Solving the mystery of booming sand dunes

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[1] Desert booming can be heard after a natural slumping event or during a sand avalanche generated by humans sliding down the slip face of a large dune. The sound is remarkable because it is composed of one dominant audible frequency (70 to 105 Hz) plus several higher harmonics. This study challenges earlier reports that the dunes' frequency is a function of average grain size by demonstrating through extensive field measurements that the booming frequency results from a natural waveguide associated with the dune. The booming frequency is fixed by the depth of the surficial layer of dry loose sand that is sandwiched between two regions of higher compressional body wave velocity. This letter presents measurements of the booming frequencies, compressional wave velocities, depth of surficial layer, along with an analytical prediction of the frequency based on constructive interference of propagating waves generated by avalanching along the dune surface. **Citation:** Vriend, N. M., M. L. Hunt, R. W. Clayton, C. E. Brennen, K. S. Brantley, and A. Ruiz-Angulo (2007), Solving the mystery of booming sand dunes, *Geophys. Res. Lett.*, *34*, L16306, doi:10.1029/2007GL030276.

1. Introduction

[2] Explorers including Marco Polo [*Polo*, 1984] in the Gobi Desert, the Emperor Baber [*Marquess Curzon of Kedleston*, 1923] in Afghanistan and Charles Darwin [*Darwin*, 1839] in Chile have been mystified by the booming sounds of the desert. Sustained booming is defined as the continuous, loud droning sound emitted from a large sand dune after inducing a sand avalanche on its leeward face [*Criswell et al.*, 1975; *Lindsay et al.*, 1976]. An avalanche of sand can be initiated naturally when sand exceeds its angle of repose or can be induced by a man-made slide. Booming is a seasonal phenomenon and investigators [*Haff*, 1986; *Lewis*, 1936] have noted that moisture in the sand can eliminate the booming sound completely. The booming sound differs fundamentally from the "squeaking" sound on sand beaches at frequencies around 1000 Hz [*Humpries*, 1966; *Nori et al.*, 1997; *Sholtz et al.*, 1997] and from "burping" sounds when sand is shaken back-and-forth in a jar [*Goldsack et al.*, 1998; *Haff*, 1979]. These burping sounds consist of short ($t < 0.25$ s) bursts at frequencies (150–300 Hz) higher than booming sounds and with different spectral characteristics.

[3] An explanation for the booming sound is found in *Poynting and Thompson*'s [1909] classic 1909 physics textbook, proposing that the frequency is related inversely to the time required to pass between successive collisions of individual grains. *Bagnold* [1954] provides a similar argument based on shearing and dilation, and finds that the frequency should vary as $(g/D)^{1/2}$, where g is the acceleration due to gravity and D is the average particle diameter. More recently, *Andreotti* [2004], *Douady et al.* [2006] and *Bonneau et al.* [2007] support the $(g/D)^{1/2}$ scaling and argue that the frequency is controlled by the shear rate inside the avalanche. The dependence on granular properties alone suggests that booming should occur on all dunes, in contradiction to observations. The current work presents new experimental evidence that support an alternative interpretation of the booming based on a resonating waveguide. This waveguide model explains why the booming phenomena only occur in certain locations and at certain times of the year. It also provides an explanation for the continuation of booming for up to a minute when all visible shearing has ceased (auxiliary material Animation S1[1]).

2. Method

[4] At Dumont Dunes, just south of Death Valley NP, California, USA, measurements of the booming frequencies were made at two dunes on 11 and 12 September 2006. The elevation above the desert floor was approximately 45 m and 11 m for the large and small dune respectively. Both dunes had a slip face near the crest at an inclination of 30°. To initiate the booming sounds, human sliders descended the steep face at a constant speed of 1.1 m/s, creating a slide in the surrounding sand. Figure 1 shows the free-surface profiles of the large and small Dumont dune.

