Explosions and periodic tremor at Karymsky volcano, Kamchatka, Russia

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SUMMARY

The explosions of Karymsky volcano often produce signals containing a sequence of repeating pulses recorded on acoustic and seismic sensors, known as chugging. The amplitudes of these pulses correlate with the time interval between pulses. For a given measured acoustic pressure, seismic amplitudes take on arbitrary values up to a specific, empirically determined threshold. Conversely, events with a small seismic amplitude yielded acoustic waves with large variations and large-amplitude seismic events corresponded to large acoustic waves. These observations are not consistent with a source modelled by a resonating conduit. Rather, a model consisting of a sequence of discrete pulses explains the data and provides a framework for understanding the dynamics of degassing at the vent. The physical model for chugging involves a time-varying narrowing vent where gasses are released in a series of oscillations which appear to be harmonic but instead are modelled as short-term transients, or discrete pulses, suggestive of choked flow.

Key words: eruption dynamics, harmonic tremor, Kamchatka, volcanic explosion.

1 INTRODUCTION

Harmonic tremor, recorded at many active volcanoes around the world, has been described using several different models (see McNutt 1989, 1992, for reviews). In general, nearly all proposed models explain harmonic spectral characteristics of tremor in terms of fluid flow in magma conduits. For example, Chouet (1985) proposed a model where ground displacement of harmonic tremor reflects organ-pipe modes of a conduit excited by fluid flow as a response to short-term pressure perturbations and where the pressure perturbation is triggered by a sudden expansion of a hemispherical gas cavity. Alternatively, Julian (1994) suggested that flow of an incompressible viscous fluid through irregularly shaped magma conduits could induce non-linear instabilities. As a result of the decrease in flow pressure due to the Bernoulli effect, the channel walls move toward each other and constrict the flow, causing an increase in fluid pressure forcing the channel to open again. In Julian's model, tremor is an oscillatory response to a pressure input due to fluid flow, although the parameters chosen in his simulations may not be applicable to the conduit dynamics presented here. Laboratory experiments designed to simulate conditions in volcano conduits (Jaupart & Vergniolle 1988; Tait *et al* . 1989; Lane *et al.* 2001) reveal the rich and complex nature of acoustic and seismic responses in magma-filled conduits where two- and three-phase flows fluctuate over a multitude of possible fluid dynamic regimes. Other models, however, suggest that site or path effects may be also responsible, in some cases, for the apparent harmonic nature of volcano tremor (Gordeev 1993; Kedar *et al.* 1996). Since harmonic tremor is one of the few observable manifestations of fluid flow in magma systems, its investigation provides one of the central means for understanding the dynamics of volcanic explosions and degassing.

In recent years, infrasonic records at some volcanoes have shown that during episodes of volcanic tremor the magma system undergoes degassing, exhibiting small (<1 Pa) infrasonic transients that propagate in the atmosphere at a rate of 1–0.5 s^{-1} (Ripepe *et al.* 1996; Ripepe & Gordeev 1999). A comprehensive physical model for this type of harmonic tremor should account for the observed infrasonic wavefield in addition to elastic wavefield descriptions provided by seismic records. Infrasonic waves may be produced at the surface of the magma when gas overpressure breaks a thin ($\approx$0.1 m) bubble film (Vergniolle & Brandeis 1994, 1996); alternatively energy transfer at the magma–air interface can generate shock waves by inducing sudden pressure drops in the magma column (Buckingham & Garces 1996; Garces 1997; Morrissey & Chouet 1997; Garces & Hansen 1998).

From 1996 January 1 to 1999 November Karymsky volcano was active in a quasi-periodic eruptive mode (Gordeev *et al.* 1998), exploding, typically, every 5–15 min. This Strombolian activity is not atypical for Karymsky volcano; numerous episodes of quasi-periodic explosions have been observed in previous eruptive phases (Zobin & Levina 1998). In 1997 August–September a curious phenomenon was observed near the exploding vent and subsequently recorded at broad-band seismic stations (Johnson *et al.* 1998). During this period, once per hour, on average, initial explosions were followed by a series of impulsive signals recorded on seismic and infrasonic sensors located 1.6 km from the active vent. These impulsive signals, their line spectra and apparently harmonic nature, and their source characteristics have become the subject of some controversy among volcanic seismologists (Hagerty *et al.* 2000). Similar signals at Arenal, Costa Rica, (Benoit & McNutt 1997; Garces *et al.* 1998; Hagerty *et al.* 2000) have been interpreted as emanating from the resonance of a conduit containing a mixed two-phase fluid body in the upper hundreds of metres in the volcano edifice. Since other volcanoes around the world exhibit similar behaviour (Mori *et al.* 1989; Schlindwein *et al.* 1995; Hellweg 2000; Johnson & Lees 2000; Neuberg *et al.* 2000; Rowe *et al.* 2000), it is important to develop a general understanding of these volcanic signals in terms of the complete seismo-acoustic wavefield (Garces & McNutt 1997). In this paper we illustrate the highly transient nature of the tremor following explosions at Karymsky which suggests that these explosions are quasi-periodic, discrete events, exhibiting non-linear behaviour produced by fluid flow through narrow conduits located near the vent opening.

2 DATA ACQUISITION AND ACTIVITY AT KARYMSKY

In 1997 September American and Russian seismologists installed a small network of seismic stations around Karymsky s(Fig. 1), including one station with an infrasonic sensor (Johnson *et al.* 1998, 2003). Only three sets of seismic instrumentation were available at the time so stations were leapfrogged around Karymsky's cone to achieve azimuthal coverage. Seismic stations were equipped with three-component broadband (PASSCAL) sensors (natural period of 30 s) with sensitivity of 800 V m^{-1} s^{-1}. The infrasonic sensor included a Monacor MC2005 condenser microphone with sensitivity 0.46 V Pa^{-1} in the range 2 to 20 Hz (Poggi & Ripepe 2002). Signals were sampled on an IRIS/PASSCAL data acquisition system at a rate of 125 samples/s. Explosions were observed approximately every 12–15 min, and extended tremor occurred once per hour, on average (Fig. 2). The tremor, recorded on seismograms and one infrasonic microphone (for example, Fig. 3), ranged from 10 to 70 s with a median value of 30 s, and consisted of chugging (Benoit & McNutt 1997) sequences of apparently impulsive explosions at intervals of 0.7–1.5 s. Sounds from the pulsations were clearly audible, although signals in this frequency band were not recorded. High-frequency whistling and puffing was also audible on occasion, although these signals were also beyond the bandwidth of the infrasonic microphone. The initial arrivals of seismic signals from chugging events are typically emergent, while the associated acoustic signals are distinctly impulsive (Fig. 3). Chugging signals following the initial blasts have several common characteristics:

(1) Chugging events were always preceded by an initial explosion, although not all explosions were followed by chugging. The

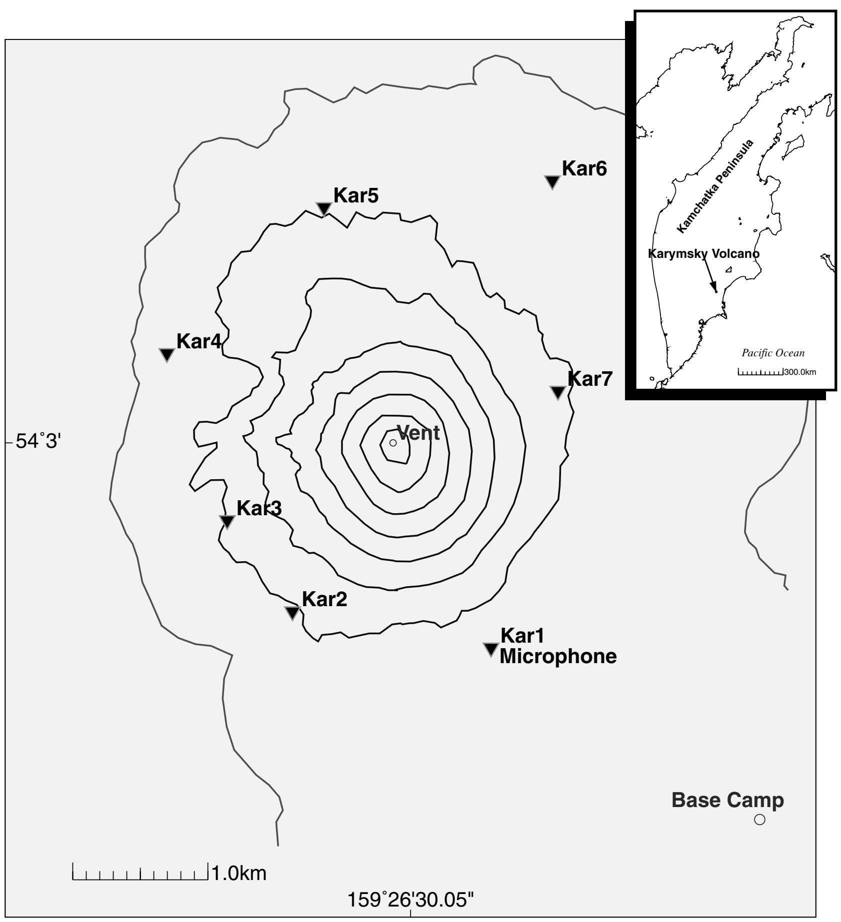

Figure 1. Map of Karymsky volcano with the station configuration in 1997. The data presented in this paper are from the station Kar1 where acoustic and seismic sensors were collocated. Three stations were active simultaneously in 1997, and two of these were leapfrogged around the cone for spatial coverage. Station Kar1 remained stationary throughout the deployment.

