# Booming Sand Dunes

Melany L. Hunt and Nathalie M. Vriend

Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125; email: hunt@caltech.edu; nmvriend@caltech.edu



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## Key Words

musical sands, dune structure, seismic refraction

## Abstract

"Booming" sand dunes have a remarkable capacity to produce sounds that are comparable with those from a stringed instrument. This phenomenon, in which sound is generated after an avalanching of sand along the slip face of a dune, has been known for centuries and occurs in at least 40 sites around the world. A spectral analysis of the sound shows a dominant frequency between 70 and 110 Hz, as well as higher harmonics. Depending on the location and time of year, the sound may continue for several minutes, even after the avalanching of sand has ceased. This review presents historical observations and explanations of the sound, many of which contain accurate and insightful descriptions of the phenomenon. In addition, the review describes recent work that provides a scientific explanation for this natural mystery, which is caused by sound resonating in a surface layer of the dune.

## OBSERVATIONS FROM HISTORICAL ACCOUNTS

Desert travelers have referred to mysterious sounds originating from sand dunes for hundreds of years (Darwin 1835, Curzon 1923, Bagnold 1941). In 1923, the Marquess Curzon of Kedleston published *Tales of Travel*, which documented his own observations and reports of booming dunes from earlier world travelers. Although this work does not include scientific data or analysis, it does present an accurate and detailed description of the phenomenon as well as a list of locations where the booming sound can be heard.

At the beginning of the 78-page chapter entitled "The Singing Sands," Curzon wrote:

> I alluded to the phenomenon known in different places and parts of the world as singing sands, sounding sands, rumbling sands, musical sands, barking sands, moving sands, i.e. cases in which certain sands either when set in motion, or even in some cases when apparently quiescent, give forth sounds as of music, which are sometimes audible at great distance. In former days these tales, when they appeared in the pages of medieval travelers, were attributed to local superstition or to an excited imagination, and were not supposed to have any scientific basis. In the course of my travels I have made a study of these cases, about which I have found a good deal not only of literary inexactitude, but of scientific uncertainty, to prevail. . .The subject is one which, while severely scientific in one aspect, is in another full of a strange romance, since the voice of the desert, speaking in notes now as of harp strings, anon as of trumpets and drums, and echoing down the ages, is invested with a mystic fascination to which none can turn a deaf ear.



Supplemental Material

As described by Curzon and shown in this review, the sounds generated by the dune have a musical quality because the sound occurs at discrete frequencies with higher harmonics (Lindsay et al. 1976, Haff 1979, Vriend et al. 2007). The sound results from an avalanching at the surface and can be transmitted sizable distances across the dune where no avalanching occurs. (To watch a video that demonstrates the sounds of booming sand, follow the **Supplemental Materials link** from the Annual Reviews home page at **http://www.annualreviews.org.**) As noted by Curzon, there has been considerable scientific disagreement about the cause of the sound. Although "booming" is not one of the adjectives used by Curzon, it is the term most commonly used in the current scientific literature (Bagnold 1941, Humphries 1966, Nori et al. 1997, Sholtz et al. 1997). **Figure 1*a*** shows a booming dune located in southern California.

The earliest citation by Curzon is circa 800 A.D. from China, with later references to Marco Polo in the Gobi Desert (1295), the Afghan Emperor Baber outside Kabul (1519), and Charles Darwin in Chile (1835), as well as other reports from the Arabian Peninsula, the Western Sahara, the Libyan Desert, South Africa, the Hawaiian Islands, and North America. Other explorers or researchers produced documentation about many of the locations described by Curzon, including the extensive summary of locations provided by Lindsay et al. (1976). Carus-Wilson wrote in an 1890 letter to *Natur*e that "only observers are rare—not the sands," and now up to 40 locations with booming sand dunes have been identified. **Table 1** summarizes the locations of the booming sand dunes, the approximate sizes of the dunes, and the sources of the references.

In addition to identifying desert locations, Curzon's accounts provide an accurate description of the circumstances in which the sounds are produced, a report of the nature and duration of the sounds, and some conjuncture about the scientific basis for the sounds. Although there were conflicting stories about the types of dunes that emit sound, Curzon concluded that although the dunes are of varying height and dimension (as demonstrated by the listing in **Table 1**), the sound was produced by avalanching sand along the face of the dune inclined at approximately 31° from the horizontal: sand's angle of repose. Curzon also noted that the phenomenon became more likely

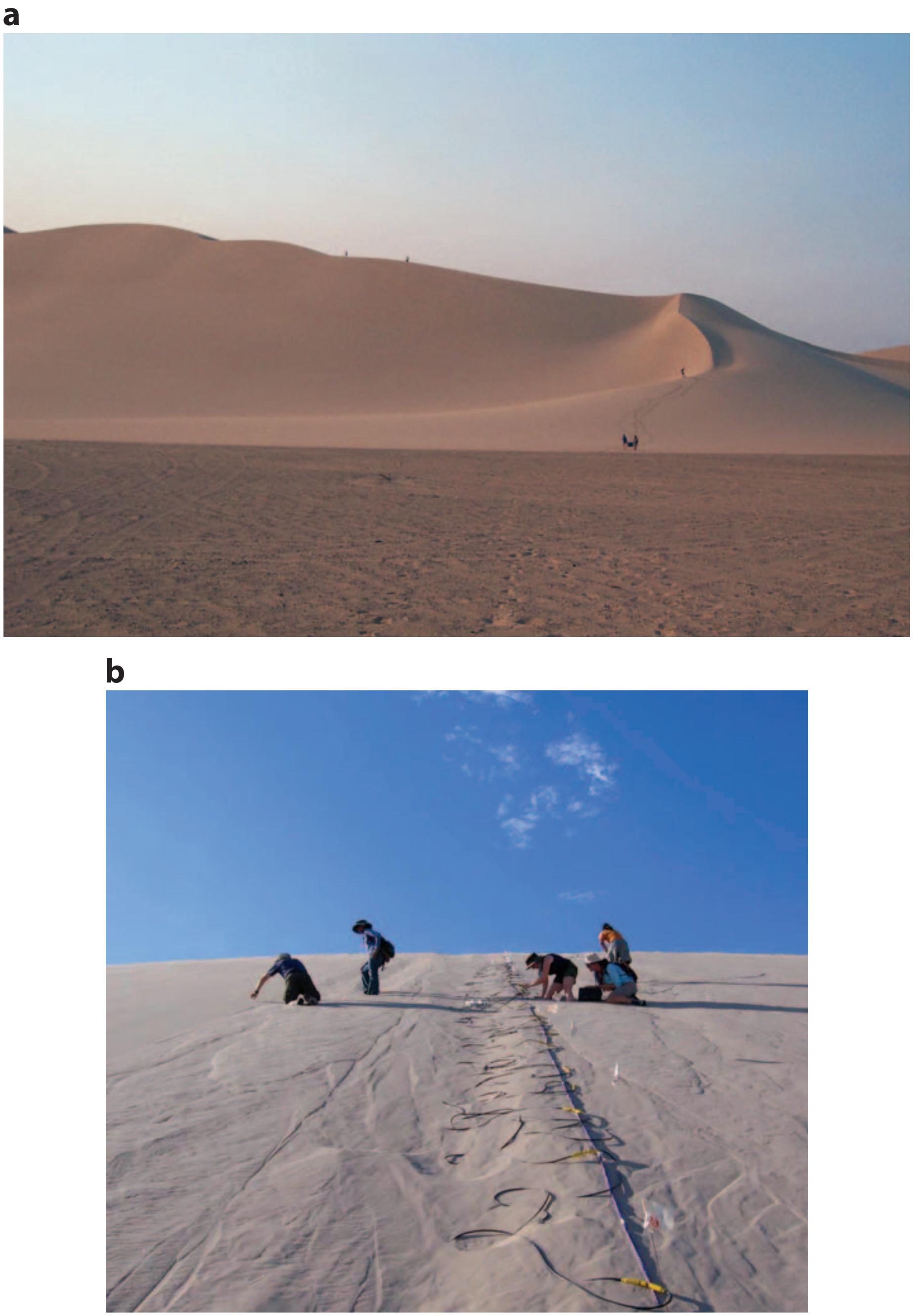

**Figure 1**

(*a*) The ascent of the booming sand dune at Dumont Dunes in the arid Mojave Desert. (*b*) The setup of the geophone array on the slip face of the dune.