[5] Figure 2 presents recordings of the sustained booming frequency created during the slide, measured with a microphone at location B (auxiliary material Audio S3) and with an array of seismic geophones positioned downhill from location A. The sound did not start immediately, varied somewhat during the slide and showed one dominant frequency with several higher harmonics (Figure 2a). The largest amplitude measured by the geophone signal was obtained around location B (Figure 2c). The booming sound diminished and disappeared as the sliders descended farther down the dune where the surface slope lessened. Visible surface avalanching occurred during the slide on the smaller dune (Figure 2f), but booming could not be initiated resulting in a broad band emission at low magnitude. When the experiment was repeated on the larger Dumont Dune in the winter on 5 December 2006 (not shown here), no sustained booming could be initiated, although faint, short

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl030276. Other auxiliary material files are in the HTML.

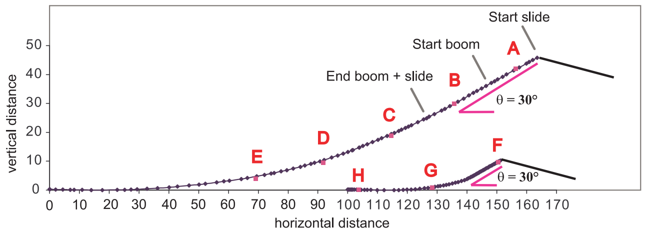

Figure 1. Free-surface profiles and seismic set-up on the large and small Dumont dune. The geophones are separated 1 meter apart and positioned on the large dune (h = 45 m, 96 geophones) in two deployments from A to E and on the small dune (h = 11 m, 48 geophones) in one deployment from F to H. The pressure impulses are provided by striking a plate with a sledge hammer at locations A–H. Both dunes have a slipface near the crest at an angle of repose of 30 degrees.