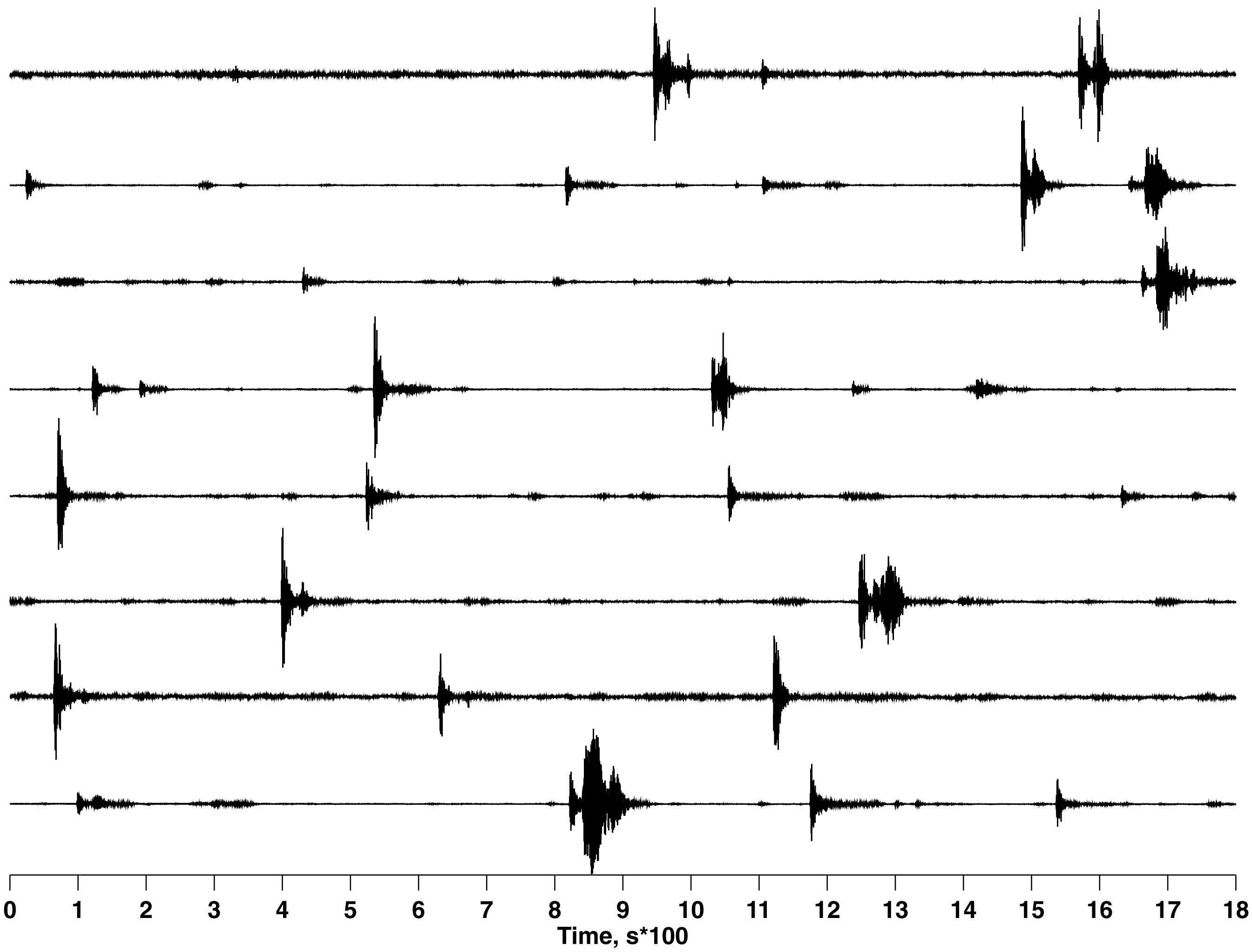

Figure 2. Three hours of continuous recording on the vertical component seismogram located 1.6 km from the vent. Events occur, on average, five to six times per hour. Once per hour, on average, chugging was observed. During the period of deployment no tectonic events were observed below Karymsky.

strong correlation of chugging with explosions suggests that the chugging occurred as a post-explosion response to overpressure in the conduit. Since explosions were observed every 5–15 min but chugging occurred much less frequently, we surmise that special conditions are required to achieve a state of chugging.

(2) There was almost always a lag time (10–20 s) between the initial explosion and the commencement of intense chugging (Fig. 3). The lag times varied considerably, and there were often several chugging episodes following an explosion before the system returned to a quiet background state. We assume that periods of low-amplitude signals after the initial explosions prior to the onset of chugging were preparation intervals where the conduit system was storing gases and pressures were rising.

(3) Chugging was fairly regular, with a dominant fundamental period that fluctuated, from series to series, between 0.7 and 1.5 s.

(4) Individual acoustic pulses during chugging had a transient, impulsive appearance, were very uniform and were sometimes near duplicates of the initial explosive pulses.

(5) A typical sequence of events had an envelope that grew rapidly in amplitude (5–15 s) and later diminished gradually (20–50 s).

Lava flows at Karymsky varied over the 1996–1999 eruptive cycle. In 1996, following the initial blast events at Karymsky and Karymsky Lake that triggered the Strombolian activity (Gordeev *et al.* 1998), lava flows were extensive and chugging was not observed. In 1997 September, when the lava flows subsided, chugging increased significantly. The following year, in 1998 September, lava flows were pronounced and chugging decreased. Finally, in 1999 September, near the cessation of the Strombolian activity and lava flows, chugging was again observed although not nearly at the same rate as in 1997. There thus appeared to be a correlation of chugging activity and lava production where periods of decreased flow produced the most intense chugging.

3 PROPERTIES OF VOLCANIC CHUGGING SPECTRA

Chugging events can be separated into two different classes at Karymsky volcano. We designate as 'continuous chugging' those events that include one prolonged sequence of pulses, and as 'intermittent chugging' those that have several modulated envelopes of chugging (Fig. 4). Spectra of both types ofchugging show that

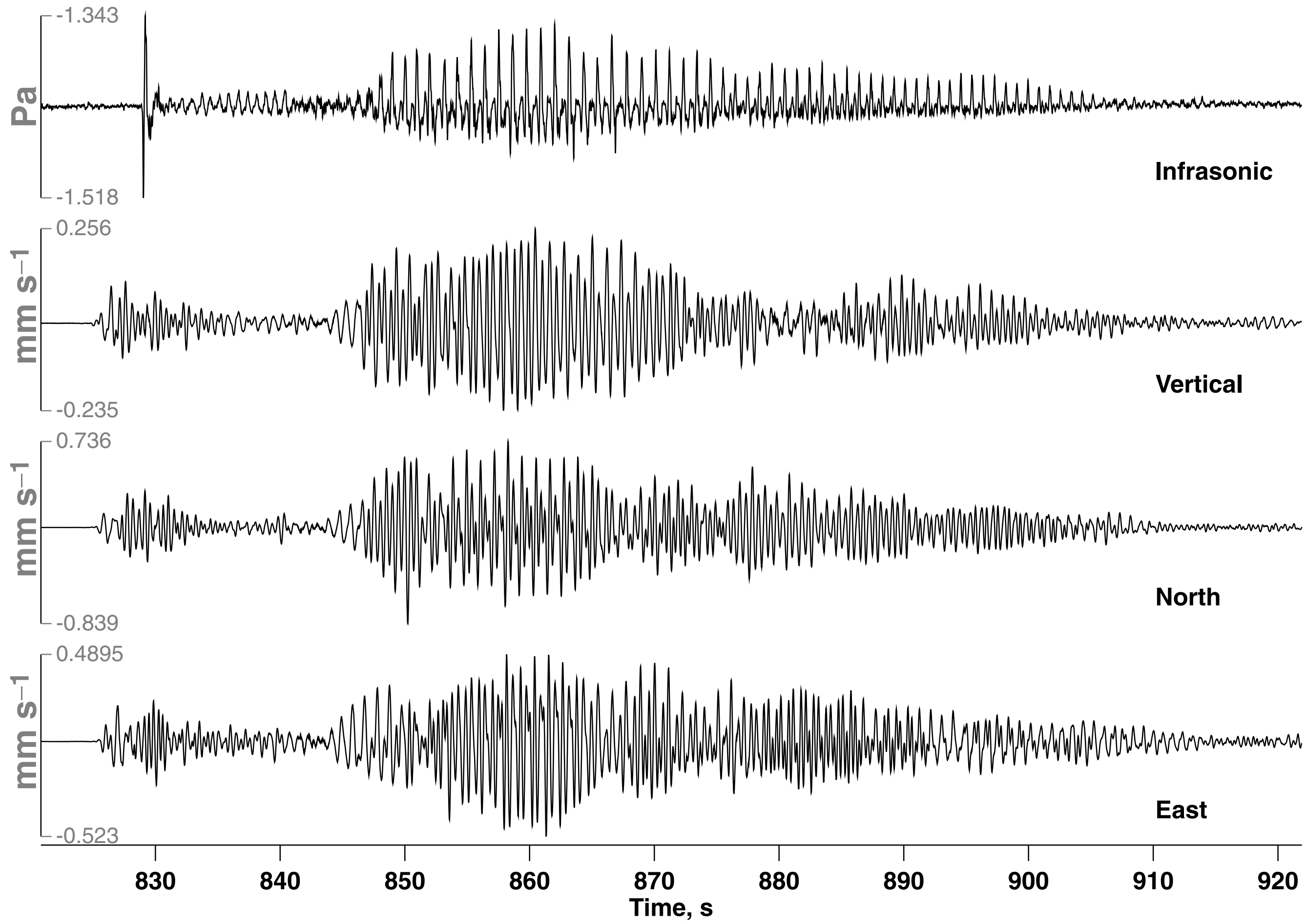

Figure 3. Example of an explosion followed by a sequence of continuous chugging. The top trace is the microphone sensor and the lower three are vertical, north and east seismograms respectively. All acoustic records in this paper represent compression as down. The seismic arrivals begin about 4.1 s before the acoustic wave arrives. Chugging appears as a series of discrete pulses on the acoustic record. The seismic signals are complicated by wave path effects that conceal the impulsive nature of the chugging. This event is present on the bottom row of Fig. 2 between 800 and 1000 s.

they contain a fundamental frequency and several integer harmonic peaks. Within a single series, the fundamental frequency can fluctuate moderately (0.01 to 0.25 Hz s^{-1}), giving rise to the phenomenon called 'gliding' (Fig. 5). On first analysis it might seem logical to assume that these signals originate from a linear resonating body producing tremor with harmonic peaks. In this approach the volcano conduit is represented as a stack of multiphase fluids with varying physical properties that sustain standing waves producing harmonic tremor. Extensive analysis of this physical model has successfully reproduced spectra similar to those of observed signals and has been used to analyse tremor at Arenal volcano (Hagerty *et al.* 2000). At Karymsky, cursory inspection of chugging tremor sequences appears to Reveal a fundamental frequency with nearly evenly spaced harmonic overtones, although the overtones typically change over short time intervals (minutes to hours). On closer inspection, however, we show below that it is very unlikely that the spacing between pulses at Karymsky form a true harmonic series. The conduit resonance model, used to explain tremor at Arenal, requires that the geometry of the conduit or the physical properties of the conduit materials change over the characteristic gliding timescales (seconds) of the harmonic tremor. Possible physical variations include the effects of gas exolution associated with violent shaking of the fluid–gas mixture, changing the depths of the upper and lower boundaries of the conduit, introduction of new material during explosions and changes of impedance contrast associated with degassing at the roof and floor of the conduit column. In this paper, however, we present evidence suggesting that a linearly resonating conduit is inappropriate for explaining the intermittent series of pulsations for the Karymsky chugging tremor.

