Sound-Producing Sand Avalanches

Franco Nori*, Paul Sholtz, and Michael Bretz

Department of Physics, The University of Michigan, Ann Arbor, MI 48109-1120

Sound-producing sand grains constitute one of nature's most puzzling and least understood physical phenomena. They occur naturally in two distinct types: booming and squeaking sands. Although both varieties of sand produce unexpectedly pure acoustic emissions when sheared, they differ in their frequency range and duration of emission, as well as the environment in which they tend to be found. Large-scale slumping events on dry booming dunes can produce acoustic emissions that can be heard up to 10 km away and which resemble hums, moans, drums, thunder, foghorns or the drone of low-flying propeller aircraft. These analogies emphasize the uniqueness of the phenomenon and the clarity of the produced sound. Although reports of these sands have existed in the literature for over one thousand years, a satisfactory explanation for either type of acoustic emission is still unavailable.

There exist two distinct types of sand that are known to produce manifest acoustic emissions when sheared. The more common of the two, known colloquially as "squeaking" or "whistling" sand, produces a short (< 1/4 sec), high-frequency (500-2500 Hz) "squeak" when sheared or compressed. It is fairly common in occurrence, and can be found at numerous beaches, lake shores and riverbeds around the world. The other, rarer type of sound-producing sand occurs principally in large, isolated dunes deep in the desert (Nori et al.,1996; Criswell et al., 1975). The loud, low-frequency (typically 50-300 Hz) acoustic output of this "booming" sand, resultant upon avalanching, has been the subject of desert folklore and legend for centuries. Marco Polo (1295) wrote of evil desert spirits which "at times fill the air with the sounds of all kinds of musical instruments, and also of

* Author to whom correspondence should be addressed.

drums and the clash of arms." References can be found dating as far back as the *Arabian Nights* (Carus-Wilson, 1915), and as recently as the science fiction classic *Dune* (Herbert, 1984). Charles Darwin (1889) also makes mention of it in his classic *Voyages of the Beagle* . At least 31 desert and back-beach booming dunes have been located in North and South America, Africa, Asia, the Arabian Peninsula and the Hawaiian Islands (Lindsay et al., 1976; Miwa and Okazaki, 1995). Sharply contrasting differences between squeaking and booming sands have led to a consensus that although both types of sand produce manifest acoustic emissions, their respective sounding mechanisms must be substantially different. More recent laboratory production of "squeaks" in booming sand (Haff, 1979) has nonetheless suggested a closer connection between the two mechanisms. A satisfactory explanation for either type of acoustic activity is still unavailable.

This brief review is not a closed chapter in a well-understood research area, but is a summary of the incomplete and unsatisfactory proposals put forward to explain sound production in squeaking and, especially, booming sand. Our review points out the serious problems, unsatisfactory theories, and the severe limitations of different approaches published so far.

Booming and squeaking sands each show a markedly different response to water exposure. Booming occurs best when the grains are very dry, preferably several weeks after the last rain. Small amounts of atmospheric humidity, which creates a fluid surface coating on the grains, effectively preclude booming emissions in these desert sands (Lewis, 1936). Even mixing as little as five drops of water into a 1-liter bag full of booming sand can silence the acoustic emissions (Haff, 1979). Similarly, squeaking sand that is visibly moist is not acoustically active either. However, sound is most easily produced from squeaking sand immediately after the grains have been "washed" in water and subsequently dried. It is not clear whether this is due to the washing away of fine impurities in the sample (Brown et al., 1961) or to the creation of a looser, more natural grain packing (Clarke, 1973), although it may explain why squeaking sand typically does not extend inland more than 30 m from the shore (Richardson, 1919). This process of cleaning can also “revive” squeaking sand that has lost its ability to squeak, a condition that often occurs after repeated compression (Hashimoto, 1951). Finally, squeaking sand can emit sound even when completely submerged in water (Lindsay et al., 1976; Brown et al., 1961), suggesting that intergranular cohesion in moist sand precludes acoustic output.