Table 1 Collection of the world's known booming sand dunes, subdivided into the regions Asia, Middle Eastern peninsula, Africa, and North and South America

| Name and location of booming dunes[a] | Latitude, longitude[b] | Type: size field (width × breadth), elevation loss[c] | Source[d] |
|---|---|---|---|
| **Asia** | | | |
| Ming Sha San, near Dunhuang, Gansu province, China | 40° 05′ 00°N, 94° 40′ 29°E | Star dune field in the Taklamakan sand desert: 20 × 20 km, 300-m drop | A, B, K, Internet |
| Golden Bell of Resonant Sand, near Shapotou, Ningxia province, China | 37° 28′ 10°N, 105° 01′ 23°E | Isolated dune on the edge of the Tengger sand desert: 0.5 × 0.5 km, 100-m drop | Internet |
| Xiangshawan (Resonant Sand Gorge), near Baotou, Inner Mongolia, China | 40° 14′ 39″ N, 109° 56′ 23″ E | Sand drift on the edge of the Kubuqi sand desert: 500-m wide, 50-m drop | Internet |
| Southeast edge of the Badain-Jaran Desert, China | 39° 37′ N, 102° 29′ E | Extended star dune field: 50 × 50 km, up to 200-m drop | G |
| Echoing-Sand Dune of Hami, near Balikun, Xinjiang province, China | 43° 24′ 59″ N, 93° 42′ 06″ E | Linear ridge in a dune field: 3 × 5 km, 100-m drop | Internet |
| Ming Sha near Mori, Xinjiang province, China | 44° 36′ 17″ N, 91° 38′ 19″ E | Star dune field: 5 × 10 km, 80-m drop | G |
| Jeminay sand desert, Xinjiang province, China | 47° 47′ N, 86° 23′ E | Linear dune field: 15 × 8 km, up to 200-m drop | G |
| Khongor Sand Dune, near Khongoryn Els, Mongolia | 43° 49′ 13″ N, 102° 07′ 24″ E | Star dune field: 25 × 5 km, 200-m drop | Internet |
| Akkum-Kalkan, Altyn-Emel National Park, Kazakhstan | 43° 51′ 43″ N, 78° 34′ 12″ E | Barchan dune field: 3 × 1 km, 100-m drop | A, Internet |
| Reg-I-Ruwan, near Kabul, Afghanistan | 35° 03′ 47″ N, 69° 22′ 07″ E | Mountain with sand drift: 100-m wide, 100-m drop | A |
| Rig-I-Riwan, near the Kalah-I-Kah mountain range, Afghanistan | 32° 11′ 20″ N, 61° 20′ 54″ E | Mountain with sand drift: 600-m wide, 200-m drop | A, R |
| **Middle Eastern peninsula** | | | |
| Singing dunes near Umm Said, Qatar | 25° 02′ 19″ N, 51° 24′ 25″ E | Barchan dune field: 15 × 30 km, 20-m drop | B, Internet |
| Dunes south of the Liwa Oasis, UAE | 23° 08′ N, 53° 46′ E | Complex dune field in the Rub' Al Khali Desert: 1200 × 650 km, up to 120-m drop | U, Internet |
| Sharqiya (Wahiba) Sands, near Al Ashkharah, Oman | 22° 21′ N, 58° 49′ E | Linear dune field: 70 × 100 km, up to 70-m drop | Internet |
| Sand of Yadila, Uruq Adh Dhahiya region, Oman | 18° 47′ N, 52° 15′ E | Extended complex dune field: 300 × 150 km, up to 100-m drop | M |
| Uruq Subay (Arq-al-Subai), Saudi Arabia | 22° 14′ N, 43° 04′ E | Linear dune field: 30 × 80 km, up to 100-m drop | A |
| Sand near Khanug, Saudi Arabia | 24° 22′ 33″ N, 43° 42′ 33″ E | Mountain with sand drift: 100-m wide, 60-m drop | A |
| Jabal-al-Thabul (Mount of Drums), near Badr, Saudi Arabia | 23° 48′ 25″ N, 38° 45′ 57″ E | Star dune field: 1.5 × 6 km, 180-m drop | A, W |
| El-Howayria of Madain Saleh (also known as Al-Hijr), Saudi Arabia | 26° 46′ N, 37° 51′ E | Mountain with sand drifts: up to 800-m wide, up to 40-m drop | A, L, X |
| Goz Et-Hannan (Moaning Sand-heap) at Wadi Ratiyah, Saudi Arabia | 28° 04′ 27″ N, 35° 25′ 45″ E | Sand drift shaped as a pyramid, 300 × 400 m, 15-m drop | A, S |

(*Continued*)

Table 1 (*Continued*)

| Name and location of booming dunes[a] | Latitude, longitude[b] | Type: size field (width × breadth), elevation loss[c] | Source[d] |
|---|---|---|---|
| **Africa** | | | |
| Jebel Nakus, near Tor, Sinai Desert, Egypt | 28° 21′ 14″ N, 33° 30′ 57″ E | Mountain with sand drift: 500-m wide, 70-m drop | A |
| Umm Shumar, Sinai Desert, Egypt | 28° 17′ 28″ N, 33° 51′ 03″ E | Mountain with sand drift: 400-m wide, 50-m drop | A |
| Dunes near the Dakhla Oasis, Egypt | 25° 12′ 42″N, 28° 47′ 03″ E | Barchan dune field in two belts: 5-km long, 400-m wide, 15-m drop | A, N |
| Gilf Kebir Desert, near the Nubian Sandstone Platform, Egypt | 23°N, 26°E (C), 26° 30′ N, 27° 10′ E (O) | Linear dune field: 350 × 250 km, up to 50-m drop | C, O |
| Gege Kourini, near the Korizo Pass, Chad | 22° 33′ 08″ N, 15° 23′ 37″ E | Linear dune in a barchan dune field: 1.2-km long, 90-m drop | I |
| Elb-Ben-Abbas, Iguidi Desert, Algeria | 26° 05′ 10″ N, 6° 17′ 46″ W | Longitudinal dune field: 300 × 30 km, 50-m drop | A, P |
| Ghourd el Hamra, near Tarfaya, Morocco | 28° 01′ 29″ N, 12° 10′ 40″ W | Barchan dune: 500 × 500 m, 25-m drop | E, F |
| Dunes near Azoueiga, Erg Amatlich, Mauritania | 19° 52′ N, 13° 33′ W | Large sand sea: 75 × 10 km | Internet |
| Dunes near Shingati, Mauritania | 20° 27′ N, 12° 22′ W | Large sand sea: 40 × 15 km | Internet |
| Skeleton Coast Park, Namibia | 19° 07′ S, 12° 36′ E | Large sand sea: 120 × 20 km | Internet |
| Sossusvlei, Namib-Naukluft Park, Namibia | 24° 40′ 19″ S, 15° 31′ 13″ E | Star dune field in a longitudinal desert: 275 × 100 km, 340-m drop | A |
| Witsands, Kalahari Dunes, South Africa | 28° 34′ 31″ S, 22° 27′ 39″ E | Star dune field: 5.5 × 1.5 km, 40-m high | H |
| **North and South America** | | | |
| Great Sand Dunes National Park, Colorado, USA | 37° 44′ 54″ N, 105° 31′ 59″ W | Star dune field: 12 × 9 km, 200-m drop | D |
| Sand Mountain, Nevada, USA | 39° 18′ 59″ N, 118° 23′ 59″ W | Linear ridge: 1 × 2.5 km, 110-m drop | B, T, AA |
| Crescent Dunes, Nevada, USA | 38° 13′ 47″ N, 117° 19′ 45″ W | Star dune field, 3 × 1.5 km, 70-m drop | AA |
| Eureka Dunes, Death Valley National Park, California, USA | 37° 06′ 04″ N, 117° 40′ 16″ W | Linear ridge with star dunes superimposed: 1.5 × 5 km, 200-m drop | D, Y |
| Panamint Dunes, Death Valley National Park, California, USA | 36° 27′ 38″ N, 117° 27′ 21″ W | Star dune: 1 × 1 km, 70-m drop | Z, AA |
| Big Dune, Nevada, USA | 36° 38′ 52″ N, 116° 34′ 48″ W | Star dune field: 1.5 × 2.5 km, 80-m drop | D, Y, AA |
| Dumont Dunes, Mojave Desert, California, USA | 35° 40′ 43″ N, 116° 13′ 54″ W | Star dune field: 2 × 4 km, 120-m drop | D |
| Kelso Dunes, Mojave National Park, California, USA | 34° 53′ 54″ N, 115° 44′ 00″ W | Linear ridge with star dunes superimposed: 4 × 8 km, 150-m drop | B, D, Y |

(*Continued*)