The presence of peaks in a seismo-acoustic spectrum indicates a large power contribution at narrow frequency bands. If spectral peaks are separated by regular evenly spaced intervals, it may be reasonable to assume that the source of the spectral structure can be attributed to stimulation of a fundamental mode and associated longitudinal harmonics, activated by linear resonance in the medium. Longitudinal harmonics, however, are not the only way to get a Fourier spectrum showing evenly spaced peaks. In the case of Karymsky tremor, an alternative mathematical explanation for the series of pulses is a sequence of isolated, regularly spaced source impulses, each convolved with some impulse response, perhaps that of the main explosion (Johnson *et al.* 1998, Fig. 6). As stated earlier, in all cases of chugging observed at Karymsky, the pulsating sequence is preceded by an initial explosion. If we formulate a time-series of impulses and convolve this series with the wavelet of the initial explosion a simulation of the observed waveform is reproduced. Since the Fourier transform of a series of spikes is also a

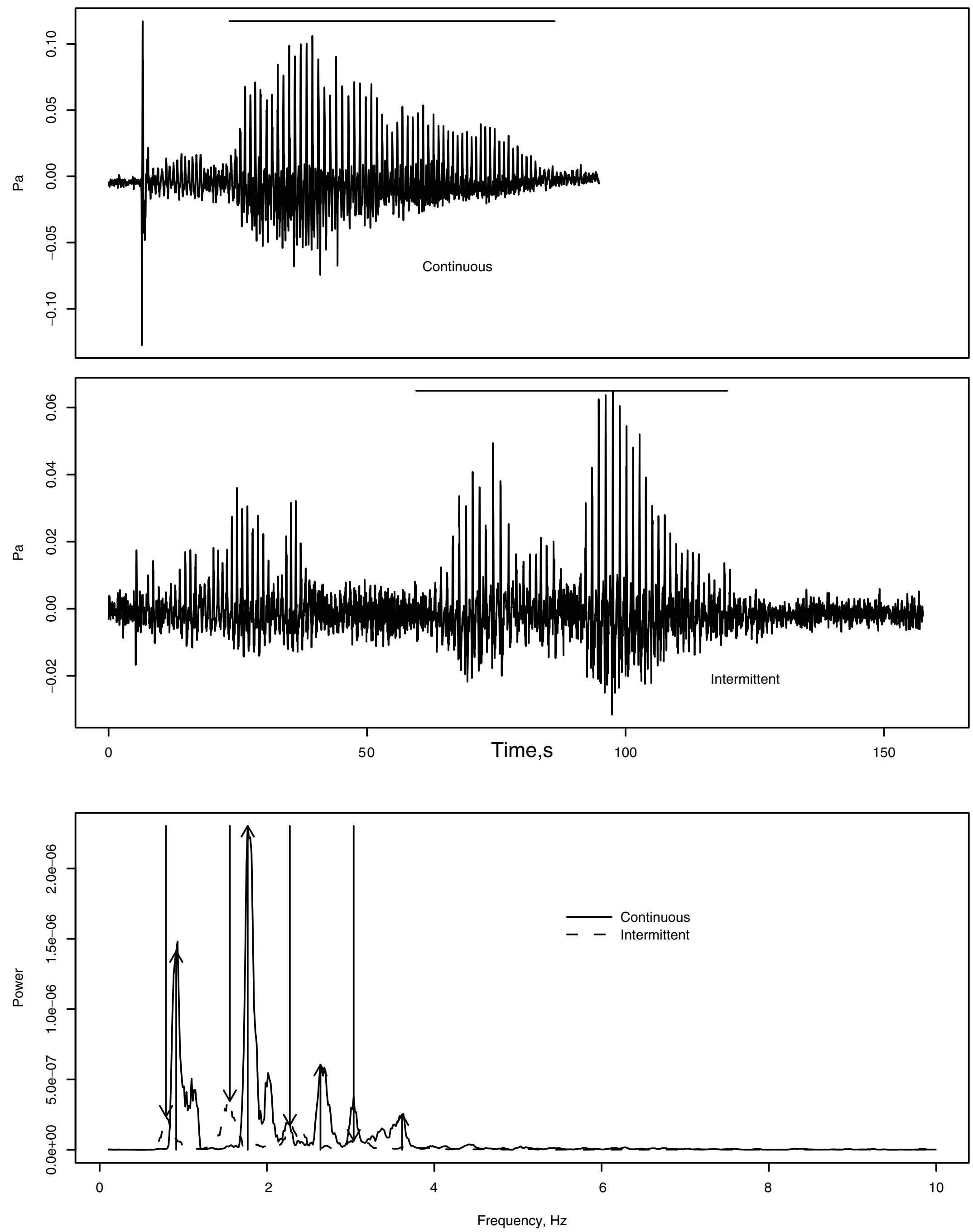

Figure 4. Acoustic examples of continuous and intermittent chugging at Karymsky volcano. Top and middle: time-series representation of chugging sequences. The horizontal line above each chugging event represents the time window used for spectrum analysis. Bottom: spectra of the corresponding signals, where the dashed line is the intermittent signal and the solid line is the continuous chugging. Arrows in the spectra point to peaks and harmonics at 0.916, 1.770, 2.640 and 3.620 Hz for continuous and 0.793, 1.560, 2.270 and 3.040 Hz for intermittent chugging respectively. Harmonics are nearly integer multiples of the fundamental modes, although fundamental modes differ for the two different sequences.

series of spikes, the spectrum of this mathematical model matches the observed fundamental harmonics described earlier.

Modelling of spectral peaks as discrete events has been previously proposed to explain volcanic tremor at Stromboli volcano, Italy. At Stromboli, however, infrasonic pulses (<1 Pa) repeat irregularly (every 1–2 s), and are inferred to be produced by the bursting of small gas bubbles rising quasi-periodically through the magma column (Ripepe *et al.* 1996). Spectral characteristics of the tremor have been modelled as a sequence of single sources with a random distribution of amplitudes and phases, whereas the random distribution of pulses represented instabilities in the bubbly flow (Ripepe & Gordeev 1999). According to this model, seismic tremor and infrasound are related to two different mechanisms of the same degassing process. Seismic tremor originates as a result of decompression induced in the magma-gas liquid by the coalescence of gas bubbles, while infrasonic peaks are produced by gas escaping at the free

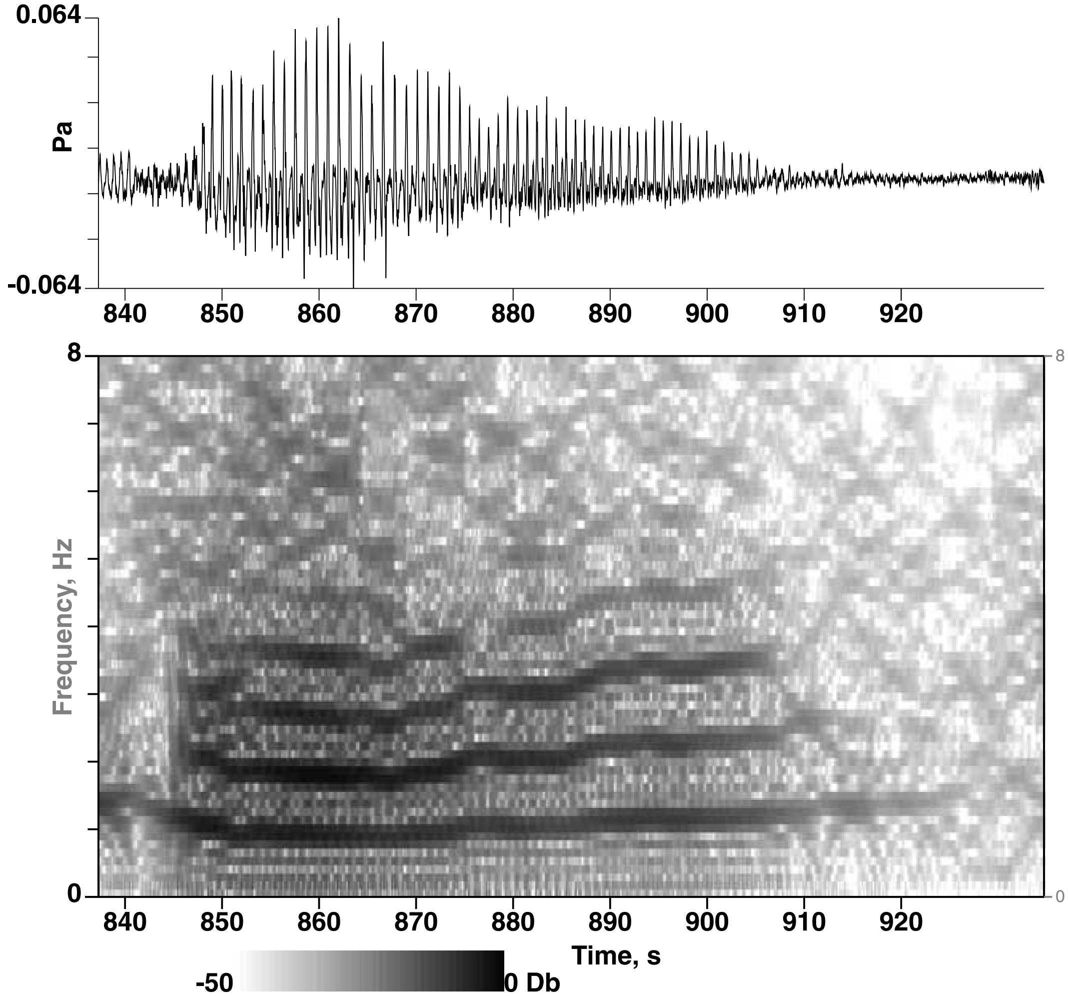

Figure 5. Spectrogram of a sequence of chugging observed on the (a) microphone sensor and (b) the vertical component seismogram. The plots show the time-series window that is analysed. The lower plots show frequency spectra plotted as a function of time along the time-series. Spectra were calculated using windows of 5 s duration with a 2 s skip interval. Bands between 0 and 4 Hz represent peaks in the frequency spectra corresponding to spikes in the time-series. The changing frequency content with time is called 'gliding' and represents variations of the physical parameters of the conduit or vent. Note the overall frequency content is lowest when the amplitudes of the pulses are largest.

surface of the magma. Harmonic tremor would thus be generated by a stationary regime in the degassing process.

