that the vent and conduit are not static. Rather, they are constantly changing and adjusting to the apparent influx of new material and degassing associated with this flow. These dynamic processes are somewhat substantiated by the characteristic activity at Reventador between 2002 and 2005, in which intermittent lava flows were periodically extruded and explosive activity waxed and waned. It is useful to compare this behavior to similar observations at other volcanoes, which exhibit somewhat more steady-state behavior. For example, volcanoes that exhibit stable Strombolian style activity, e.g. Stromboli (Ripepe et al., 1996; Ripepe and Gordeev, 1999), Karymsky (Johnson et al., 1998; Ozerov et al., 2003; Lees et al., 2004), Sangay (Johnson and Lees, 2000; Lees and Ruiz, 2007 — this issue), Tungurahua (Johnson et al., 2005; Ruiz et al., 2005) and Arenal (Benoit and McNutt, 1997; Hagerty et al., 2000), also include low level explosions and other quasi-periodic signals like chugging and longer spanning harmonic oscillations. At Reventador, at least during the brief period described here, we see a much broader range of seismo-acoustic activity. Reventador in August–September 2005 was not in a steady state: rapid fluctuations,

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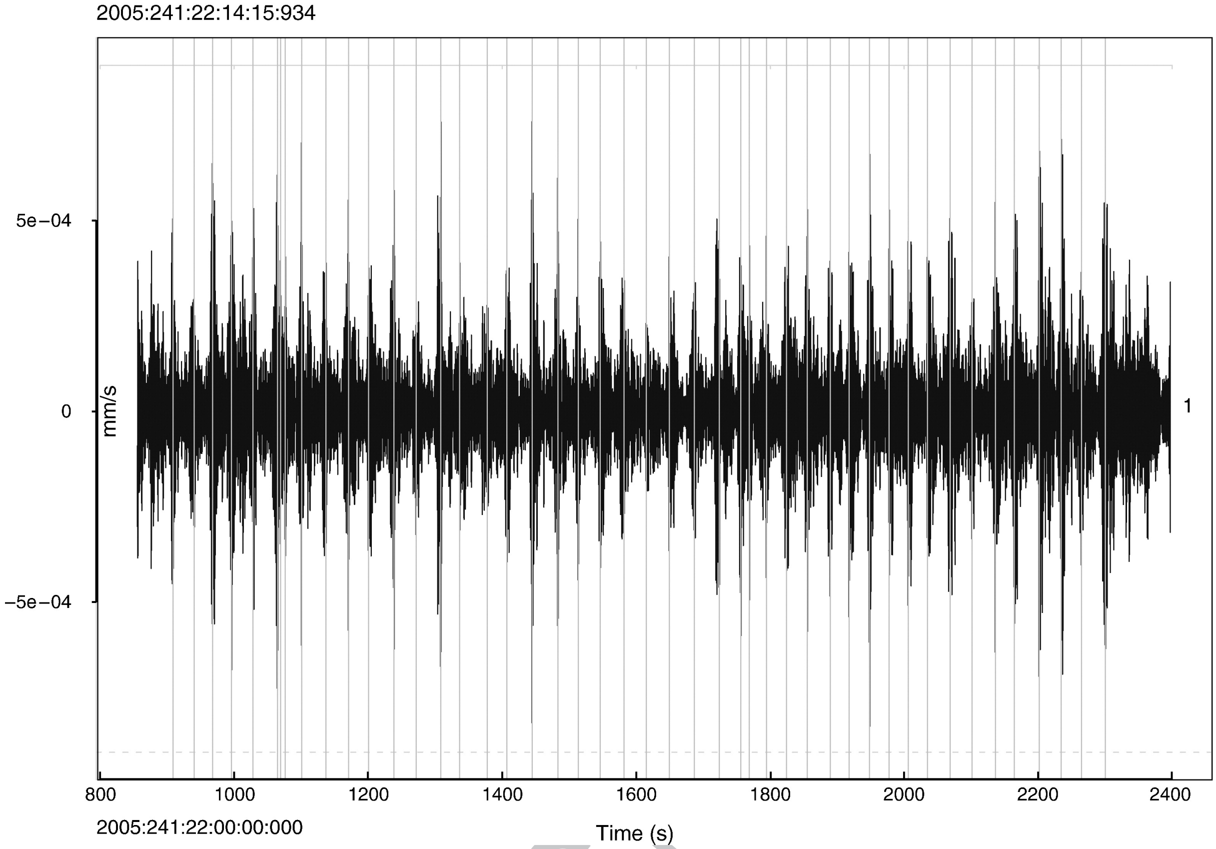

Fig. 12. Detail of the Drumbeats. Record was band-pass filtered between 1–2 Hz and wavelet transformed to determine peaks of arrivals as described in Fig. 9. Vertical lines show the arrivals of drum pulses, approximately 32 s in interval spacing.

large explosions and periods of quiescence followed by vigorous activity all point to dynamic intrusion and episodic magma flux.

Volcanic activity at Reventador Volcano in 2005 included a full range of eruption styles accompanied by a wide range of seismicity, ranging from low level tremor to large discrete events. The temporary deployment of broad band seismo-acoustic stations recorded nearly 6 weeks of fluctuating behavior. During this period numerous LP, VLP, chugging, harmonic tremor, drumbeats, regional and teleseismic signals were recorded and identified. Variations in the total seismic energy correspond to temporal variations in the density of explosions, the level of quasi-periodic tremor and long period earthquakes originating deep in the conduit. This suggests a relatively rapid influx of magma which gave rise to intensified degassing and higher levels of explosive activity. Periods of seismo-acoustic activity tremor are temporally modulated over spans of minutes, hours or days, indicating vent/conduit geometry variations, introduction of new material and modification of obstructions at the vent opening.

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