**Table 1 (*Continued*)**

| Name and location of booming dunes[a] | Latitude, longitude[b] | Type: size field (width × breadth), elevation loss[c] | Source[d] |
|---|---|---|---|
| Cerro Unita (El Bramador) in the Tarapaca Desert, Chile[e] | 19° 57′ 04″ S, 69° 37′ 58″ W | Mountain with sand drift: 100-m wide, 15-m drop | A, B, Q |
| El Medanoso, Mar de Dunas, Chile | 27° 07′ 11″ S, 70° 07′ 56″ W | Star dune field: 4 × 6 km, 450-m drop | E, Internet |
| El Punto de Diabolo (El Bramador), near Copiapo, Chile | 27° 18′ 58″ S, 70° 25′ 06″ W | Mountain with sand drift: 100-m wide, 70-m drop | A, B, E |

[a]Certain locations previously mentioned in other overviews have been omitted. Some locations referenced once in older travel literature cannot be located: Wadi Hamadi dunes (A); dunes near the city of Jahura (A); dunes in the An Nafud Desert near El-Hyza (A,L) in Saudi Arabia; the Ojrat Ramadan sand drift near Wadi Werdan (A), Egypt. The sand drift Es-Sadat in western Beirut (A), Lebanon, is now a residential area and no evidence of a drift remains. The back beach dunes of Kaua'i (A, B, J, V) and Ni'ihau (A, J, V) in Hawaii, USA, and the Mountain of the Bell in Baja California (B, J), Mexico, are low drifts (~10 m) where only short "barking" sound can be generated.
[b]Latitudes and longitudes with degrees and minutes indicate a general area, whereas locations with degrees, minutes, and seconds pinpoint the highest crest of a given booming dune.
[c]The elevation loss is calculated from the highest peak in the dune system to the desert floor.
[d]Several references to booming dunes appear on the Internet (i.e., on travel Web pages) without a proper scientific reference.
[e]Bollaert (1851) described that the Cerrito de Huara is situated 6 miles WNW from Pozo de Ramirez on the road from Tarapaca to Guantajaya in a desert plain. The Cerro Guara (20° 02′ 13″ S, 69° 46′ 32″ W) is actually 4 miles WNW from Pozo de Ramirez, but it is completely devoid of sand and borders a mountain chain. The Cerro Unita, situated 8.5 miles NNE from Pozo de Ramirez, is a lone hill in the desert plain and has sand gullies. It is possible that Bollaert mislaid El Bramador.
Sources: A: Curzon (1923), B: Lindsay et al. (1976), C: Bagnold (1941), D: Vriend et al. (2007), E: Douady et al. (2006), F: Andreotti (2004), G: Miwa & Ozaki (1995), H: Lewis (1936), I: Humphries (1966), J: Bolton (1890), K: Polo (1295), L: Doughty (1888), M: Thomas (1932), N: Harding King (1912), O: Shaw (1936), P: Lenz (1912), Q: Bollaert (1851), R: Yate (1897), S: Burton (1879), T: Holliday (1976), U: Hagey & Hope (2008), V: Clark (1990), W: Peters (1996), X: Hoye (1965), Y: Haff (1979), Z: personal communication with E.C. Koos, AA: Trexler & Melhorn (1986).



**Crescentic/transverse/barchan dune:** dune shaped like a half moon, whose migration is perpendicular to the wind with the tails leading the migration

**Linear/longitudinal/seif dune:** a long, extended, narrow dune, whose migration is parallel to the wind

**Star dune:** dune shaped like a star, with several arms originating from the crest; fairly stationary because of changing wind regimes

**Compound dune:** dune consisting of multiple dunes of the same type, superimposed

when the sand was very dry. Many of the desert explorers found that the sound was produced after they walked or rode along the tops of the dunes, initiating an avalanching of sand. However, the sound could also be initiated by the wind: "Where the music is heard in circumstances which admit of no mechanical or artificial causation, the wind is capable by itself of playing upon the chords, and producing the vibration that is necessary for the manufacture of the sound" (Curzon 1923).

Curzon's chapter also includes a section about musical beach sands that emit a high-pitched sound when walked upon or struck. As suggested in later studies, the singing or booming sand dunes differ from the beach sands. Curzon recognized that the physical conditions associated with the beach sounds are quite different from those associated with the booming sounds and that the former phenomena are on "a far smaller and quite inconsiderable scale." He noted that the noises generated at the local scale are "not caused by the dislodgement off comparatively large masses of sand, striking against each other, and humming or booming as they collide and fall." Generally, squeaking beach sounds are found to have frequencies of ~1000 Hz—several orders of magnitude higher than the booming sounds (Humphries 1966, Ridgway & Scotton 1973, Takahara 1973, Miwa et al. 1995).

Desert travelers described the sounds using a variety of analogies, including sounds emanating from an organ pipe's bass, a kettle drum, a didgeridoo, and a clash of arms. Curzon's astute observations noted that a single comparison might not suffice because the sound varies with time: "First there is a faintly murmurous or wailing or moaning sound, compared sometimes to the strain of an Aeolian harp . . . Then as the vibration increases and the sound swells, we have the comparison sometimes to an organ, sometimes to the deep clangor of a bell . . . Finally, we have the rumble of distant thunder when the soil is in violent oscillation." Curzon's observations are supported by recent measurements of the acoustic and seismic signals produced by the dune. In addition to these observations, Curzon wrote that the sound could be heard at distances of up to one mile and that the sound could last for several minutes. Observers also feel the vibratory motions of the sand, even when standing in a region removed from the avalanching sand.

**Complex dune:** dune consisting of multiple dune types

**Fines:** smallest fractions of a particle size distribution

**Bed:** assembly of grains in a confined geometry

In the 1930s, the work by Lewis (1936) focused on the roaring sands in the southeastern corner of the Kalahari Desert. Like Curzon, Lewis noted that the sounds were different depending on the excitation process. Specifically, a "roar" results from short movements of the sand by a hand or foot, or by "sliding down the slope in slow jerks on one's 'sit-upon,'" and a "hum" results when the sand continuously flows down the slope. A roar precedes a hum. Using a series of pitch pipes, Lewis provided the first estimates of the frequencies of the sound. When Lewis inserted a plank a few centimeters into the sand and moved it at a fixed speed, the sand roared at different notes. At 15 cm $s^{-1}$, the roar was close to a low C (132 Hz); at 60 cm $s^{-1}$, the roar was higher by approximately an octave; at more than 1 m $s^{-1}$, the roar turned into a "swish." During avalanching (the sand surface speed was estimated at 15 cm $s^{-1}$), the "hum was much more regular than a roar and might be likened to the noise made by an aeroplane at a distance in steady flight" (Lewis 1936). Here he observed that the dominant note was between a G (198 Hz) and a D (297 Hz)—not far from middle C on a piano (264 Hz).

In addition to the frequency measurements, Lewis also made extensive measurements of the sand using a series of sieves. He found that the sand taken from dunes that roared or hummed had a narrower size distribution than sand obtained from other locations within the dune field. Most notably, the roaring dune contained few fines (whose average grain diameter is less than 0.1 mm), which he noted "is of great significance in considering hygroscopic moisture." According to the distribution provided by Lewis, the roaring sand had an average grain size and standard deviation of $0.22 \pm 0.07$ mm, whereas the size distribution for sand samples from many different dunes was $0.175 \pm 0.115$ mm.

## THE EARLY THEORIES

Curzon's assessment of the "scientific uncertainty" of the booming sound resulted from conflicting theories. In 1891, Carus-Wilson attributed the sound to friction between grains and noted that the sand grains were clean, rounded, polished and free of fines, uniform in size, and free to dilate when sheared (Carus-Wilson 1891). The sound emitted by two rubbing grains might be inaudible, but an audible note may result from the rubbing together of millions of grains. This explanation was dismissed by Bolton & Julien (1888), who attributed the sound to "films of air or gases condensed upon the surface of the sand-grains during gradual evaporation." Curzon wrote that Bolton & Julien had never published experimental proof of their conjecture, and he noted that their explanation was not generally accepted.

In 1909, Poynting & Thomson published in their textbook of physics an explanation that was linked to Reynolds's theory on the dilatancy of sand (Reynolds 1885). Poynting & Thomson (1909) suggested that the sand grains be considered spheres of equal size. At rest, the bed has a minimum volume. When sheared, the grains pass through many successive volume minima. "If we can suppose that the time occupied in passing from one minimum to the next is constant, a musical note should issue."