4 ASYMMETRY OF ACOUSTIC WAVES

At Karymsky individual acoustic pulses in the wave train following the initial explosion (chugging) are usually asymmetric about the zero-amplitude point (Fig. 3; by convention, compression is represented as down and rarefaction as up on the figures). While initial explosions are not perfectly symmetric, they do not have a pronounced asymmetry, in marked contrast to individual chugging pulses. Chugging asymmetry may result, in part, from the convolution of an impulse response function whose temporal extent is longer than the distance between pulses so that constructive interference in the pulse train produces an asymmetric amplitude series. Asymmetric acoustic signals at volcanic vents have been observed before at Stromboli (Vergniolle & Brandeis 1996), and were modelled in terms of acceleration and contraction of a gas volume prior to explosion. Photographic and video observations of explosions at Karymsky, however, suggest that simple bubble explosions do not explain the nature of eruptions modelled here. Rather, it has always appeared that the vent at Karymsky is closed, i.e. it is covered with debris and ash. The initial explosions often include two distinct simultaneous plumes: one light coloured, probably consisting primarily of steam; the other dark and dominated by ash and volcanic debris.

Signals produced by non-linear excitations of tremor in a constricted fluid channel (for a detailed discussion see Julian 1994, 2000) also bear a striking resemblance to the asymmetric acoustic waveform recorded at Karymsky. Julian's non-linear resonant process creates 'period doubling', eventually leading to chaotic behaviour. The non-linear effect of the fluid flow excitation in the conduit should also produce a corresponding asymmetric seismic tremor (Julian 1994). We note, however, that the seismic records do not show the same asymmetric chugging as observed on the acoustic signals (Figs 6a and b). While we do not have a detailed explanation for the difference between the seismic and acoustic signal symmetries; it is probably due to a different coupling efficiency for seismic versus acoustic wave propagation in the atmosphere for these very shallow sources.

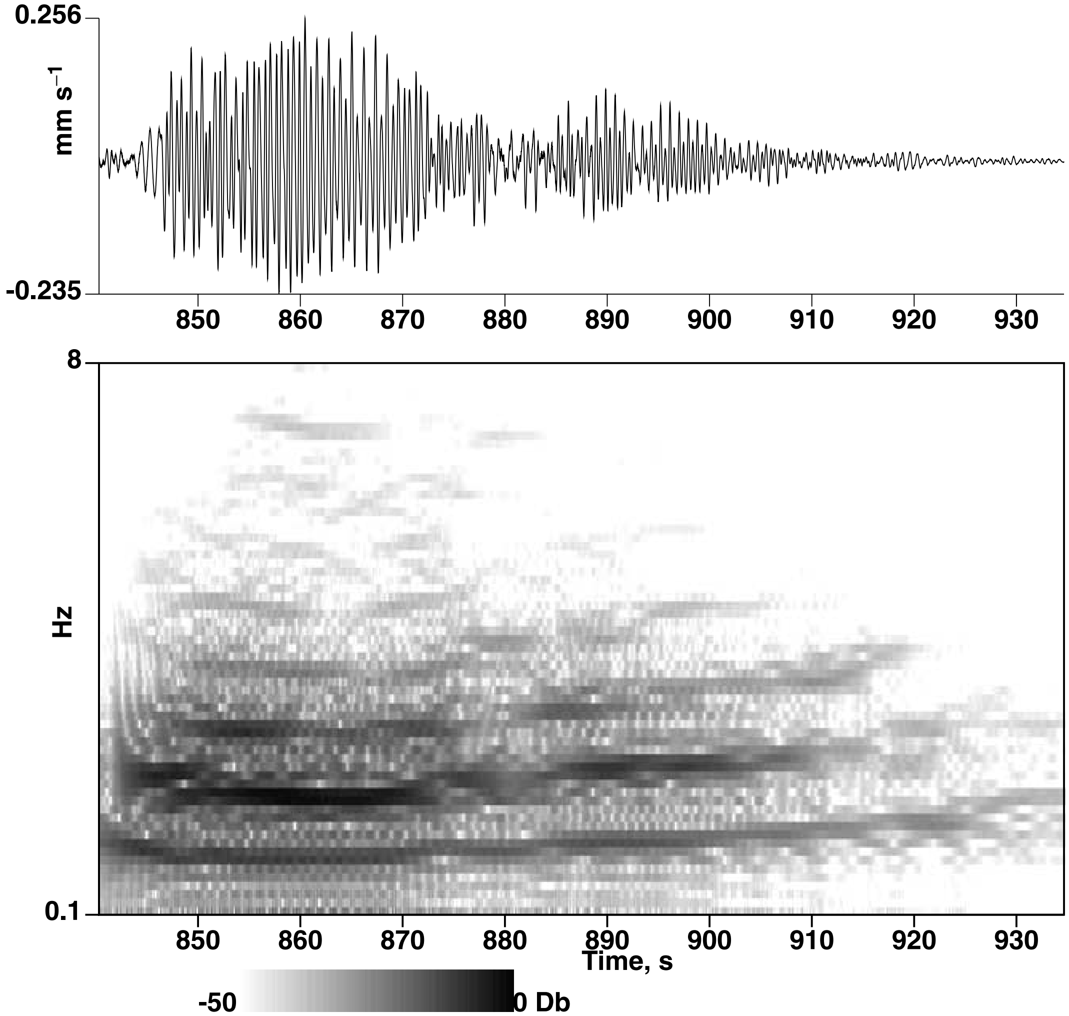

Figure 5. (*Continue*)

Chugging appears to have a strong rarefaction signal and a weaker pressure pulse. As rarefactions, the sequence of asymmetric pulses represent an inward force (away from the acoustic sensor) larger than the corresponding pressurizing force of gases being expelled into the atmosphere. This implies suction at the vent, or at least a rapid readjustment of a viscous plug in response to a succession of impulsive gas expulsions. These considerations reinforce our conjecture that the dynamics of the tremor are controlled by the sources within the topmost tens of metres of the conduit.

5 POLARIZATION ANALYSIS

Polarization analysis can help distinguish between arrivals of body waves versus surface waves. To accomplish this signals are first filtered between 0.7 and 2.1 Hz, according to the maximum amplitude of their respective spectra. A sliding 2 s window, shifted by 0.1 s along the three-component time-series, is used to calculate eigenvalues and eigenvectors for the set of points represented by the seismic particle motion. Strong linearity in the orientation of the eigenvectors is reached at two different azimuths: (i) directly towards the crater (335°N) and (ii) perpendicular to the crater azimuth (245°N) (Fig. 7). Where the particle motion linearity coefficient (the correlation) is above 0.8, waves with an azimuth coinciding with the crater direction are interpreted as *P* waves. As expected, *P* waves were observed at the onset of the explosion and at the commencement of chugging (Fig. 8b). Linear polarization (>0.8) with an azimuth perpendicular to the crater direction is present only during chugging sequences (Fig. 8b). This result suggests that in this example chugging is mainly composed of *SH* polarized or Love (*LQ*) waves. A large *SH* content in seismic signals produced by volcanic activity was observed by Chouet *et al.* (1997) for volcanic tremor recorded at Stromboli volcano and has been reported in chugging events at Arenal volcano, Costa Rica (Benoit & McNutt 1997). Chugging apparently includes a source effect that differs from the initial explosions that precede the onset of the tremor. However, since chugging always commences after an initial isolated explosion it is clear that the presence of a chugging sequence depends on the explosion event to either trigger or set in place the conditions required for chugging oscillations to be activated.

6 TIME DELAY CHUGGING WAVEFORM ANALYSIS

Careful inspection of the pulse trains shows a linear relationship of pulse amplitude and interpulse time interval (Fig. 9). In general, linearly resonating bodies do not behave in this manner. Signal

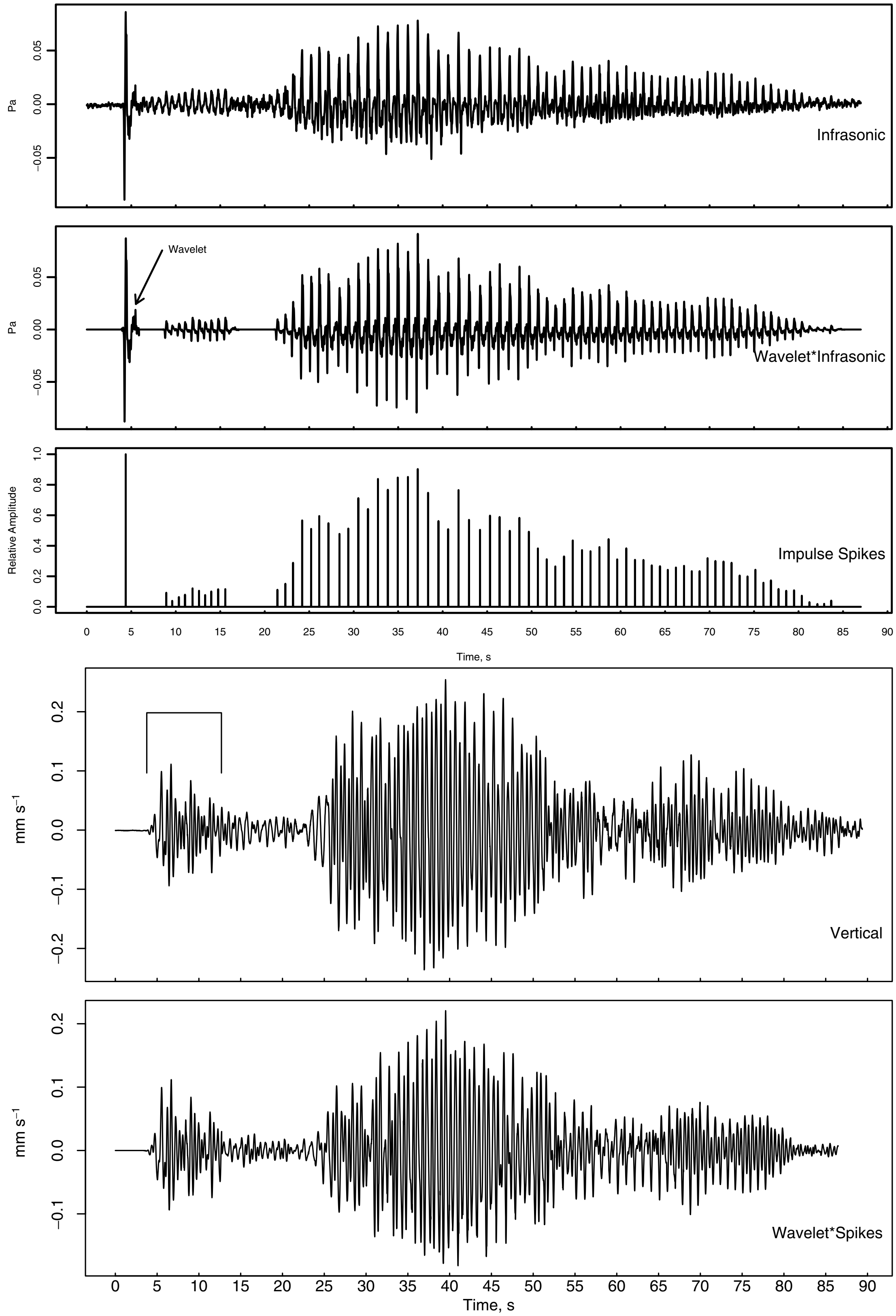

Figure 6. Convolution of a spike series with initial explosion wavelets. (a) Acoustic signal. Top: original acoustic time-series. Centre: convolution of the first pulse, designated as a wavelet, and the spike series represented below. The acoustic wavelet length is 245 points (1.96 s). Bottom: spike series determined from large-amplitude pulses scaled according to the amplitude estimated from the time-series in the top. (b) Vertical component seismic time-series. The spike series used is the same as that in (a). The seismic wavelet is 1165 points (9.32 s) long.

