

## Reply to comment by B. Andreotti et al. on “Solving the mystery of booming sand dunes”

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### 1. Introduction

[1] This reply addresses three main issues raised in the comment of *Andreotti et al.* [2008]. First, the turning of ray paths in a granular material does not preclude the propagation of body waves and the resonance condition described by *Vriend et al.* [2007]. The waveguide model still holds in the dune for the observed velocities, even with a velocity increase with depth as implied by *Andreotti et al.* [2008]. Secondly, the method of initiation of spontaneous avalanching does not influence the booming frequency. The frequency is independent of the source once sustained booming starts; it depends on the subsurface structure of the dune. Thirdly, if all data points from *Vriend et al.* [2007] are included in the analysis (and not an average or selection), no correlation is observed between the sustained booming frequency and average particle diameter.

### 2. Curved Ray Paths and the Existence of a Resonance Condition

[2] *Andreotti et al.* [2008] claim that for granular media, the body waves are non-existent near the surface. The basis of this claim is that the velocity increases with depth in a granular material. The ray paths of seismic waves will bend toward the surface and the bending depends on the velocity gradient and the angle of incidence.

[3] The velocity increase with depth in a granular material is often modeled [*Jia et al.*, 1999] as  $c \sim A z^\alpha$ , with  $\alpha = 1/4$  for low confining pressure and  $\alpha = 1/6$  for high confining pressure. The proportionality constant  $A$  determines the magnitude of the velocity increase and hence the turning of the ray paths. *Andreotti et al.* [2008] state that the velocity in sand typically increases between  $\alpha = 1/3$  and  $\alpha = 1/4$ , but do not give any numerical value of  $A$ .

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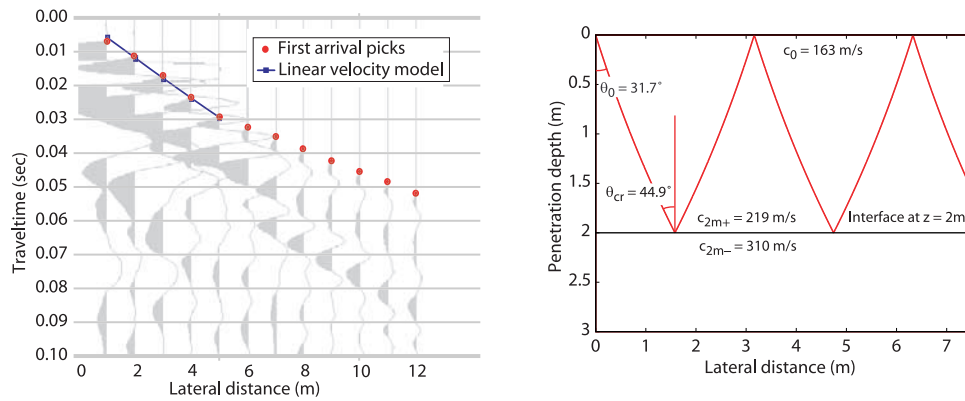
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[4] The near-surface structure of Dumont Dunes for the seismograph of 09/12/2006 displayed a constant velocity with a sharp jump in seismic velocity at a subsurface interface, as presented by *Vriend et al.* [2007, Figure 4a]. This detail is reiterated in Figure 1a with the first arrival picks highlighted in red. For the resonance condition it is not essential that the velocity is constant with depth. A gradual gradient with depth will produce essentially the same result. To illustrate, a small linear gradient is added to the top layer for which an analytic solution exists [*Slotnick*, 1959]. The resonance ray path is shown in Figure 1b.

[5] Another point of clarification is our use of the seismic refraction survey, a standard procedure used in geophysical research. The method determines the velocity from the travel time of the first arrival wave, but is not related to the resonant frequency of spontaneous booming. The hammer blow is simply the source for the refraction survey and is not intended to (and does not) initiate booming. In a second set of measurements, the resonance frequency of the sustained booming after the creation of an avalanche was measured with an array of geophones. By applying cross-correlation on the array, the propagation velocity results to a speed close to the p-wave velocity in sand  $\sim 250$  m/s and not 50 m/s as given by *Andreotti et al.* [2008]. More recent experiments with a 3-component geophone buried at a depth of  $\sim 20$  cm did not show a significant reduction in amplitude with depth, as described by *Andreotti et al.* [2008]. Details of these experiments will be presented in an upcoming paper (N. M. Vriend et al., Further field evidence supporting the waveguide theory for booming sand dunes, manuscript in preparation, 2008).