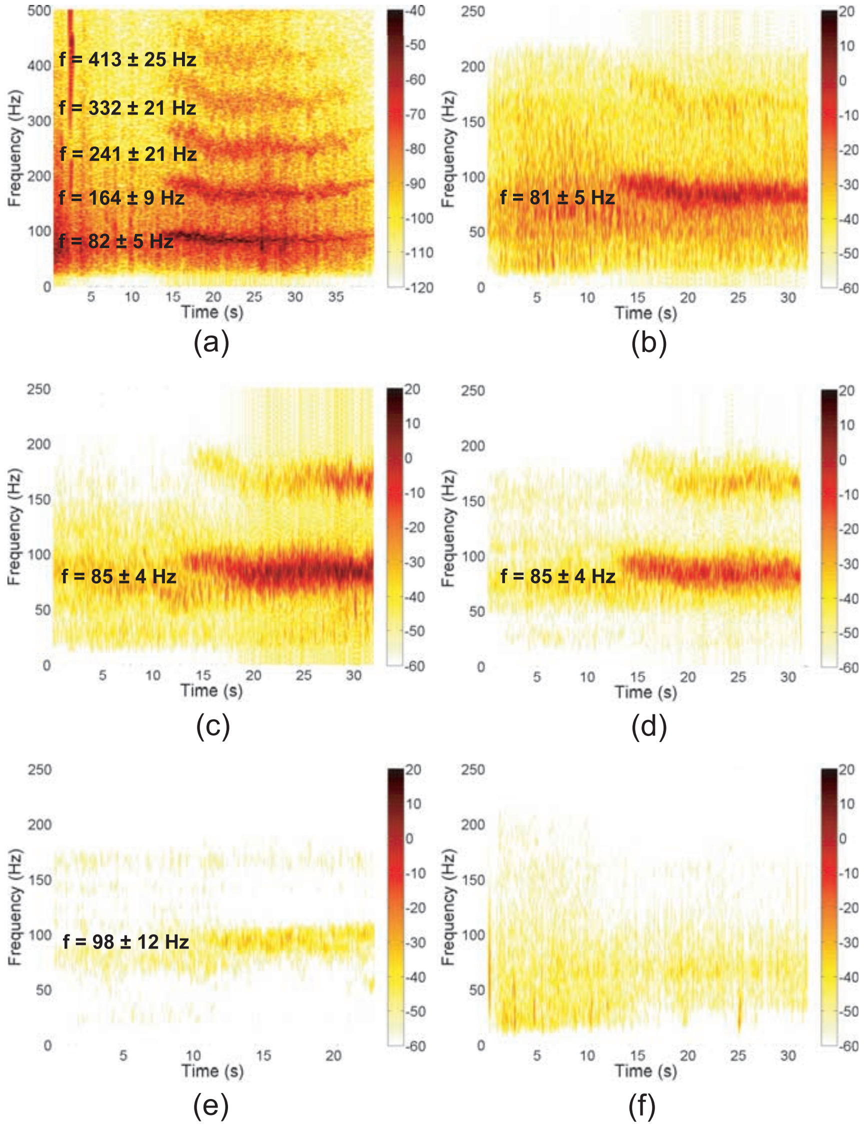

Figure 2. The Booming Sound. Spectrograms at different locations with the voltage amplitude in decibels. (a) Microphone record with the dominant frequency at 82 Hz and several higher harmonics at multiples of the dominant frequency. The location of the microphone is at station B, 33 meters from the crest of the large dune. (b–e) Geophone records showing the change in amplitude and sustained dominant frequency down the dune from Figure 2b near the top to Figure 2e near the bottom. The recordings in Figures 2b–2e were at stations A (8 m), B (33 m), C (58 m) and E (106 m), measured from the crest of the large dune. The highest amplitude of the booming is obtained close to station B. (f) Geophone record of the slide on the small dune showing broadband noise and a three orders of magnitude lower magnitude of the recording. No audible squeaks or sustained booming sound were heard. The location of the geophone is at station F (0 m), measured from the crest of the small dune.

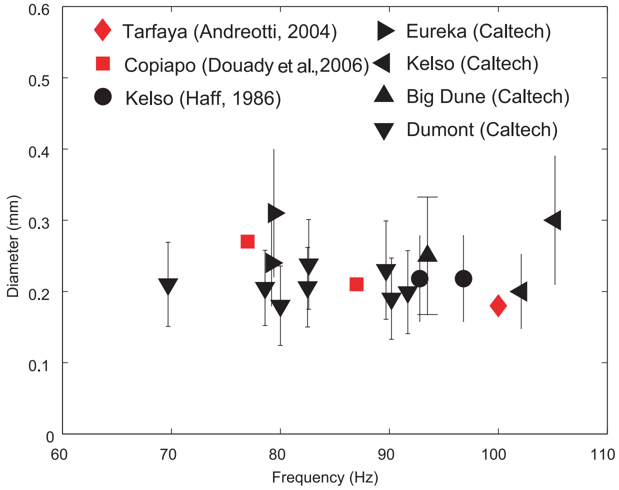

Figure 3. Sustained booming frequency f as a function of average grain size diameter D. Data are derived from the work of previous investigators [*Andreotti*, 2004; *Douady et al.*, 2006; *Haff*, 1986] and from four different locations visited during the current research. Sustained booming frequency does not correlate with particle diameter. The bar on the diameter represents the standard deviation.

squeaks were audible during the slide. These squeaks had a lower frequency (~65 Hz), a shorter duration (~0.2 seconds) and lower amplitude than the booming emission. The definition of sustained booming sound does not apply here as the acoustic emission is short and not sustained.

[6] Over the course of 5 summers, visits were made to Dumont Dunes and to 3 other booming locations: Big Dune near Beatty, NV; Eureka Dunes in Death Valley National Park, CA; and Kelso Dunes in Mojave National Preserve, CA. At each location the dune had a clear slip face below the crest at the angle of repose of the sand. The sustained booming frequency was measured with either a microphone or with a single geophone during an induced avalanche of sand. Booming could never be initiated on faces that were below the angle of repose.