The mean grain size (diameter) of most sand, whether or not it is acoustically active, is roughly 300 μm. The frequency of emission generated by squeaking sand is thought to vary as the inverse square root of the mean grain size (Bagnold, 1954a, 1966), although mean grain size does not by itself determine the ability of sand to sound (Lindsay et al., 1976). It is unlikely that booming frequencies depend similarly on grain size alone, as a fairly wide range of fundamental frequencies is often generated in large-scale slumping events. Particle-size distributions (Folk and Ward, 1957) of sound-producing grains usually only extend over a narrow range, a condition that is called “being well-sorted.” Also, booming and squeaking grains tend to be both spherical and lack abrupt surface asperities. The latter condition is called “being well-rounded” (Powers, 1953), a term not to be confused here by our use of the word “polished,” which we take to mean granular surfaces which are smooth on the 1-μm length scale. Both types of sand further exhibit an unusually high shear strength, and in the case of squeaking sand, a decrease in shear strength has been shown to correspond to a decrease in sounding ability (Hashimoto, 1954; Humphries, 1966). Experiments in which spherical glass beads produce acoustic emissions similar to those of genuine squeaking sand when compressed, albeit under somewhat contrived experimental conditions (Brown et al., 1965), provide further support for the notion that squeaking is caused primarily by frictional effects. The combination of these four grain properties (a high degree of: size-sorting, sphericity, roundedness and resistance to shear) is thought to be critical for the onset of squeaking. Booming, on the other hand, is substantially less sensitive to differences in grain shape and sorting, and is likely governed by the unusually smooth and polished surface texture present in all booming grains (Lindsay et al., 1976).

Exactly what governs either sounding mechanism is still an open question. Research has been hindered both by the rarity of the phenomena and the difficulty in reproducing the sounds in a laboratory environment. Moreover, the increasing traffic of vehicles on dunes appears to suppress the natural sounds of sands. Furthermore, many researchers had problems differentiating between booming and squeaking sands, and the early literature on the topic is often marred by inconsistencies as well as vague and imprecise terms such as "musical" or "barking" sands. One of the first scientific treatments of the subject attributed the squeaking sound to periodic oscillations of air pockets located between the grains (Bolton, 1889a). Also, a preliminary explanation of booming relied on observed electrical charging of the grains (Lewis, 1936). Such air-cushion and electrical charge models were, however, based on misguided evidence and have been discredited by more recent experiments. Most modern theories stress the importance of intergranular friction. It has been suggested that the unusually smooth and polished surfaces of booming grains may allow for exaggerated vibration at the natural resonant frequency of sand (Criswell et al., 1975; Lindsay et al., 1976). Differences in grain packing have also been considered (Humphries, 1966). The most complete development is given by Bagnold (1954a, 1966), who argues that both types of emission result from non-linear oscillations of dispersive stress in the layer of moving grains, or shear layer. Even this analysis, however, fails to address key aspects of the booming mechanism.

Acoustic and Seismic Output of a Booming Event

Booming emissions produce a wide variety of sounds that have been compared to moans, hums, roars, drums, tambourines, thunder, cannon fire, the rumble of distant carts, foghorns, the buzzing of telegraph wires and the drone of low-flying propeller aircraft (Lindsay et al., 1976; Curzon, 1923). These analogies all emphasize the distinct quality of the booming sand phenomenon and the clarity with which these sounds are produced. The comparisons to drums and tambourines moreover illustrate how the booming mechanism can produce characteristic beat frequencies (1 to 10 Hz), thought to result from periodic amplitude modulation of the acoustic emissions which are often observed in prolonged, large-scale flows. Perhaps most illuminating, however, are those analogies which compare booming emissions to musical instruments, such as trumpets, bells or low-stringed instruments. Such clear emissions usually occur only in small-scale flows, whereby only one fundamental frequency of vibration is produced. Criswell et al. (1975) point out the similarities in the acoustic amplitude trace of a small-scale, *in situ* booming emission and that of a pipe organ. It is remarkable that an avalanche of granular material could produce an acoustic oscillation comparable in purity to an finely-crafted musical instrument. Our 1994 observations of small, induced avalanches at Sand Mountain, Nevada, during the second driest summer on record, reveal emissions similar to a didjeridoo (an aboriginal instrument from Australia) with its low, droning cadence.