### 3. Relation between the Resonance Frequency and the Method of Initiation

[6] The creation of an avalanche on the leeward face of a dune creates the shearing motion to induce the so-called “burping” effect - pulse-like, short bursts of sound. This sound is due to shearing of well-rounded and smooth sand grains [*Haff*, 1979] and can be reproduced in the lab by shaking a sand-filled jar. However, when this shaking motion ceases (and hence the shear), the sound stops abruptly as well. For a booming emission, the sound is amplified and sustained, up to a minute after the sliding stops and no shearing of sand is visible [*Vriend et al.*, 2007, Animation S1]. For this type of sound generation, the well-rounded and smooth sand may be necessary, but the required sub-surface structure is essential to the amplification and resonance of the booming sound. In the winter-



**Figure 1.** Seismograph and ray-path. (a) Detail of the seismograph of the seismic refraction experiment of the first 12 receiver geophones. The picks of the first arrivals are indicated in red points and show a constant velocity in the surficial layer. The blue line shows the velocity picks if the velocity would be modeled as a linear velocity increase  $V = c_0 + kz$ , with  $c_0 = 163$  m/s and  $k = 28$  m/s/m as determined from the best-fit of the travel time curve. (b) Ray-path for a linear velocity increase with angle of emergence  $\theta_0 = 31.7^\circ$  and critical angle for these velocities  $\theta_{cr} = 44.9^\circ$ . Although the wave is slightly curved, resonance and constructive interference still occurs. Constructive interference is strongest for waves impacting on the interface at the critical angle [Vriend *et al.*, 2007].

time, the same sand is present and short bursts can be created, but the sustained booming sound cannot be generated [Vriend *et al.*, 2007, Figure 2f]. This result is because of the change in sub-surface structure, possibly due to water saturation of the upper layer of the dune. Field measurements of the frequency and propagation velocity of the booming and burping emission indicate a fundamental difference between these two phenomena [Vriend *et al.*, manuscript in preparation, 2008].

[7] Direct measurements of the method of source initiation have been executed by inducing slides at two different speeds. Spectrograms of high quality audio recordings of the sustained booming in Figure S1<sup>1</sup> in the auxiliary material show the same frequency. Our experience from comparing natural to man-made avalanches is that the method of initiation does not influence the frequency, only the amplitude.

[8] Andreotti *et al.* [2008] also state that the booming frequency is constant for different flow thicknesses, at different places and different weather conditions. In the past summer, our group recorded natural (wind-induced) avalanches on 05/29/2007 and 09/17/2007 at the same location. The recordings of these natural avalanches showed a 20-Hertz difference in sustained booming frequency, while the subsurface structure showed a quantitative difference for these two cases from ground penetrating radar images (Vriend *et al.*, manuscript in preparation, 2008). This is a direct contradiction to observation of Andreotti *et al.* [2008] that the frequency is constant for one location.

#### 4. Variation of Resonance Frequency With Grain Size

[9] The data shown by Andreotti *et al.* [2008, Figure 2c] is a subset of the many data points that were shown by Vriend *et al.* [2007], which were taken in different seasons spanning several years. A range of frequencies were