The explanations by Carus-Wilson (1891), Poynting & Thomson (1909), and Curzon (1923) all describe a process of rubbing grains. In his 1940s classic text entitled *The Physics of Blown Sand and Desert Dunes*, Bagnold (1941) provided a simple mathematical model of the physical processes that was consistent with these earlier explanations. Using an analogy of a finger running over the corrugations of a book, Bagnold defined the frequency $f$ in terms of the speed $v$ associated with the motion of the finger (or the sand) and the grain size $d$ associated with the spacing between the corrugation. He speculated that the frequency was directly proportional to the speed and inversely proportional to the grain diameter:

**Microphone:** sensor to measure acoustic vibrations in the air

**Geophone:** sensor to measure seismic vibrations in the ground

$$f \sim v/d. \tag{1}$$

He also noted that the speed associated with the mean motion of the sand is less than the speed at the surface $V$. Using $v = Vh/H$, where $h/H$ is the ratio of the depth of maximum vibration of the grains to the depth of the sheared layer, Bagnold concluded that

$$f = hV/Hd. \tag{2}$$

To determine the value of the ratio $h/H$, Bagnold used Lewis's reported measurements for avalanching sand and his own observations from the Gilf Kebir plateau, which were based on estimates: "I had no means of exact measurements, but I put the note heard as somewhere around 132 cycles/sec." He estimated the steady speed of flow of the natural avalanche as 12 cm $s^{-1}$ and the grain size as 0.35 mm. From these two data sets, the value of $h/H$ was estimated as 0.35. Although Bagnold had noted that whistling sounds differed fundamentally from booming sounds, he included a third data point in his analysis from the whistling sands from North Wales, which emitted a squeak at approximately 1000 Hz when the 0.3-mm sand was struck at a speed of 9 cm $s^{-1}$. This additional data point further supported his analysis.

Approximately 20 years later, Bagnold (1966) refined his predictions by arguing that the sand must dilate to be sheared—similar to what was argued by Poynting & Thomson (1909)—and that the amount of dilation depended on the linear concentration ($\lambda$). The free separation between particles could then be calculated from $d/\lambda$. Using this free-separation distance, Bagnold computed the frequency simply from the inverse of the rise and fall time of a particle acted on by gravity over a distance $d/\lambda$,

$$f = (g\lambda/8d)^{1/2}, \tag{3}$$

where $g$ is the gravitational constant. For sheared sand, Bagnold used a solid fraction of 0.51 and a maximum solid fraction of 0.644, resulting in a value of $\lambda = 12.4$. Using the data from Lewis for the avalanching sand (0.2 mm), Bagnold computed a frequency of 275 Hz, which he noted was comparable with the frequency that Lewis found by using a pitch pipe.

## MEASUREMENTS OF THE FREQUENCY AND GRAIN DIAMETER

More recently, researchers have measured the frequency of the booming sound and found it to be significantly lower than the values noted by Bagnold or Lewis. Humphries (1966) published a paper on the booming sand of Korizo, Sahara (average grain diameter of $0.26 \pm 0.066$ mm) and noted a booming frequency between 50 and 100 Hz and a beating frequency of ~1 Hz. In the mid-1970s, Criswell et al. (1975) and Lindsay et al. (1976) measured the frequencies at Sand Mountain, Nevada. In these studies, the researchers used both an air microphone and a geophone planted in the sand to pick up ground vibrations. They concluded that the acoustic emissions overlay the seismic peaks with frequencies between 80 and 100 Hz; the measurements also showed first-order harmonics. In addition, the papers presented detailed spectral analyses showing peaks at 65 Hz of short bursts of sound (less than 1 s in duration) triggered by shoveling sand near the dune crest. The researchers sampled the sand from the dune base to the top to determine the distribution of grain diameters and obtained average grain diameters from 0.26 mm to 0.38 mm (Lindsay et al. 1976). The average diameter of the booming sand was $0.31 \pm 0.07$ mm, and the sand was well sorted.

Several years later, Haff (1979) performed similar studies at Kelso Dunes in the Mojave Natural Preserve, Calif., in which he recorded sounds in the field using a microphone and spectrally

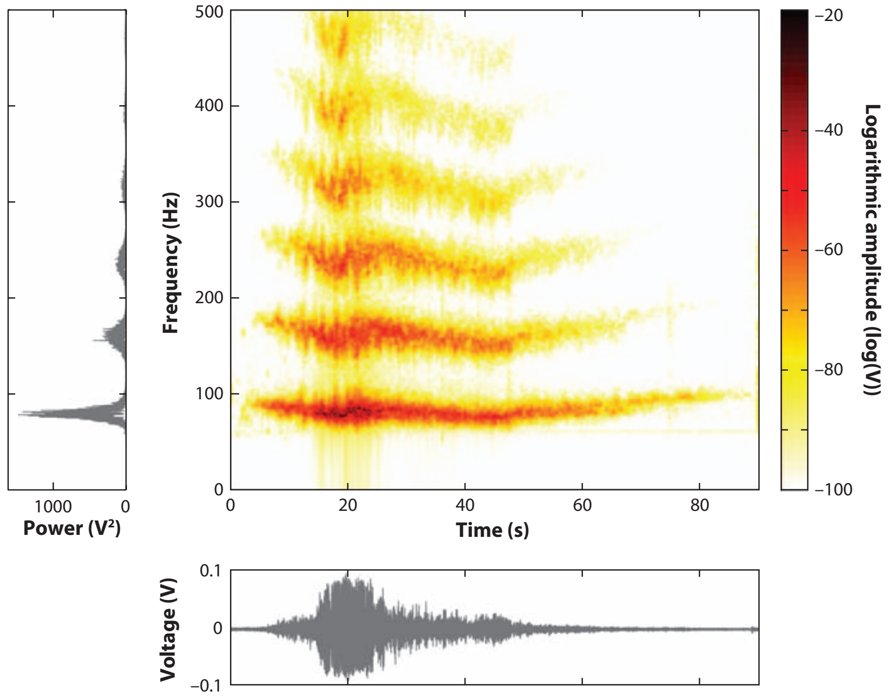


**Figure 2**

Microphone recording of the booming sound at Eureka Dunes on October 27, 2007.

analyzed the sound. From one set of data, he found a spectral peak at 92.8 Hz with a width of 4 Hz at half the maximum amplitude; however, he noted that in a subsequent recording the frequency was higher at 96.8 ± 4 Hz (average grain diameter of 0.24 mm). More recently, Andreotti (2004) investigated barchan dunes in Tarfaya, Morocco, and recorded the frequency of the booming with an accelerometer and an air microphone. The author noted that the measured frequency of 100 ± 5 Hz did not depend on the size of the dune or the localization of the avalanche. The data presented, however, included only a small sample of experimental booming data (the measurement occurred over 0.1 s). The average grain diameter was reported as 0.18 mm; the standard deviation was not given. The study by Douady et al. (2006) also reports measurements made at Tarfaya ($d = 0.160$ mm, $f = 105 \pm 10$ Hz) and at two sites near Copiapo in Chile ($d = 0.210$ mm, $f = 90 \pm 10$ Hz; $d = 0.270$ mm, $f = 75 \pm 10$ Hz); however, the acoustic signal, the length of the recording, and the measurement technique were not presented.

At Caltech, researchers measured the booming frequencies at four locations in the southwestern United States: Big Dune near Beatty, Nev.; Eureka Dunes in Death Valley National Park, Calif.; Dumont Dunes just south of Death Valley; and Kelso Dunes (Vriend et al. 2007). At each of these locations, the sustained booming sound (or the "hum" as described by Lewis) was measured with either a microphone or a geophone planted near the avalanching sand. All recordings were made over many seconds. **Figure 2** shows a signal from Eureka Dunes recorded with an air microphone, along with the spectral distribution as a function of time and the average power spectra. The beginning of the recording was synchronized with the start of the avalanching of sand. As noted by earlier researchers, the sound builds over the first few seconds. After approximately 10 seconds, there is a dominant frequency of ~90 Hz; as the signal strength builds, the frequency drops

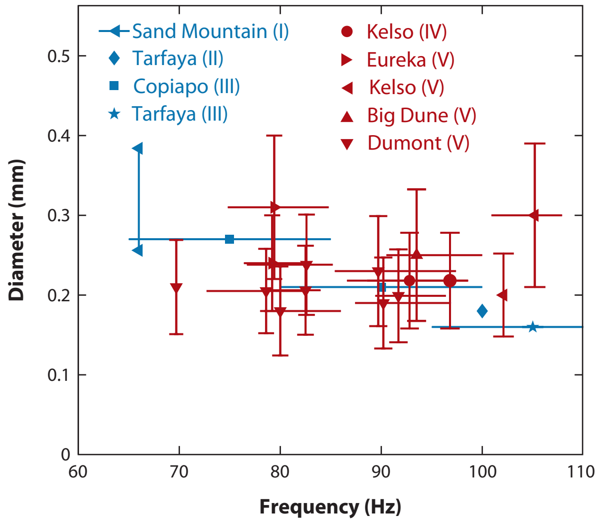


**Figure 3**

Sustained booming frequency $f$ as a function of grain diameter $d$. Data are from I: Lindsay et al. (1976), II: Andreotti (2004), III: Douady et al. (2006), IV: Haff (1986), V: Vriend et al. (2007). The data points indicated by a blue marker suggested in Douady et al. (2006) a relation between the frequency and diameter. The data point from Lindsay et al. was obtained by shoveling sand and does not result from a sustained boom. When reported, the bar for diameter indicates the standard deviation; the bar for frequency indicates the frequency width at half amplitude.

to 80 Hz for the next 40 seconds. The acoustic signal also contains several harmonics, which are especially evident when the signal strength is strongest. The entire record shows that the dominant frequency is 79 ± 4 Hz. In the visits to the dunes, sand samples were also taken. The sand was single grained and the size distribution followed a log-normal distribution, except at the smallest and largest distributions, in which there were fewer fine and coarse particles.