[7] Sand obtained at each location was sieved in the laboratory to determine the average grain diameter and its standard deviation. The average grain diameter ranges from 0.18 to 0.31 mm. Compared with other sands, dune sand is well sorted with a relatively small standard deviation because of its aeolian history [*Humpries*, 1966; *Lindsay et al.*, 1976]. The sustained booming frequency is presented in Figure 3 as a function of the average grain size and does not correlate with the particle diameter.

[8] In addition to the booming frequencies, the geophones were used to determine the body wave velocities within the dune using a seismic refraction survey technique. An array of 96 geophones was positioned, beginning 8 m from the crest (location A), with a spacing of 1 meter. The geophones recorded the wave propagation initiated by the striking of a plate with a sledge hammer, as exemplified in Figure 4 for an impulse at A.

3. Results

[9] The seismic records are particularly clean as the surface waves, which propagate at a speed of approximately 50 m/s, are strongly attenuated. By analyzing the slopes in Figure 4, discrete velocity layering is apparent in this summer recording, while the velocity gradually increases without distinct layers for the same dune in winter. The first-arriving body waves for the large (shots A–E) and the small (shots F–H) dune at Dumont are used to determine the subsurface velocity distribution. The large dune (Figure 5a) has a large lateral velocity gradient and contains a low-velocity layer to a depth of 1.5 meters that acts as a waveguide for acoustic energy. On the small dune (Figure 5b) the surficial velocities are similar in magnitude; however, the layering is less apparent and the first refraction velocity, 600 m/s, is higher, presumably because of the limited height of the dune and the relative proximity of the desert floor.

[10] As suggested by *Andreotti* [2004], the wave velocities can also increase due to hydrostatic pressure within the dune. The standard scaling between velocity and pressure in granular materials states that $c \sim P^{1/6}$. This relation predicts a 16% increase in velocity at a depth of 10 m for sand with a density of 1500 kg/m^3, compared to a 250% increase observed in the data. Hence, the velocity increase is not explained by a simple increase due to hydrostatic pressure. The jumps in velocity cannot be explained by pressure increases and are instead a result of structural differences. These structural changes are due to a local high water content or chemically altered sand. Andreotti only considers low-speed surface waves of around 50 m/s as the speed of the booming sound. By cross-correlating the geophone signals, the phase speed of booming is measured at 200 m/s near the crest of the dune and increasing to 350 m/s further downhill. Hence, booming results from the propagation of body waves not surface waves.

[11] The dune can act as a seismic waveguide [*Ewing et al.*, 1957; *Officer*, 1958] because of the subsurface layering. The avalanching of the surface layer acts as its moving source of energy. Waves propagating at c_1 in the surficial layer are reflected at the atmospheric boundary and the substrate half-space. The surficial layer of thickness H is sandwiched between the higher velocity atmosphere (c_0) and substrate half-space (c_2). For the frequency f_n associated with mode n (where $n = 1, 2, 3, \ldots$) for which the phase difference between two subsequent descending waves is an integral number of 2π, wavefronts interfere constructively when:

$$4\pi \cdot H \cos\phi \frac{f_n}{c_1} - \varepsilon_{10} - \varepsilon_{12} = 2(n-1)\pi \tag{1}$$

For the special case of incidence at the critical angle $\phi = \phi_{cr}$ the phase changes ε_{10} and ε_{12}, as defined by *Officer* [1958], are zero. No attenuation occurs in either the atmosphere, or the substrate half-space, resulting in the maximum excitation of the waveguide. For the condition where the velocities c_0 and c_2 are equal, the amplitude of the booming is at its maximum magnitude as experimentally observed in Figures 2b–2e and Figure 5a. The frequency is computed as,