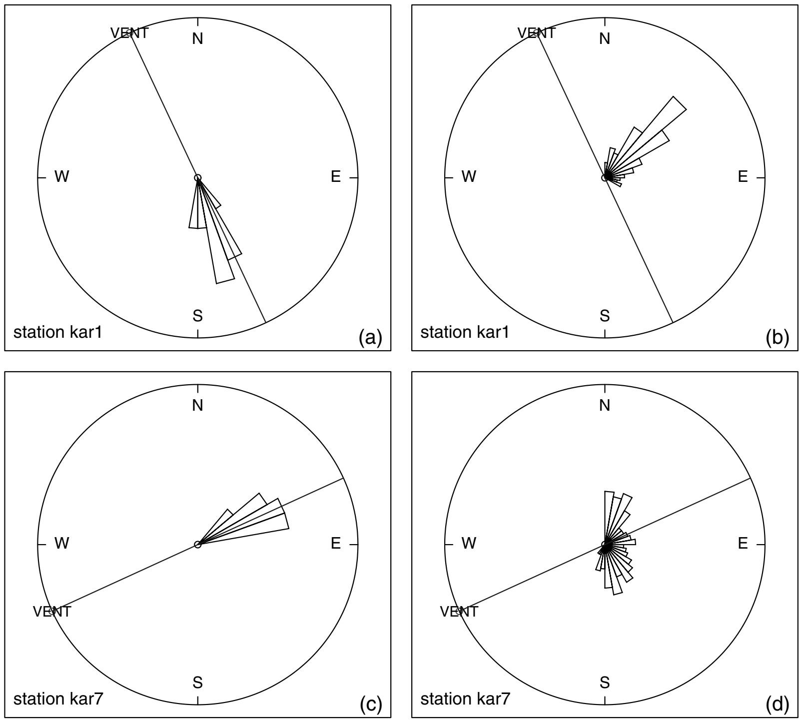

Figure 7. Azimuthal distribution of seismic waves with linearity above 0.8. (a, b) Chugging contains highly polarized waves such as *P*, *S* and *LQ* waves with two main backazimuth: 335°N towards the crater and 245°N perpendicular to the crater direction. (c, d) For the same events recorded at station 7, approximately 90° around the cone, we see the same pattern of initial polarization in the direction of the vent and the chugging sequence polarized in the perpendicular orientation.

processes that are made up of a linear superposition of harmonic sequences do not show a correlation of amplitude and pulse time interval. We therefore reject the model of standing waves (organ pipe modes) as a physical explanation for chugging events at Karymsky. Instead we propose that the correlation of amplitude and time interval between chugs is related to the storage of energy in the system between pulses, and that the longer the delay the more energy is stored. In this scenario pressure builds in the vent until it reaches a critical level when gasses are forced out. This mechanism can be modelled as a constricted vent releasing gases spasmodically. On a much simpler level sequences of explosions of this kind have been modelled using a standard kitchen pressure-cooker as an analogue (Lees & Bolton 1998). In that case a small weight constricts the flow of water vapour until a critical level is reached. After the system begins releasing vapour, in an unstable manner, the internal pressure gradually returns to a lower level and the vent returns to a state of closure. Our model of the explosions and chugging at Karymsky follows this line of reasoning: explosions normally open a vent and release nearly all gasses stored in the degassing preparation phase. On occasion, the vent is choked off and gasses are prevented from leaving the vent. This corresponds to the short repose period on the acoustic records: pressure is building up in the choked gas storage zone below the closed vent. After the short repose period gasses are finally released through narrow cracks, or conduits, near the surface, inducing the chugging signals. Fluids flowing through a constricted vent often exhibit this behaviour, for example air escaping from a balloon whose opening is partially clamped.

This analysis emphasizes one of the main features of chugging dynamics; the overpressurized magma–gas fluid does not always recover its equilibrium instantaneously. More often than not, recovery is achieved via gradual decompressive fluctuations. These fluctuations have also been measured with infrared image analysis in the explosions at Stromboli (Ripepe *et al.* 1993; Ripepe 1996) and therefore may represent a normal mechanism for the magmatic fluid to restore its equilibrium pressure.

It is useful to compare the initial explosion signals on the seismic versus the acoustic records. The infrasonic signals are typically impulsive as compared with the more emergent seismic signals (Fig. 3). The pressure pulse transmitted to the atmosphere during the initial expulsion of gases and ejecta is pronounced in the frequency range recorded by the microphone. The seismic signals, furthermore, are considerably more emergent than typical tectonic or volcano-tectonic events for this region. This is partly due to the fact that acoustic signals are not contaminated by the complicated Earth structure encountered by seismic waves; however, source effects may also be a factor.

To estimate the partitioning of energy at the explosion source we measured initial explosion amplitudes on vertical component seismic records and corresponding acoustic records by estimating peak–peak deviations (Fig. 10). For the seismic arrivals we further measured low-frequency asymptotes (Ω_0), corner frequency (f_c) and attenuation factor t^* for 177 events on days 233 and 234 of our deployment. Corner frequencies have a mean value of 2.6 ± 0.41 Hz. The mean attenuation factor, t^*, was 0.10 ± 0.03 s. Converting t^* to Q, the quality factor, assuming a constant velocity $V_P = 1.2$ km s^{-1} we get a mean Q-factor 15 ± 6. The relatively low Q factor suggests we have significant seismic attenuation in the volcano edifice.

Seismic and acoustic amplitudes exhibit a large degree of apparent variance in contrast to the bubble bursting events at Erebus (Johnson *et al.* 2003). The variance of the seismic amplitudes

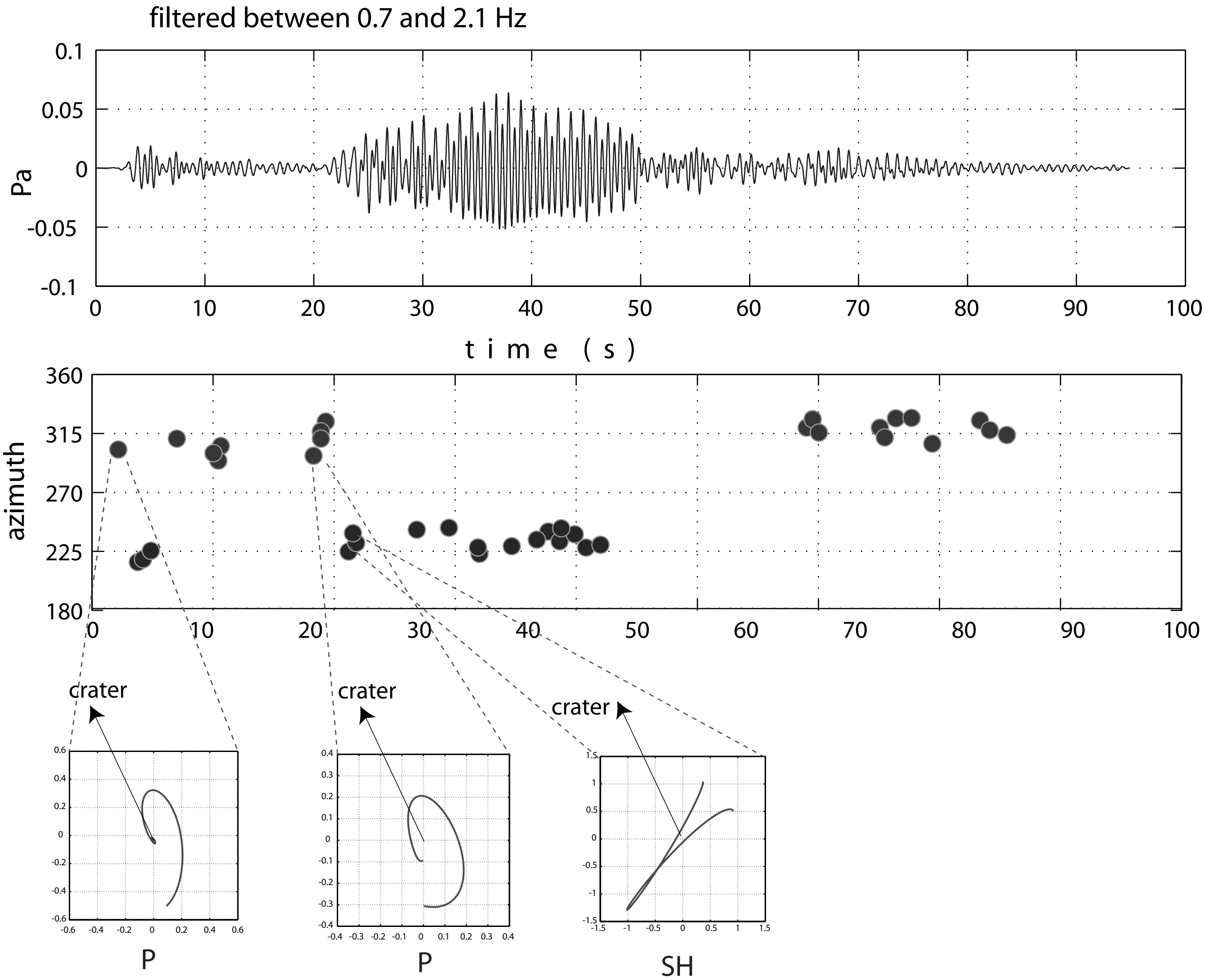

Figure 8. Example of longitudinal and transverse seismic polarization. Chugging was first filtered between 0.8 and 2 Hz. Dots indicate where polarization in the seismogram assumes linearity above 0.8. The transverse polarization (dots) is mainly present during the chugging.

appears to be related to the size of the acoustic amplitudes. We suggest, however, that for a given acoustic pressure, seismic amplitudes take on arbitrary values up to a specific, empirically determined threshold. Conversely, for events with a small seismic amplitude, acoustic waves vary with no apparent threshold whereas for events with a large seismic amplitude corresponding acoustic events will be larger. The impulsive onset of acoustic signals at Karymsky suggests that acoustic coupling is relatively efficient, whereas the emergent seismic arrivals indicate complicated source and path effects for elastic waves. Thus we cannot model explosions at Karymsky simply as bubbles bursting at the top of a fluid conduit of magma. At Karymsky we expect that the conduit is composed of a mixture of gas, fluid and solids and as gasses expand and decompress explosions generate waves in the conduit through solid cracks filled with variable fluids. The attenuation in this case is expected to be considerable, although the narrow range of time differential between acoustic and seismic arrivals ($\delta t = 4.06 \pm 0.27$ s) suggests that nearly all events share a common seismo-acoustic source.