**Figure 3** presents the frequency and average grain size from the locations investigated by Caltech, along with the measurements of Lindsay et al. (1976), Haff (1979), Andreotti (2004), and Douady et al. (2006). The pitch-pipe measurements by Lewis and the estimates by Bagnold are not included. At all locations, the measured frequencies ranged from 70 to 110 Hz, and the average grain diameter fell within a narrow size distribution between 0.18 and 0.32 mm. The repeated measurements were taken either on different visits or from measurements at different areas within the dune field (Vriend et al. 2007). Although earlier studies and more recent studies (as described below) have assumed that the booming frequency depends on the grain diameter, **Figure 3** does not show this dependency.

## RECENT STUDIES RELATING FREQUENCY AND GRAIN MOTION

In the work by Andreotti (2004), the author concludes that avalanching of sand excites elastic waves in the sand dune. These elastic waves synchronize the individual collisions of the grains inside the avalanche, creating what he termed a wave-particle mode locking. The waves are localized to the surface, like Rayleigh surface waves, and are nonlinear and dispersive with a wavelength of 42 cm and a phase speed of 40 ± 10 m s$^{-1}$. The grain collision rate depends on the local shear rate within the flowing region, which the authors measured by imaging the grains through a transparent plate. From the velocity measurements, the shear rate near the free surface was computed as 100 s$^{-1}$, approximately the same value found for the booming frequency. Hence, the author concluded that the shear rate and the booming frequency are "intimately related." The shear rate Γ, and hence the booming frequency, was correlated to the average diameter of the sand grains as

$$\Gamma = 0.4(g/d)^{1/2} \approx f. \tag{4}$$

The scaling factor was verified by the data points $d = 0.180$ mm and $f = 100$ Hz as measured by the author and $d = 0.38$ mm and $f = 66$ Hz as published by Lindsay et al. (1976) from the shoveling experiments. The average grain diameter of 0.38 mm was the largest average grain diameter from the 25 samples obtained by Lindsay et al. Equation 4 has the same dependency on grain diameter as suggested by Bagnold (1966); the multiplicative factor is 30% of the earlier value.

In a later paper by Bonneau et al. (2007), the authors present additional analyses on the coupling of the surface waves and the grain motion along with data on the dispersion relations for these low-speed waves. Because of Hertzian contact between the grains, the wave speed increases with depth, and the elastic waves are refracted back to the surface. The nonlinear Hertzian contact between grains in the elastic skeleton and the dispersive behavior of the elastic wave produce a discrete number of modes in the two planes perpendicular to the free surface. The vanishing confining pressure at the surface and the propagation speed that increases with depth result in curved propagation rays. Hence, the booming threshold can be explained as a waveguide cutoff frequency below which no sound can propagate. Although the explanation was refined from the 2004 study, the authors did not provide any new theoretical basis for the booming frequency.

The analytical expression (Equation 4) found by Andreotti (2004) was later supported by the data from Chile presented by Douady et al. (2006). However, these authors suggest an alternative mechanism in which the acoustic excitation results from the synchronization of the sand grains. They used laboratory experiments, as described in the next section, to support their argument.

## LABORATORY STUDIES USING BOOMING SAND

In addition to experiments in the field, several researchers have conducted laboratory-scale experiments on sands taken from booming dunes. In these cases, the researchers usually recognized that the sand needed to be well sorted, free from fines, rounded, and dry. The earliest of these laboratory experiments involved the compression of sand grains with a mortar or other object (Carus-Wilson 1888, Bagnold 1941). Haff (1979) measured the squeak resulting from compression at frequencies of ~1000 Hz. In controlled experiments involving a penetrating rod, Hidaka et al. (1988) measured frequencies from 250 to 355 Hz depending on the penetration speed. The authors attributed the sound to rupture layers forming periodically within the bed.

In his 1936 paper, Lewis described laboratory experiments involving Kalahari Desert sand; the roar could be emitted when the sand flowed through a funnel or when it was shaken in a jar. As was found in his plank-in-the-dune studies, the speed at which the sand moved affected the quality of the roar. The sand lost its ability to roar if left in an environment in which it could absorb moisture, and the roaring could be restored by heating the sand to remove the moisture. "By placing the heated sands into airtight glass fruit-preserving jars to about 1/2 full we could produce a violent roar by rapid tilting of the jar, and we could preserve that roar indefinitely so long as there was no possibility of the damp outside air entering the jar," Lewis wrote. Lewis also realized that he could produce the same roar using sands from different regions and even common table salt. These other granular materials had to be dried and had to have a specified distribution of grain sizes. Subsequently, Haff (1979, 1986) and Leach & Rubin (1993) performed similar jar experiments and reported frequencies of several hundred Hertz. Brantley et al. (2003) described the sound as a "burp" and reported a broad spectral peak from 150 to 300 Hz without harmonics. Patitsas (2003) measured similar power spectra for bursts of sound emitted by sand sheared in a small rotating drum.

**Refraction survey:** geophysical technique using Snell's law to connect the angle of incidence of a slow medium with the angle of refraction of a fast medium

Douady et al. (2006) performed a laboratory experiment involving a blade rotating at a fixed speed in an annular container filled with sand. These experiments led the authors to suggest that the frequency is controlled by the relative motion of the sand grains, which could be varied by changing the depth and speed of the blade. The authors indicated that the emitted frequency was roughly 10 times the mean shear rate (determined from the blade speed divided by the sand depth), which differs from the dune relationship in Equation 4 found by Andreotti (2004). The characteristics of the frequency spectra were not provided. The authors conclude that the sound comes from the synchronized motion of the grains and that "the dune is not needed for sound emission."

As described by Lewis (1936), a dune's velocity-dependent roar is distinct from its low-frequency sustained hum or boom. Similar distinctions have also been made by other researchers including Curzon (1923), Haff (1979, 1986), Nori et al. (1997), Sholtz et al. (1997), and Brantley et al. (2003). Although these small-scale experiments are valuable in explaining the initiation process of the booming phenomena, they do not show the same acoustical characteristics of the sustained booming sound that have been generated in the field.



## BOOMING AND RESONANCE EFFECTS ASSOCIATED WITH BODY WAVES

Throughout the literature on booming dunes, the sounds have been compared with a stringed instrument such as a bass, cello, or violin. In these instruments, the bowing of the strings inputs energy into the system, but the string vibration provides little sound. The strings, however, are attached to the instrument's bridge and body, which serve to convert the string's vibrational energy into sound. The body and the air within the instrument vibrate at certain resonant frequencies. The size of the instrument determines the range of the sounds; the lowest notes are produced by the bass, the largest of the stringed instruments.

**Figure 4** presents the spectral distribution of four seconds of sound emitted from Dumont Dunes as compared with an F note (86.4 Hz) produced by a cello. The sound generated by the dune is noisier; however, the comparison between the two signals suggests that the booming event is a resonance and that the range of frequencies may also be set by a characteristic length associated with the dune. The observations by Humphries (1966) suggested a similar line of thinking: "The enormous volume of the sound produced suggests that in some way a natural resonator must be involved in magnifying the sound. The free movement of the surface layers suggests that the stationary sand beneath may act as a sounding board."

The recent work at Caltech has focused on modeling the dune as a waveguide, in which the resonance results from the body waves (not the surface waves as suggested by Andreotti 2004) and depends on the wave speeds and the size of the waveguide. The wave speeds were measured using a seismic refraction technique (see **Figure 1*b***), involving the installation of an array of geophones (up to 96) spaced 1 m apart beginning from the dune's crest and following a line down its slip face (Reynolds 1997). The geophones recorded the wave propagation that was initiated by the striking of a plate installed at different locations along the dune.