$$f_n = \frac{nc_1}{2H\left[1 - (c_1/c_2)^2\right]^{1/2}} \tag{2}$$

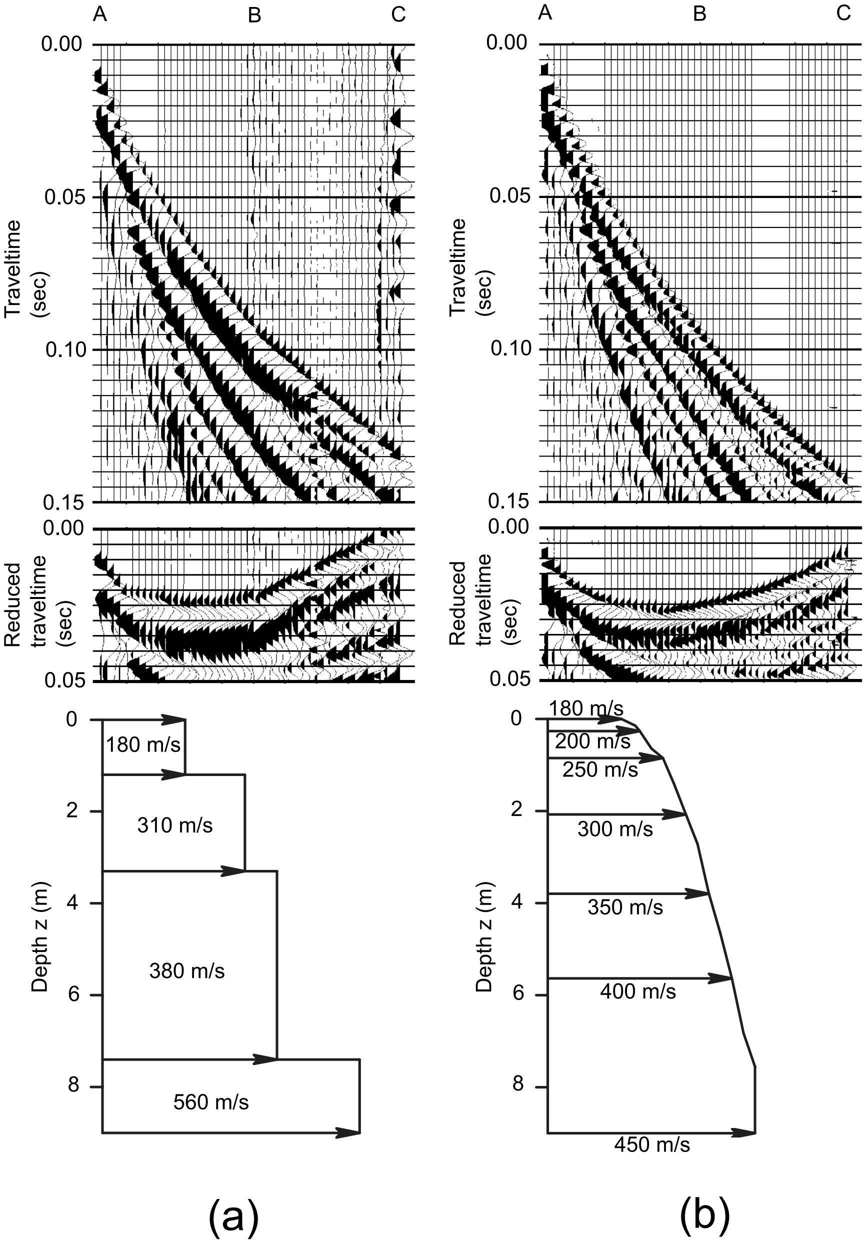

Figure 4. Evidence for the change of a dune structure with seasons. Results from the seismic surveys done on: (a) 12 September 2006 and (b) 5 December 2006. The top plot shows the seismograph resulting from a pressure impulse, the seismograph in the middle plot is reduced by a velocity of 350 m/s and the bottom plot shows the resultant velocity structure. The September data points out a discrete velocity layering whereas the December data indicates a continuous velocity variation.