7 SPECTRAL GLIDING AND SOURCES OF VOLCANIC EXPLOSIONS

A source that is regularly spaced in time (Fig. 11) can give rise to a harmonic-like tremor. It has been pointed out, however, that small deviations from regular spacing (standard deviations as small as 10 per cent of the mean time delay between two successive pulses) may destroy the harmonic character of the resulting seismic spectrum (Hagerty *et al.* 2000) (Fig. 12). This is only partially true: a gradual shift in the time delay between pulses will still produce a gliding harmonic tremor even with a standard deviation as large as ± 0.3 s (Fig. 13). Harmonic tremor is degraded, as claimed by Hagerty *et al.* (2000), only if individual pulses are randomly spaced in time. However, if the pulses are systematically controlled by pressure fluctuations, harmonic tremor is readily preserved, e.g. when the pulses get closer to each other the harmonic tremor will glide towards higher frequencies, while when the time delay between pulses is gradually increasing, then spectra will glide towards a lower frequency.

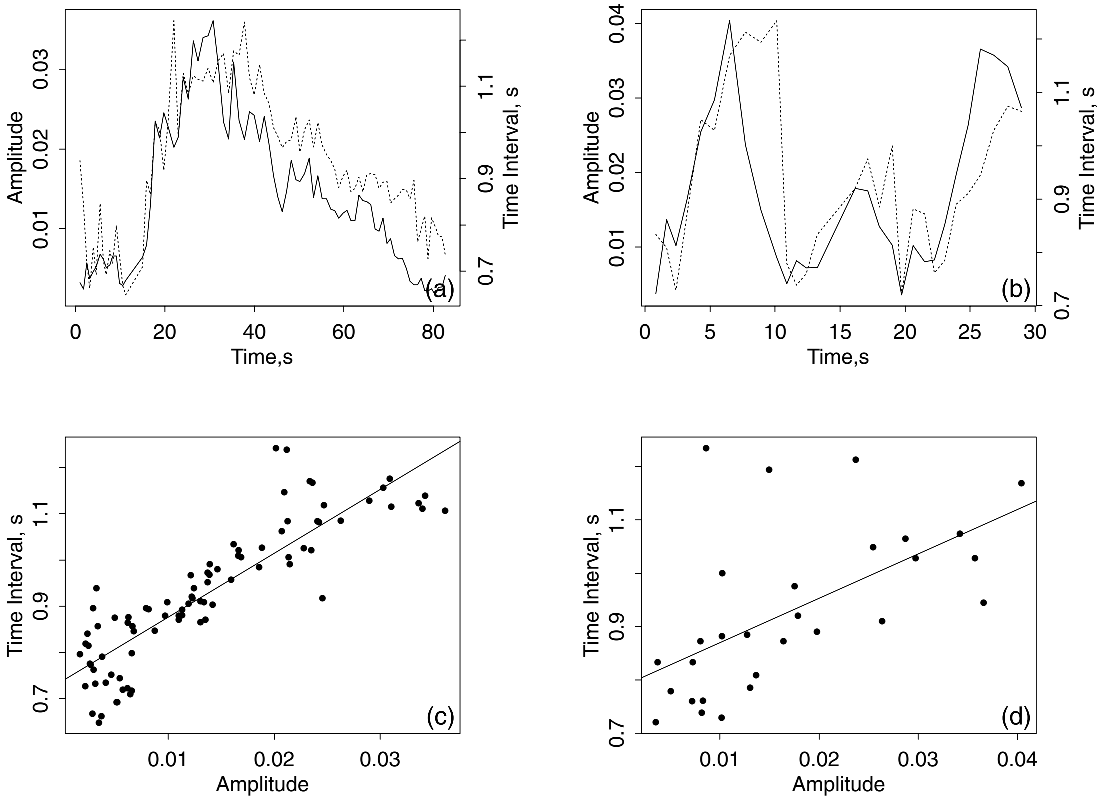

Figure 9. Correlation of pulse amplitudes within a given sequence and time interval between pulses. A strong correlation exists for both continuous and intermittent pulse trains. The corresponding chugging sequences, recorded on acoustic sensors, are presented in Fig. 4. The upper figures (a, b) show amplitude versus time in solid lines and time interval versus time in dashed lines while the lower figures (c, d) illustrate the linear relationship between amplitude and interpulse time intervals. The left-hand diagrams (a, c) correspond to the continuous chugging of Fig. 4 and the right-hand diagrams (b, d) corresponds to the intermittent example.

Following this idea, we calculated a theoretical spectrogram as a function of the time delay between pulses. The fundamental frequency and its harmonics were calculated, respectively, as the inverse of the time delay (Fig. 6a) and multiple integers of the fundamental. The theoretical spectrogram perfectly fits the real spectrograms of the infrasound (Fig. 14a). The seismic spectrograms (Fig. 14b) can also be explained in terms of time delays between infrasonic pulses. This is an important point and nicely demonstrates that the seismic spectrum is not necessarily controlled by resonance in the conduit but rather by the rate at which the source repeats in time (Ripepe *et al.* 1996; Ripepe & Gordeev 1999). In a dynamic model controlled by instability in fluid pressure, random fluctuations (e.g. Stromboli, Etna) will lead to a peaked spectral tremor while time-dependent pressure fluctuations tremor will show a steady and/or gliding harmonic spectrum according to the nature of the pressure release (e.g. Arenal, Semeru, Karymsky).

At Karymsky chugging sequences generally glide towards a higher frequency prior to cessation. Gliding typically ranges between 0.01 and 0.25 Hz s^{-1} during a chugging sequence. The initial explosion possibly originates deeper in the conduit as degassing takes place within the first couple of hundred metres of the vent. The source for the chugging, on the other hand, is near the surface where debris and cooled magma blocks choke off the release of excess gasses following the initial explosions. As the source migrates to the surface, and returning debris fills the vent, cracks where gasses extrude to the atmosphere are being closed off. The closing of cracks increases the frequency which gives rise to the positive slope gliding observed on nearly all Karymsky chugging sequences.

8 CONCLUSION

In this paper we have presented several observations regarding the sequence of quasi-periodic pulses following explosions at Karymsky volcano. These transient signals have characteristics that suggest that the sources are near-surface events, possibly originating in the top100 m of the magma conduit. The remarkable acoustic and seismic similarity of the events (Fig. 15) suggests that the signals share a common source. This is true of both acoustic and seismic recordings. The correlation of pulse interval and amplitude, the similarity of initial explosions to subsequent pulses, the varying fundamental frequency of the spectra and the relationship between acoustic and seismic amplitudes lead us to conclude that the source of signals is not an extended, resonating body.

In the alternative model, all sources of the signal are very close to the vent where degassing occurs. We suspect that, from degassing, a significant amount of a pressurized fluid/gas mixture flows into a constricted vent. Such a vent can be a source of harmonic pulsation, as shown by (Julian 1994). Following most explosions gases escape completely. Occasionally the gases are trapped while degassing continues. The remaining gases and the potential energy associated with their pressurized storage are the source of both acoustic and seismic signals. The emergent seismic signals suggest that the source is not well coupled, which would be true if the seismic signals were attributed to the jetting of gases as they escape into the atmosphere. These observations and considerations lead us to reject resonance of a conduit as an explanation of chugging or sustained tremor at Karymsky. Rather, they support a model that puts the sources of

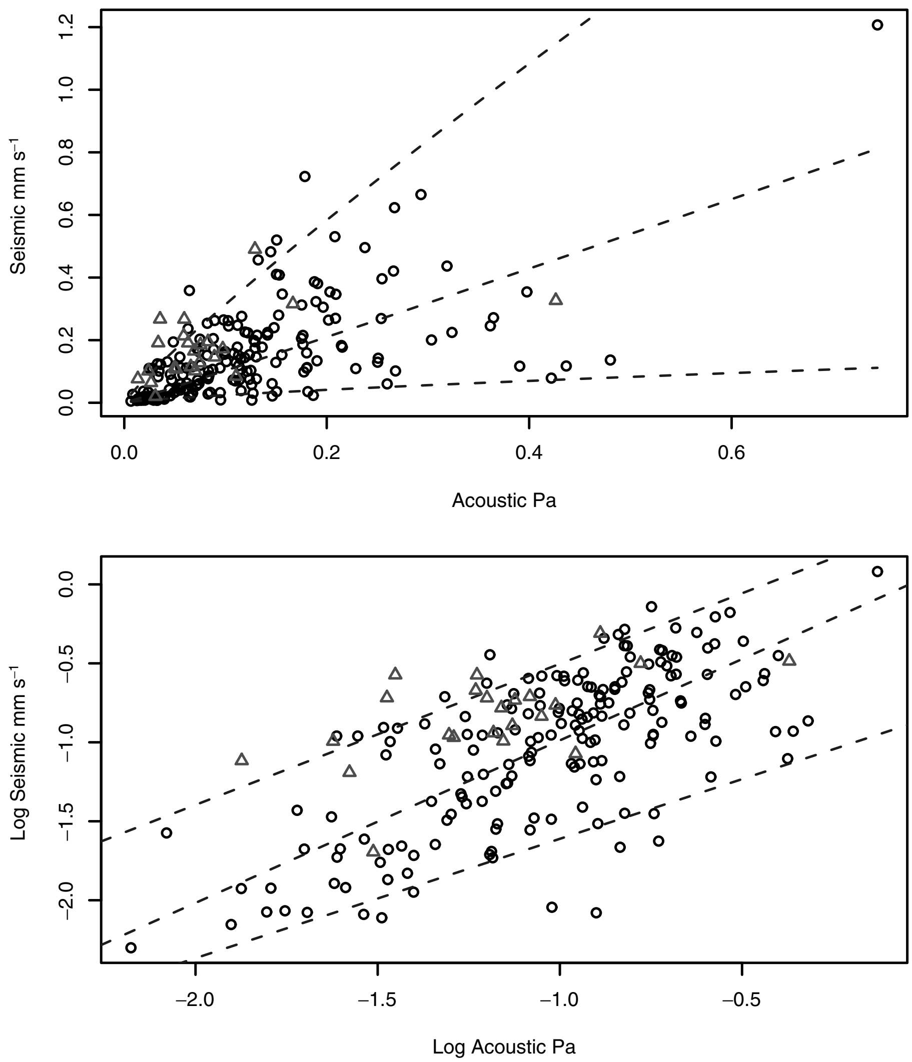

Figure 10. Top: seismic amplitudes (mm s^{-1}), measured by peak–peak at the maximum versus peak–peak acoustic amplitudes (Pa). Amplitudes are estimated for the initial explosion for 177 events recorded over 2 days in 1997. Seismic measurements are made prior to the arrival of the acoustic signals to avoid the influence of air–ground coupling. Dashed lines are the maximum, median and minimum curves determined on the log–log plot by binning the acoustic values and regressing the seismic amplitude statistics for each bin. Bottom: log–log plot of seismic versus acoustic amplitudes. Triangles are estimates of peak–peak amplitudes measured on chugging sequences. Chugging events cluster near the upper bound curve of the initial explosion amplitudes.

these signals very near the surface vent. After the initial explosion, when the top of the vent is breached, there is a settling effect that occasionally chokes off gas flow before the vent can completely vacate near-surface gas pockets. Chugging ensues as a response to the gases escaping through narrowing channels.