As described in Vriend et al. (2007), the seismic records show that body waves travel at a speed of approximately 200 m $s^{-1}$ near the surface of the dune. However, the wave speed increases with depth, and the dune has a layered structure, which is common in geological materials (Reynolds 1997). The seismic velocity of the surficial layer also increases from the dune crest to the base of the dune; this velocity depends on the degree of compaction of the sand, which differs between

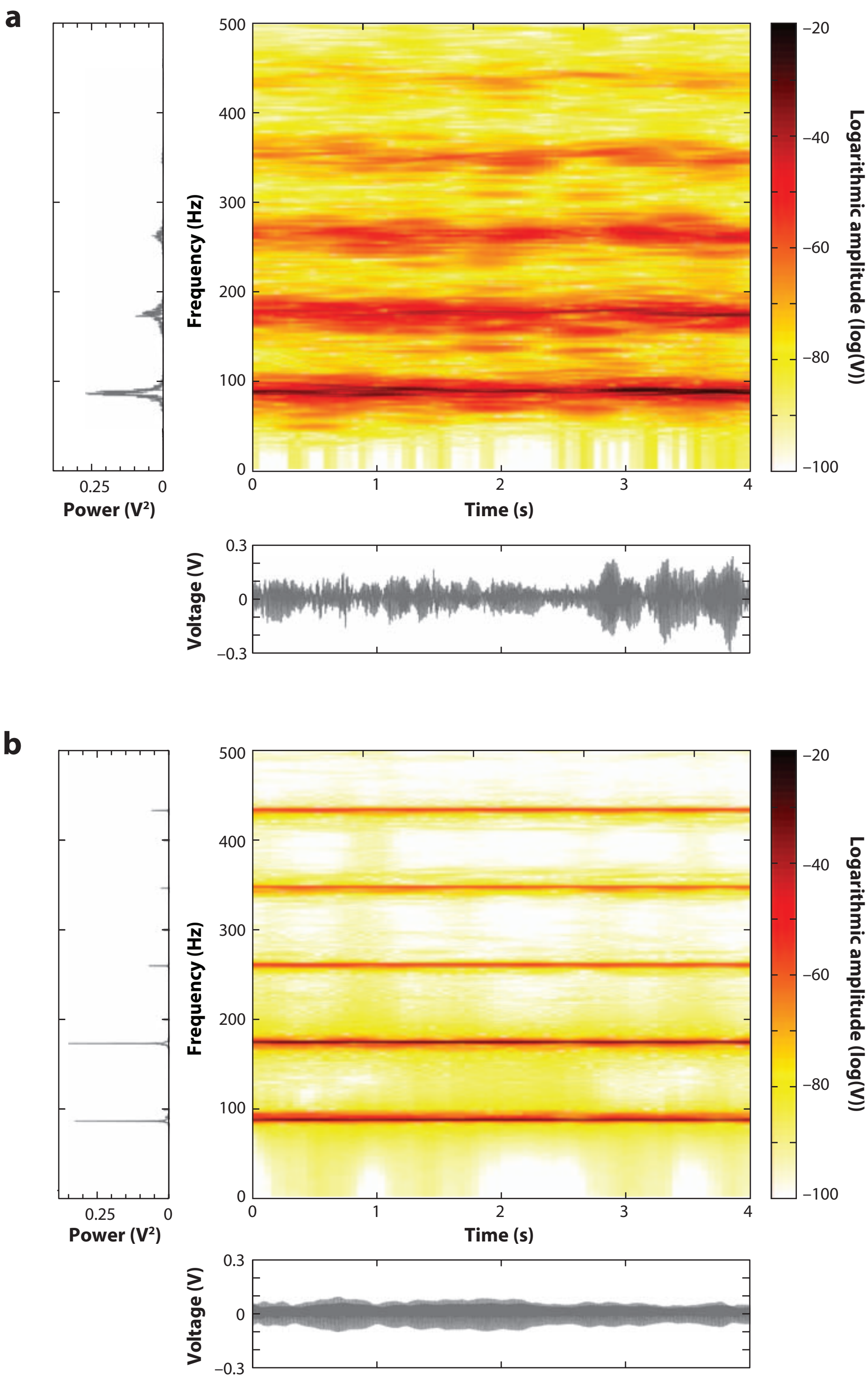


**Figure 4**

Comparison of the spectral distribution obtained using 4 seconds of (*a*) a microphone recording from the booming dune at Dumont, and (*b*) a recording of the F2 note from a cello.

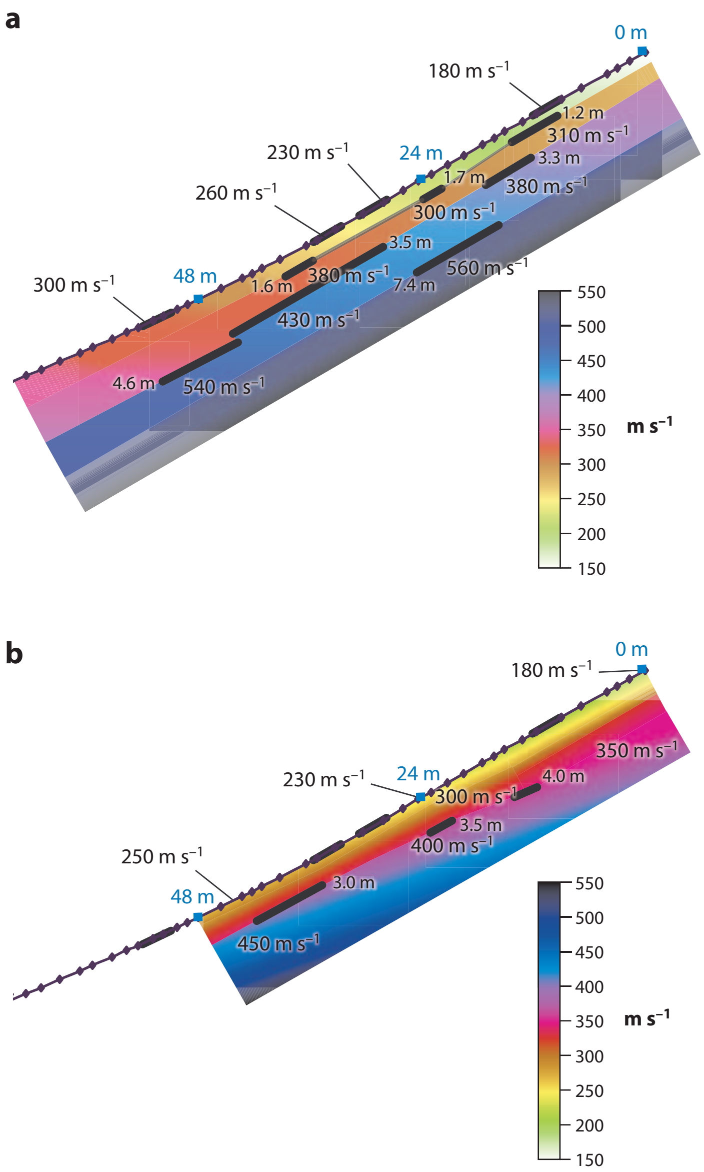


**Figure 5**

Distribution of seismic speeds at Dumont Dunes of the upper 48 m on the leeward face for (*a*) the slip face in the summer (September 12, 2006), showing a strongly layered structure, and (*b*) the slip face in the winter (December 5, 2006), displaying a diffuse increase in velocity with depth.

grainflow or grainfall areas. **Figure 5** shows an example of the distribution of seismic velocities with depth and distance from the crest, as measured at Eureka Dunes. The seismic records also show that the surface waves propagate at speeds of approximately 50 m $s^{-1}$ (similar to the measurements by Andreotti) and are strongly attenuated.

The geophones were also used to measure the local seismic vibrations during a booming event. The seismic vibrations measured by geophones installed along the slip face mirrored the acoustic

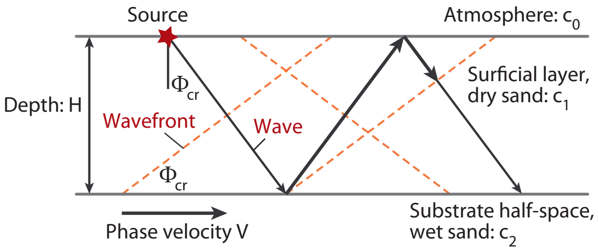


**Figure 6**

Waveguide model showing wave propagation in the surficial layer, reflecting at the atmospheric boundary and the substrate half-space.

signal, showing a strong fundamental frequency (typically at ∼80–90 Hz at Dumont) in addition to higher harmonics. However, the geophones near the base of the dune showed considerably lower power and a frequency higher than that found on the slip face. By placing the geophones at a specific elevation along the dune surface and parallel to the dune crest, Vriend et al. (2007) found the signal to originate within the region of avalanching sand and to travel radially outward at the body-wave speed. They also showed that the distribution of seismic speeds differed in smaller dunes and during the winter seasons when moisture could be felt just below the dune surface.