[12] Since the velocity c_0 is larger than the surficial velocity c_1, successive wavetrains will reinforce each other resulting in a coupling for the horizontal transmission between the waveguide and the upper medium. In practice, not all waves travel at the critical angle and some loss of energy will occur at the interface. The frequency predicted by equation (2) is compared with experimental results from the July, August and September 2006 data at Dumont Dunes (Table 1). For the 3 different dates, the agreement between the measurement and the calculated frequency is closest in the upper region of the dune where the maximum amplitude of the booming sound occurs and where the air velocity matches the substrate half-layer as assumed by equation (2). The booming sound cannot be generated where the velocity of the surficial layer of the dune approaches or exceeds the velocity of the air. The observed harmonics are explained by analyzing higher modes of the resonance at $n = 2, 3, \ldots$

[13] The effect of the avalanche speed was investigated by comparing two slides produced at different sliding speeds of $V \approx 1$ m/s (auxiliary material Animation S3) and $V \approx 2$ m/s (auxiliary material Animation S4) in August 2006. The slides occurred on two neighboring sections of the dune approximately 15 meters apart laterally. The frequency of the sustained sound was essentially the same: 83 ± 8 Hz for the

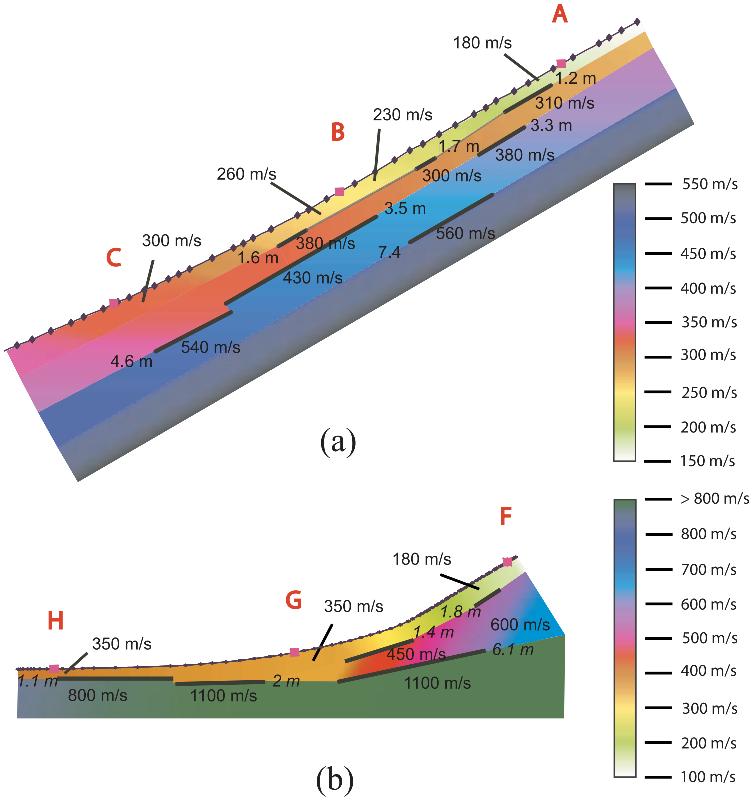

Figure 5. Structure of the large and small Dumont dune. (a) The large Dumont Dune (45 m high) shows a distinct low-velocity layer between point A and B where the booming is clearly evident. The velocity increases strongly downhill (from 180 m/s to 300 m/s). Around point C, the shallow layering disappears completely. The figure is to scale and plotted on topographic profiles with measured velocities and depths of interfaces, while the colours are added for interpretation. (b) The small Dumont Dune (11 m high) has a much shorter channel in longitudinal direction with a high deeper velocity influenced by the desert floor.