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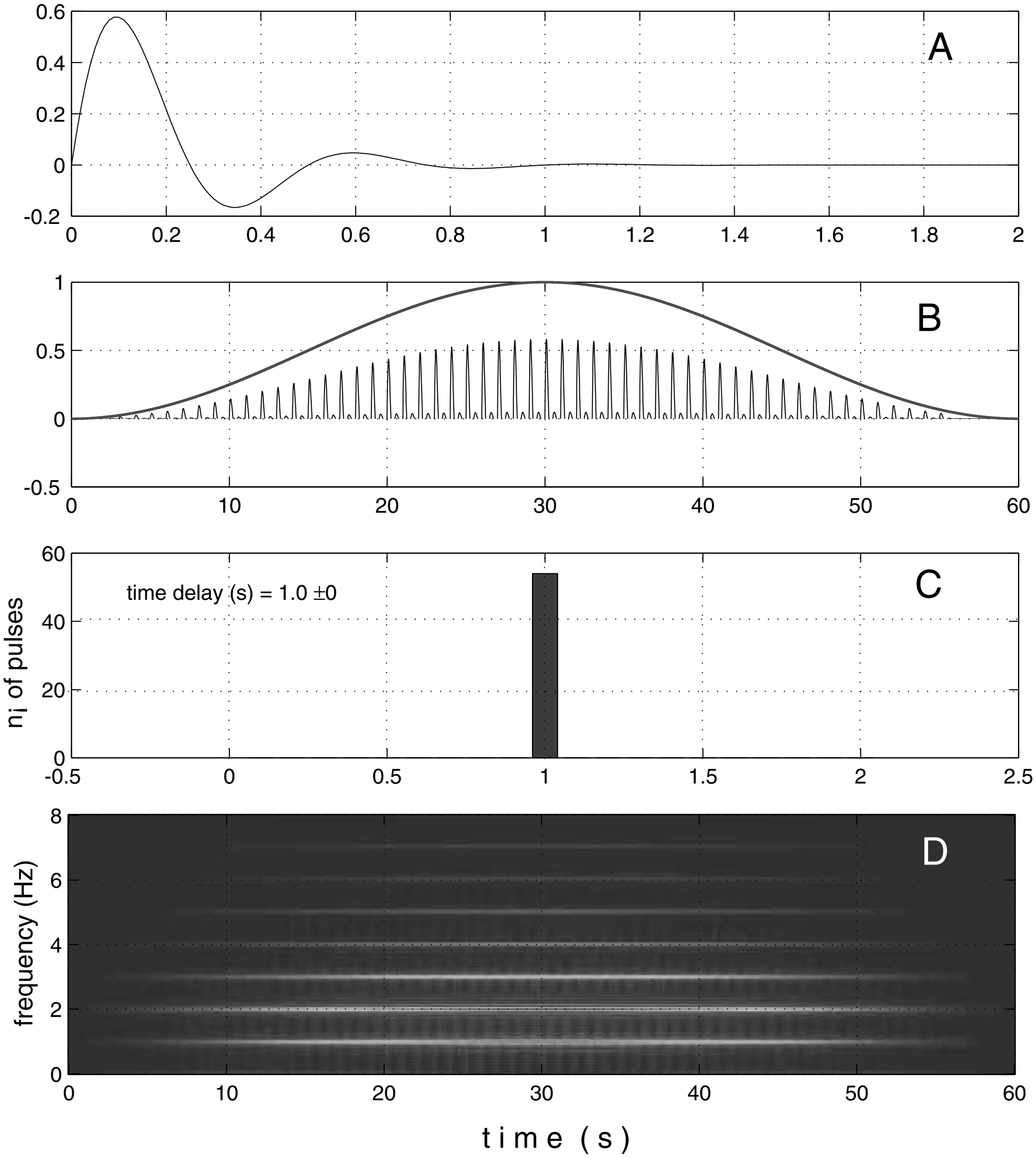

Figure 11. Spectral analysis of a series of equispaced sources: (A) the source function; (B) the equispaced series of sources with gradually changing amplitude; (c) the distribution of time delays, the standard deviation between two successive sources is 0; (D) the harmonic spectrogram.

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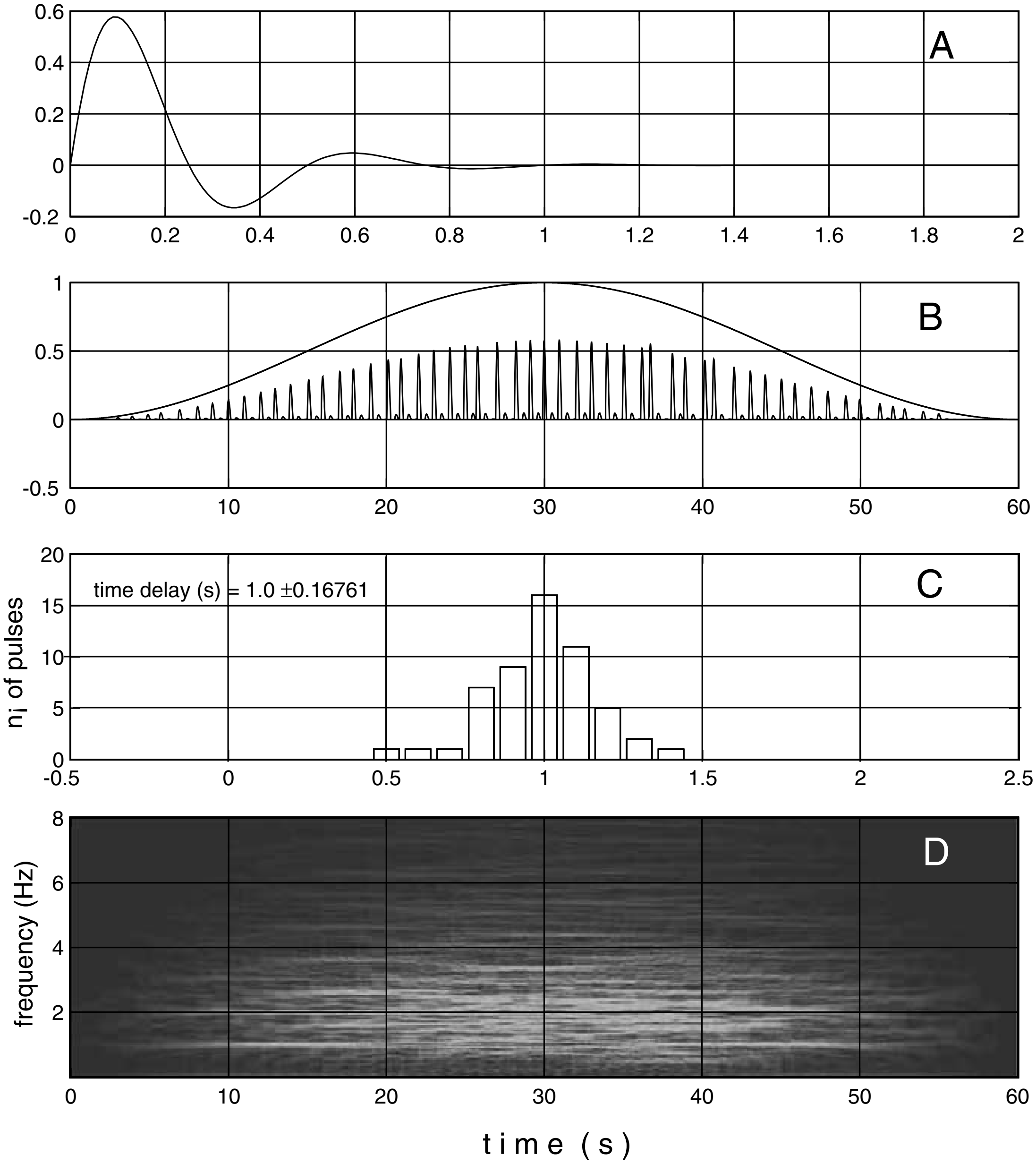

Figure 12. Spectral analysis of a series of randomly spaced sources: (A) the source function; (B) the randomly spaced series of sources with gradually changing amplitude; (C) the distribution of time delay, the standard deviation between two successive sources is ±0.16; (D) the spectrogram.