## THE DUNE AS A WAVEGUIDE

Because of the subsurface layering, the sand dune can act as a seismic waveguide (Ewing et al. 1957, Officer 1958). The avalanching and shearing of the surface layer provide a source of energy, similar to the bowing of a cello string. Waves propagating at $c_1$ in the surficial layer are reflected at the atmospheric boundary and the substrate half-space (**Figure 6**). The surficial layer of depth $H$ is sandwiched between the higher-velocity atmosphere ($c_0$) and the substrate half-space ($c_2$). For the certain frequencies $f_n$ 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 $2\pi$ , wavefronts align and constructive interference results. Consider a wave traveling at angle $\phi$ with respect to the horizontal interface; the phase difference between this wavefront and one associated with a wave that has been reflected at the upper and lower interfaces is calculated as

$$4\pi \cdot H \cos\phi \frac{f_n}{c_1} - \varepsilon_{10} - \varepsilon_{12} = 2(n-1)\pi, \tag{5}$$

where $\varepsilon_{10}$ and $\varepsilon_{12}$ represent the phase lag associated with the reflection at the atmosphere boundary and at the substrate half-space. For the special case of incidence at the critical angle $\phi = \phi_{cr}$, where the critical angle is calculated from Snell's law as $\phi_{cr} = \sin^{-1}(c_1/c_2)$, the phase velocity $V$ is equal to $c_2$ along the lower interface and $c_0$ along the upper interface. For these conditions, the phase change reduces to zero, and no attenuation occurs in either the atmosphere or the substrate half-space. This situation results in the maximum excitation of the waveguide. For this case, the frequency is governed by the following relation:

$$\tan\left(2\pi \cdot f_n H \frac{[1-(c_1/V)^2]^{1/2}}{c_1}\right) = 0. \tag{6}$$

Assuming equal atmospheric and substrate speeds, $c_0 = c_2$, the frequency is computed as

$$f_n = \frac{n c_1}{2H\,[1-(c_1/c_2)^2]^{1/2}}. \tag{7}$$

**Grainflow:** process that occurs on the slip face owing to successive failure of the slope beyond the angle of repose, usually on lower parts of the slip faces of large dunes

**Grainfall:** process that occurs when sand in suspension passes the brink and passively falls on the leeward face, usually on upper parts of large dunes

**Reflection survey:** geophysical technique using reflections off a medium, in which the angle of incidence is equal to the angle of reflection

As the velocity $c_0$ is larger than $c_1$, successive wave trains reinforce one another, 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 occurs at the interface. The observed harmonics are explained through the analysis of higher modes of the resonance at $n = 2, 3, \ldots$.

**GPR:** ground-penetrating radar

As shown in Vriend et al. (2007, 2008), there is reasonable correspondence between the predicted frequency and the experimental results. For example, using $c_1 = 200\ \mathrm{m\ s^{-1}}$, $c_2 = 350\ \mathrm{m\ s^{-1}}$, and $H = 1.5$ m, the fundamental frequency is predicted as 81 Hz. However, the simple model presented above involves several assumptions including constant properties and planar interfaces, which are idealizations of the actual structure of the dune. In addition, the estimation of the depth $H$ arises from a calculation that involves the seismic velocities. Hence, an uncertainty in the seismic velocities results in an uncertainty in the depth, compounding the uncertainty in the calculation of the booming frequency (Vriend et al. 2008).

Andreotti et al. (2008) argued that the nondispersive model used by Vriend et al. (2007) ignores the dispersive surface modes, which are responsible for the booming sound. Because a sand dune contains discrete particles, the speed of sound depends on the confining pressure; as a result, the speed increases with depth. Andreotti et al. (2008) state that "no plane wave Fourier mode can exist in such a medium; only an infinite number of surface modes guided by the sound speed gradient may propagate." In a rebuttal, Vriend et al. 2008 show that increased turning of the ray path does not preclude the propagation of body waves and the resonance condition. An increase in seismic velocity resulting from confining pressure is not sufficient to account for the increase in seismic velocities and the layer subsurface structure that was measured by Vriend et al. (2007). If the curved ray paths are taken into account, constructive interference and resonance within the waveguide are still possible.

## SUBSURFACE DUNE STRUCTURE

In addition to the data from the seismic refraction studies, images using ground-penetrating radar (GPR) further support the layered subsurface dune structure. In GPR, a radar source at the surface of the dune emits an electromagnetic wave; the surface detector measures the returned signal through the time-of-travel. The contrast in a radargram arises from the reflection of waves off interfaces with large changes in radar velocity (Reynolds 1997). By knowing the dielectric properties, researchers can determine the depth of the subsurface features. The relative permeability of the sand determines the radar velocity, and the magnetic permeability and electrical conductivity of the sand influence the amplitude and attenuation of the waves (Baker et al. 2007). At the dunes, the radar velocity was measured between 1.6 and $1.9 \times 10^8\ \mathrm{m\ s^{-1}}$ (N.M. Vriend, M.L. Hunt, and R.W. Clayton, unpublished data). In **Figure 7*a***, the raw GPR profile of the Dumont Dunes shows a strong cross-bedding on the windward south side, indicating a dune migrating to the north. Booming was never generated on this shallow windward face. (The structure of the upper 48 m on the leeward face is enlarged in the insert.) On a wet day in March 2008, booming could not be generated anywhere on the dune, whereas the subsurface structure showed strong cross-bedding close to the surface, as illustrated in the insert in **Figure 7*a***. Later that year, on a dry day in June 2008, booming was generated between 6 and 30 m from the crest. A distinct near-surface layer is visible in this region at $0.023 \pm 0.002$ μs after the arrival of the direct wave, corresponding to a depth of $1.8 \pm 0.3$ m; the layering dips into the dune close to the crest and after 30 m where the slope of the dune breaks. In comparison with Dumont, the dune structure at Eureka (**Figure 7*b***) differs (see **Table 1**) with slip faces at the angle of repose on both the west- and east-facing sides of the crest. As a result, the subsurface structure shows parallel layering on