In general, several fundamental frequencies of vibration are often present, especially when large volumes of shearing sand are involved. Exactly what precipitates the transition from one to several modes of fundamental vibration is not completely understood. Each fundamental frequency seems to exhibit its own rise and fall time, independent of the others, and they are thought to result from the collective vibration of sand grains which can occur along all directions (Criswell et al., 1975). Taken together, these frequencies can cover a fairly broad range, the width of which is determined by a variety of factors which differ from dune to dune: 50-80 Hz at Sand Mountain, Nevada (Criswell et al., 1975); 50-100 Hz at Korizo, Libya (Humphries, 1966); 130-300 Hz in booming sand from the Kalahari desert in South Africa (Lewis, 1936); and 300-770 Hz at Dunhuang, China

(Jianjun et al., 1995). Such broad-band output tends to be muddy in quality, but by virtue of the larger volumes of shearing sand, also loud. Comparisons to thunder or the drone of low-flying propeller aircraft are common. Also, the terms “roaring” and “humming” seem to have first been introduced rather loosely by Lewis (1936), and their subsequent use by later authors has at times been somewhat confusing. It seems that “humming” was the term used by Lewis when only one fundamental frequency of emission was heard, while in “roaring,” two or more were present.

Fully developed avalanches, in which sliding plates of sand remain intact for most of their motion, exploit the shear (and hence acoustic) potential of booming dunes to the utmost extent. Soundings can quickly grow to near-deafening volumes, comparable in intensity to rumbling thunder (Curzon, 1923). Under the right conditions, emissions can be heard up to 10 km away and last as long as 15 minutes. Perhaps more surprisingly, the booming mechanism produces seismic ground vibrations roughly 200 to 400 times more efficiently than the coincident oscillations in air pressure (Criswell et al., 1975). These ground vibrations, thought to occur along all directions, have on occasion been reported as being so intense so as to make standing in the midst of a fully developed flow nearly impossible (Curzon, 1923). Of course, shearing that takes place over a much smaller area, like that caused by running one’s hand through the sand, also creates acoustic emissions. In any case, a critical amount of booming sand must shear before acoustic emissions of any sort are produced. Bagnold (1954b) cites that running one’s hand through the sand provides just about the minimum amount of displacement needed in order to produce soundings. Although decidedly lower in intensity, these small-scale slumpings, or sudden small slides, produce soundings that are often likened to the low notes of a cello or bass violin. The relationship between intergranular frictional effects to sound production in booming sand becomes clear upon actually sensing the tactile vibrations caused by the grains resonating in a coherent manner during a booming event. Tactile vibrations created by small-scale slumpings are often compared with a minor electric shock (Criswell et al., 1975).

This efficiency in converting mechanical shearing energy into seismic vibrations suggests that booming may also be responsible for the curious "moonquakes," thought to originate on the slopes of Cone Crater, that have been recorded at the Apollo 11, 14, 15 and 17 landing sites (Criswell et al., 1975; Dunnebier et al., 1974). These moonquakes begin abruptly two earth days after the lunar sunrise, continue nearly uninterrupted throughout the lunar day (lunation), and cease promptly at sunset. It is likely that these seismic events are triggered by heat-induced slumping of lunar soil. However, if this seismic activity were due to conventional conversion of shearing energy into seismic energy, soil would have to shear in such large volumes that the leading angle of Cone Crater would fall below the static angle of repose in less than 100 years (Criswell et al., 1975). This is clearly at odds with the fact that Cone Crater is at least 30 million years old.

Grain Size and Morphology of Booming Sand

Much attention has been given to examining the morphology of sound-producing grains and, in particular, to addressing the role that exceptional granular polishing might play in both types of sounding mechanisms. Figure 1 presents a comparison of the morphological features of silent beach, squeaking beach and desert booming sand grains using electron microscopy. Criswell et al. (1975) and Lindsay et al. (1976) suggested that a high degree of polishing alone is responsible for booming, and that all the other physical parameters typically associated with booming sand simply serve to enhance granular smoothing in desert environments. They argue that very smooth granular surfaces will decrease the amount of energy lost during shearing as a result of low mechanical coupling between the grains. Sufficiently smooth surfaces would allow almost elastic collisions, thus narrowing the resonant frequency of what is otherwise ordinary dry sand [which is ~80 Hz (Ho, 1969), well within the range of most booming dunes]. Although straightforward, this analysis does not take into account the large amplitude of oscillation that grains in the shear plane experience during a booming event. These vibrations are nearly as large as the grains themselves (Criswell et al., 1975), and lie well outside the bounds of the linear analysis (Wu, 1971) used to model the elastic deformation of grains. Moreover, it appears that this amplitude represents only the lower bound of magnitudes attainable during a booming event (Criswell et al., 1975). Any realistic model of booming must be based on non-linear pressure vibrations.