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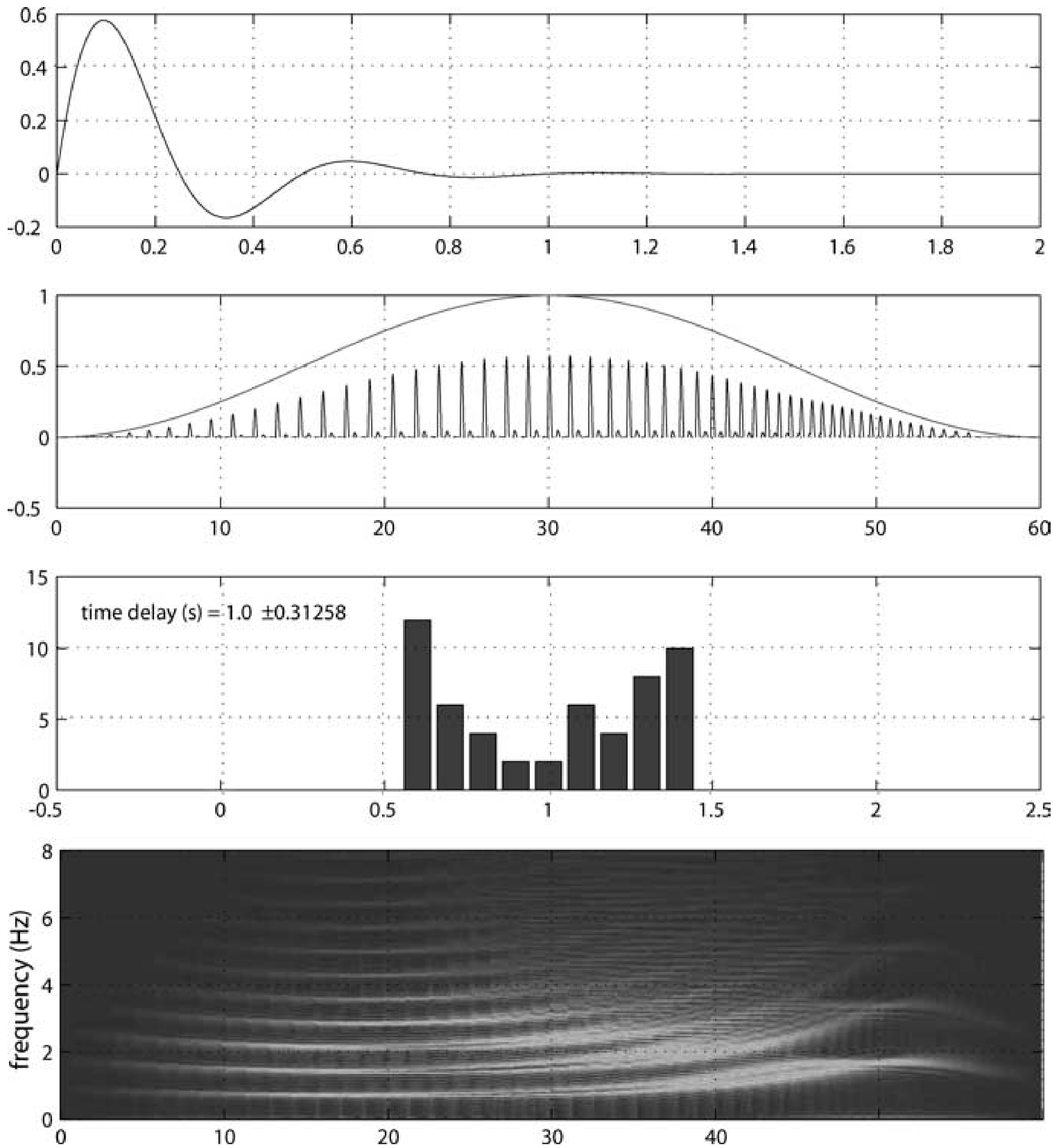

Figure 13. Spectral analysis of a series of spaced sources: (A) the source function; (B) the series of sources where the time interval depends on the gradually changing amplitude; (C) the distribution of time delays with a standard deviation between two successive sources of ±0.31; (D) the gliding spectrogram.

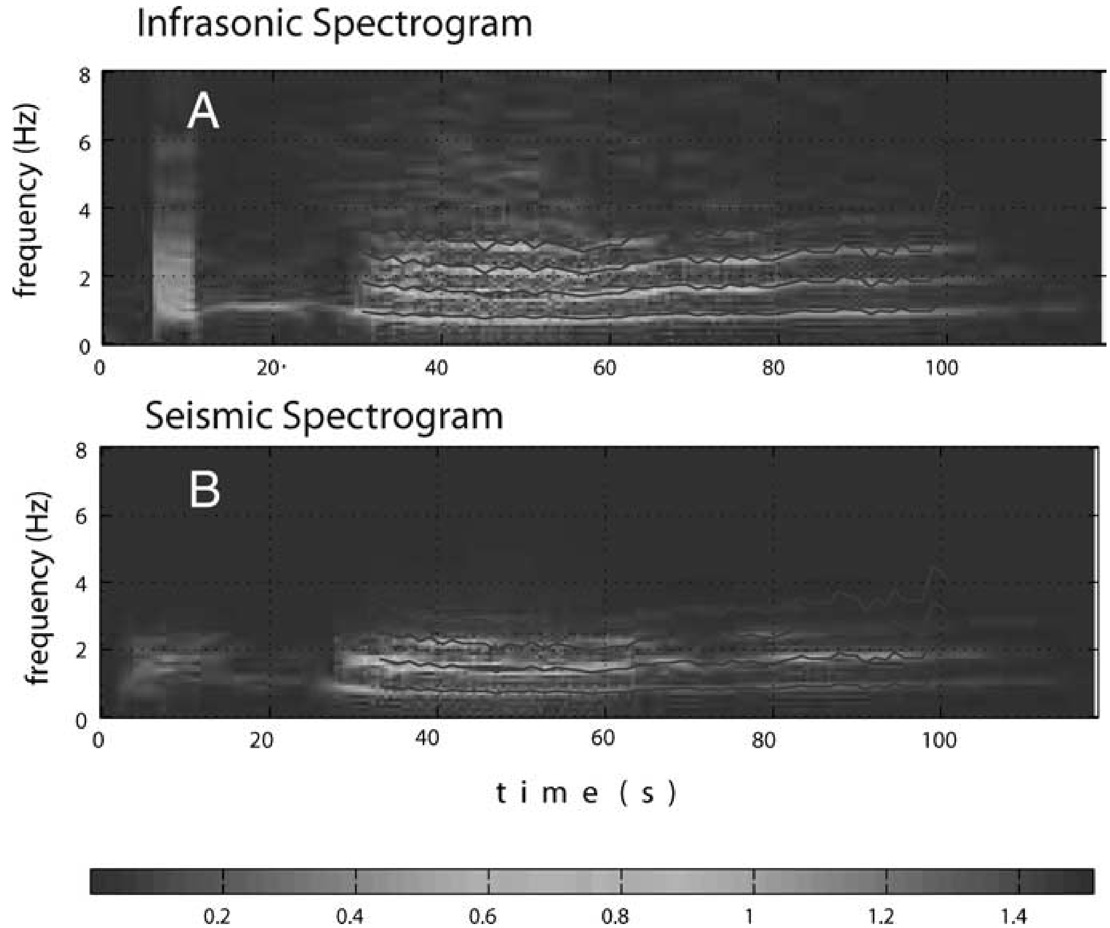

Figure 14. Spectral lines derived from the delay time between two infrasonic pulses of Fig. 6(a). Theoretical spectral lines are compared with (A) the acoustic and (B) the seismic spectrograms.

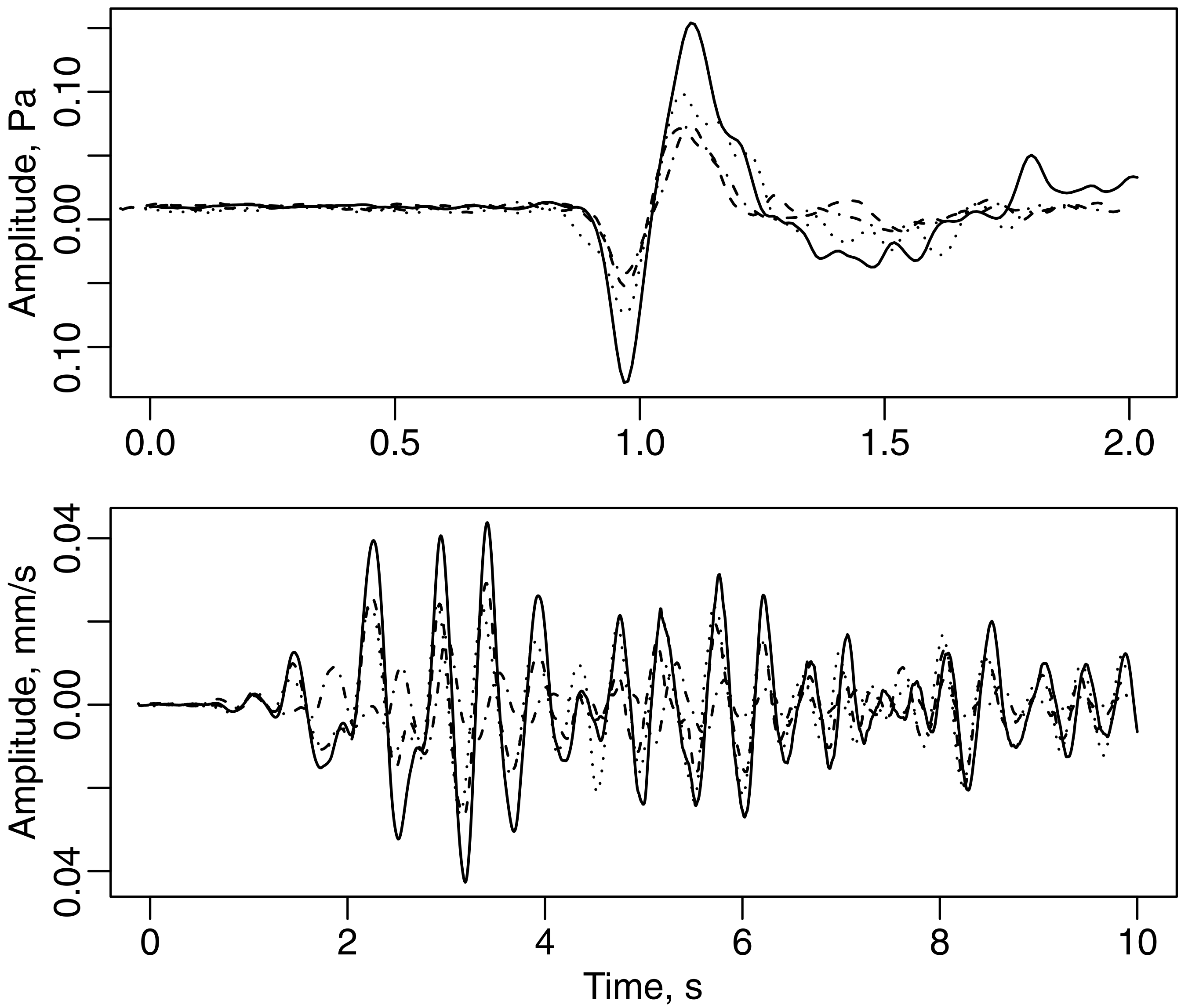

Figure 15. Overlay of several pulses showing acoustic (top) and seismic (bottom) records illustrating the similarity of waveforms for signals recorded at different times. The signals have the same source and path effects.