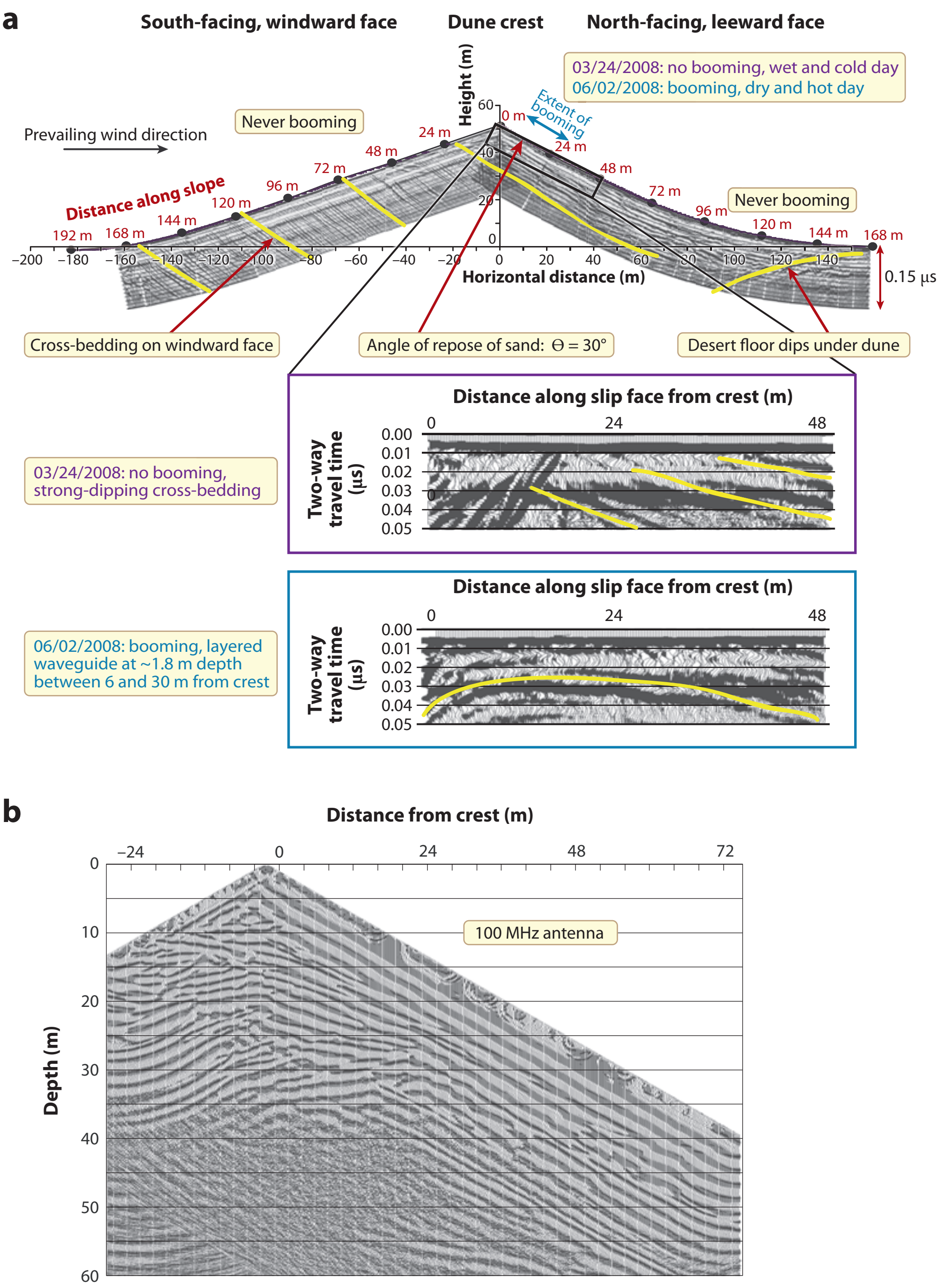


**Figure 7**

(*a*) GPR profile of Dumont Dunes, with insert of the upper 48 m on the leeward face for both the winter and summer. The yellow lines follow the local reflection profiles and are added for interpretation. (*b*) GPR profile of Eureka Dunes, migrated.

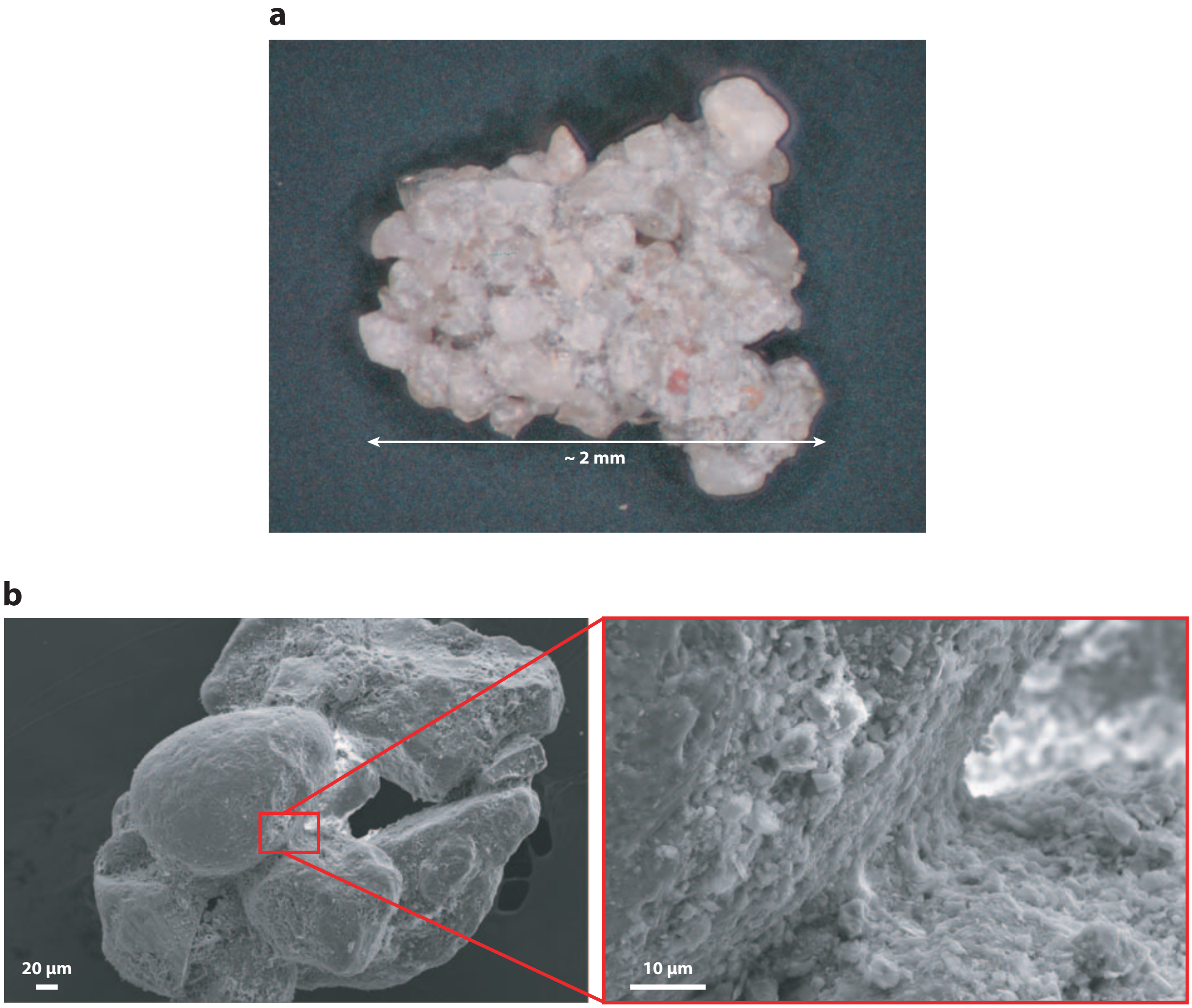


**Figure 8**

Conglomerates obtained from a sample at Dumont Dunes from a depth of approximately 2 m: (*a*) microscopic photo, (*b*) SEM photo.

either side of the crest; booming sound was produced on both sides. The internal structure of this large dune shows a remarkable history of dune building.

**Clast-supported fabric:** part of a dune in which the individual grains are in contact with one another while clay and silt fill the intermediate spaces

To complement the measurements of the subsurface stratigraphy, the research at Caltech included subsurface sampling to determine the mineralogical composition of sand. At the surface, the desert sand is single grained and composed primarily of quartz and different types of feldspar. To obtain samples at depth, researchers used a long, custom-made sampling probe. At Dumont Dunes, the maximum depth that the probe could be inserted was approximately 2 m. Although the sand was hard, a sample was retrieved from a depth of approximately 1.5–2 m. The sample included a large fraction of conglomerated sand as shown in **Figure 8*a***. The clast-supported fabric has individual grains in contact; clay particles are mixed with minerals, filling the intermediate spaces as shown in **Figure 8*b***. Using a scanning electron microscope, investigators found that the minerals in the cemented "glue" are calcite and dolomite. Periodic percolating rainwater through the permeable sand (few fine grains) supplies the necessary minerals and clay-sized particles from the surface. As a consequence, the cementing decreases the porosity of the sand layer, resulting in an increase in seismic velocity across this layer.

### SUMMARY POINTS

1. Desert sand dunes can emit a booming sound that consists of a single fundamental frequency in addition to higher-order harmonics. The sound persists for tens or even hundreds of seconds, can be heard over significant distances, and can be transmitted and measured as seismic vibrations within the dune. The booming is generated by an avalanching of sand down the slip face of the dune.
2. Sand dunes can also produce short bursts of sound when disturbed locally by a hand, foot, or shovel; the frequency of these sounds is higher than the persistent booming sounds, contains a band of frequencies, and may depend on the speed of the disturbance. Similar sounds can be reproduced in a laboratory.
3. The sand found at booming dunes has a narrow distribution of grain sizes. Although researchers have suggested a link between the frequency of a sustained booming event and the average grain diameter, a comparison of data taken by different researchers during the past 30 years does not support this dependency.
4. An alternative explanation of the booming sound models the sand dune as an acoustic waveguide in which the frequency depends on the thickness of the waveguide and the seismic velocities. The sound is trapped in the low-speed (typically $\sim$200 m s$^{-1}$) surficial layer of sand ($\sim$1–2 m in depth) that runs along the dune's slip face; this layer is bounded by a harder and denser region of sand below and the atmosphere above (the seismic speed of the denser layer and the air sound speed are both $\sim$340 m s$^{-1}$).
5. The waveguide model is supported by measurements of the seismic speeds within the dune, by radargrams of the dune's subsurface structure, and by samples of the sand and depth within the dune.

### FUTURE ISSUES

1. Laboratory experiments should be developed that differentiate between the short bursts associated with squeaking or burping sounds and the sustained booming heard from the sand dunes.
2. Wave propagation in a layered structure, such as that found in a desert dune, should be investigated through a numerical simulation incorporating two scales—the continuum modeling of the acoustic propagation in the dune, and the forces and interactions between individual sand grains by a discrete element method.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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