slow slide (auxiliary material Audio S1) and 87 ± 5 Hz for the fast slide (auxiliary material Audio S2). The sustained tone and its harmonics are not influenced by the speed of the avalanche. However, the slower slide incorporated a greater surface area involved in the avalanche and the amplitude of the acoustic emission was a factor two higher. Hence, the amplitude of the booming increases with the amount of

Table 1. Comparison of the Calculated and the Measured Frequencies on the Large Dumont Dune on 14 July, 22 August and 12 September 2006[a]

Date and Location	c_0, m/s	$c_1 \pm \Delta c$ (m/s)	$c_2 \pm \Delta c$, m/s	$H \pm \Delta H$, m	$f_m \pm \Delta f_m$, Hz	$f_l \pm \Delta f_l$, Hz	A/A_0
14 July 2006, Shot A	356	260 ± 20	340 ± 30	2.2 ± 0.6	90 ± 30	92 ± 5	–
14 July 2006, Shot B, up	356	270 ± 20	340 ± 30	2.4 ± 0.6	93 ± 34	92 ± 5	–
14 July 2006, Shot B, down	356	260 ± 20	380 ± 30	2.5 ± 0.5	71 ± 18	92 ± 5	–
14 July 2006, Shot C	356	310 ± 30	420 ± 40	3.8 ± 0.9	60 ± 21	92 ± 5	–
22 Aug 2006, Shot A	355	180 ± 20	300 ± 30	1.2 ± 0.3	94 ± 26	86 ±5	0.16
22 Aug 2006, Shot B, up	355	220 ± 20	300 ± 30	1.6 ± 0.4	101 ± 36	84 ± 8	1
22 Aug 2006, Shot B, down	355	250 ± 20	370 ± 30	1.3 ± 0.3	136 ± 41	84 ± 10	0.6
22 Aug 2006, Shot C	355	340 ± 30	450 ± 40	3.7 ± 0.9	70 ± 24	82 ± 6	0.14
12 Sept 2006, Shot A	351	180 ± 20	310 ± 30	1.2 ± 0.3	92 ± 25	81 ± 5	0.30
12 Sept 2006, Shot B, up	351	230 ± 20	300 ± 30	1.7 ± 0.5	105 ± 42	83 ± 6	1
12 Sept 2006, Shot B, down	351	260 ± 20	380 ± 30	1.6 ± 0.4	111 ± 31	84 ± 4	0.49
12 Sept 2006, Shot C	351	300 ± 30	430 ± 40	3.5 ± 0.8	60 ± 18	85 ± 4	0.13

[a] The first column is the date and the location on the dune of the measurement. The next three columns provide the velocity of the air and the seismic velocity of the surficial layer and the substrate half-space, including error bars determined by the picking uncertainty. The depth H in the fifth column has been calculated by a seismic refraction formula compensating for the strong velocity gradient in longitudinal direction and the extra distance of the ray path induced by the changing slope of the dune. The sixth column calculates the frequency from equation (2). The seventh column gives the measured frequency with an error based on the half-width of the peak. Note that the frequency on 14 July 2006 was measured with one microphone at location B. The eight column provides the normalized amplitude of the signal.

avalanching sand, as displayed for the large slide in auxiliary material Animation S2.

4. Conclusion

[14] The avalanching sand acts as a source for the acoustic emission, and the waveguide sets the frequency. Waves interfere constructively and reinforce each other resulting in a loud audible emission. The sand surface interacts with the atmosphere and acts as a loudspeaker by propagating disturbances into the atmosphere. For slopes shallower than 30°, such as on the lower foothill or the windward face, booming could not be initiated. The December experiment on the larger dune demonstrates that a continuous velocity distribution, without apparent layering, does not provide the conditions for sustained booming. Seasonal changes in environmental parameters like temperature, precipitation, irradiation and wind direction contribute to the variations in subsurface velocities and dune features. Moisture that is not evaporated seeps down into the dune, increasing the velocity and eliminating the layering structure. Smaller dunes lack the required subsurface structure and sufficient length to create the waveguide.

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