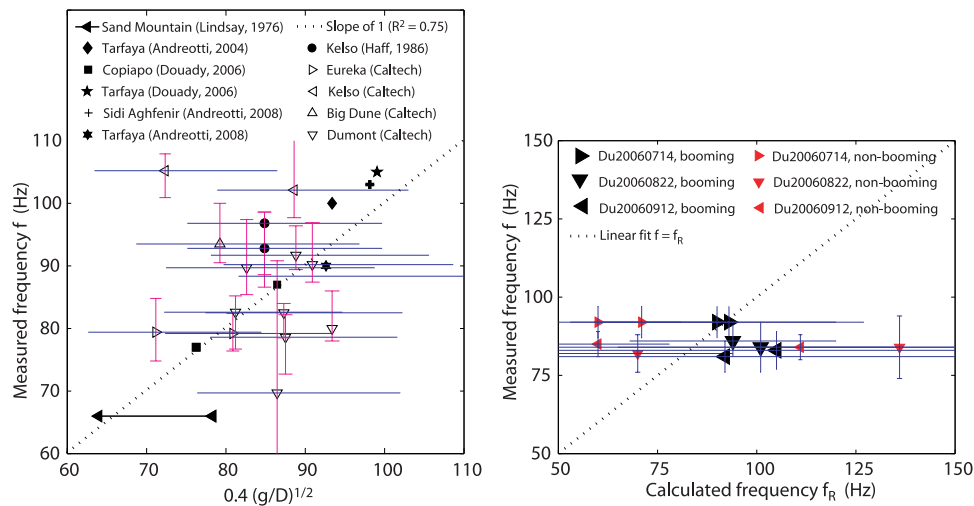
measured and therefore these data points should not be averaged. The figure with all data points is redrawn in Figure 2a. The size distributions were obtained from samples taken on the leeward face where the avalanche was recorded. On a given field date, the sustained booming frequency remains constant on a given section of the dune, and is independent of the mechanism of initiation of the avalanche.

[10] Andreotti *et al.* [2008] claim that the data points in their Table S1 were obtained in situations for which (i) avalanches where spontaneous or at least homogeneous and steady (ii) the grain diameter was determined from samples taken in the middle of the slip face. This statement is not consistent for the data obtained by Haff [1979] and Lindsay *et al.* [1976]. Furthermore, the data in table S1 contains discrepancies with values found in the literature.

[11] Haff [1979] measured at Kelso Dunes two different frequencies ( $f = 92.8$  Hz and  $f = 96.8$  Hz), which were obtained by “forcing oneself vigorously downhill by action of the hands and feet”. Using Haff’s fractional distribution of grain sizes,  $0.22 \pm 0.06$  mm was obtained, not the 0.200 mm as quoted by Andreotti *et al.* [2008]. The Sand Mountain data point (61 Hz for the microphone and 66 Hz for the geophone) collected by Lindsay *et al.* [1976], was obtained by “shoveling in the sand approximately three meters from the geophone that was buried just below the dune surface”. Furthermore, “26 sand samples were collected at regular intervals of approximately 24 m”. The mean grain size ranged from 0.256 mm to 0.384 mm. It is unclear why Andreotti *et al.* [2008, Table S1] selected 0.340 mm to report as the average grain diameter for these measurements.

[12] In Table S1 Andreotti *et al.* [2008] report a frequency of 90 Hz and an average diameter of 0.183 mm for Tarfaya. This data differs from the frequency  $105 \pm 10$  Hz and grain size 0.160 mm reported by Douady *et al.* [2006] and  $100 \pm 5$  Hz and 0.180 mm as reported by Andreotti [2004]. This indicates a significant change in frequency for the same location. Furthermore, the data point for “El

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2008GL033202.



**Figure 2.** Booming frequency as a function of grain size and resonance frequency (a) Booming frequency  $f$  with uncertainty as a function of  $0.4\sqrt{g/D}$  showing the standard deviation of the grain size. The data points published by Andreotti et al. [2008] and Douady et al. [2006] did not contain uncertainties on the diameter. No correlation between booming frequency and average particle diameter can be established by analyzing the entire data set. (b) Booming frequency  $f$  as a function of the resonance frequency  $f_R$ . The black symbols indicate a locally initiated booming emission, while booming could not be locally initiated for the red symbols. For these cases, the frequency was measured while the avalanche occurred higher up at the dune. For the booming locations, the resonance frequency follows the calculated frequency reasonable well. Note the large uncertainty on the calculated frequency due to a large uncertainty in depth of the waveguide channel.

Cerro Bramador” was reported to be at a frequency of 77 Hz by Douady et al. [2006], not 75 Hz.

[13] The calculated resonance frequencies from Table 1 of Vriend et al. [2007] were characterized by a large uncertainty in the frequency as a result of the uncertainty in the depth of the waveguide. In Figure 2b, the error bars on the calculated resonant frequency are added and booming and non-booming locations are distinguished in black and red symbols respectively. Ground penetrating radar surveys executed in the summer of 2007 give a more accurate estimate of the waveguide depth and hence the resonance frequencies (Vriend et al., manuscript in preparation, 2008).

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