Booming dunes are often found at the downwind end of large sand sources, which is a likely consequence of the need to optimize granular polishing. Specifically, wind-driven saltation of sand (the bouncing of grains upon a granular surface) across the desert floor increasingly rounds off granular asperities the further the sand is blown (Sharp, 1966). Since some preliminary degree of rounding is essential before a grain can be polished, one would expect the probability of finding large accumulations of highly polished desert grains to increase with distance downwind from large sources of sand. Granular polishing can take place either during the long-range saltation transport of desert sands, e.g., 35 miles in the case of the booming Kelso dunes of California (Sharp, 1966), or by a sufficiently long residence time within the dune itself (Lindsay et al., 1976). Examples of the latter effect are the collections of back-beach booming dunes of the Hawaiian islands of Kauai and Niihau, located no more than 300 m inland from their source beach sand (Lindsay et al., 1976; Bolton, 1889b). In this case, it is likely that preliminary rounding is brought about by the relatively long residence time of the grains on the beach itself, the result of limited sediment supply and slow off-shore currents (Lindsay et al., 1976). Substantial rounding is likely to take place before the grains are blown into the dunes behind the beach, where subsequent polishing presumably occurs. Some combination of the above arguments probably accounts for the existence of the Jebel Nakus and Bedawin Ramadan booming dunes of Egypt, located on the Sinai Peninsula 3 km inland from the Gulf of Suez. We also suspect that a variable sand source distance to Sand Mountain exists, as we observed that particular booming sand to possess a spectrum of polishing histories.

Booming dunes usually form far enough downwind from large sand sources to permit development of reasonably well-sorted grain-size distributions (Lindsay et al., 1976; Sharp, 1966). This fact has prompted much speculation as to how important certain grain-size parameters are to the sounding mechanism. Highly sorted grain-size distributions are in fact common, although by itself, this is not likely to determine the ability of sand to boom. On the contrary, the booming sands of Korizo and Gelf Kebib, both in Libya, have been noted for their uncharacteristically broad range of particle sizes (Humphries, 1966; Bagnold, 1954b). Moreover, silent dune sand is often as well-sorted as nearby booming sand (Lindsay et al., 1976), and monodisperse (i.e., identical-size) glass beads have never been observed to boom. Booming is also largely independent of grain shape. Close inspection of Sand Mountain (see Figure 1d) and Kalahari booming sand (Fig. 7 in Lewis, 1936) reveals that not all grains are highly spherical or rounded. Furthermore, quartz grains in Dunhuang, China, have obtuse edges and irregularly shaped pits distributed on their surfaces (Jianjun et al., 1995). Also, Lewis (1936) claims to have produced booming in ordinary table salt, which has cubical grains.

The role that other grain-size parameters might play in the booming mechanism has also been the subject of considerable research. For instance, booming sand usually contains an excess of slightly finer-sized grains than its average grain size (Lindsay et al., 1976). The asymmetry that this condition creates in the particle-size distribution of the sand is called "fine-skewness." Humphries (1966), in particular, gave substantial consideration to the role that fine-skewness might play in the sounding phenomena. However, since nearly any size-fraction of booming sand exhibits pronounced acoustical activity (Haff, 1986; Leach and Rubin, 1990; Miwa, Okazaki and Miura, 1995), it is unlikely that the presence of a finely-skewed particle-size distribution alone directly affects the sounding ability of the sand. Booming is also very sensitive to the addition of very fine-sized fragments and grains (on the order of 1-µm in diameter), which seem to disrupt the collective grain behavior (Haff, 1986).

Booming sand is often observed to boom best at or near the leeward dune crest. Several factors may be responsible for this, including the fact that crest sand tends to be better sorted and the grains are more rounded and polished (Lindsay et al., 1976). Another important factor is that sand around the crest tends to dry most quickly. Although precipitation is rare in desert environments, when it does occur, sand dunes retain the water they absorb with remarkable efficiency. Sand near the dune surface (< 20 cm deep) dries off fairly quickly, since water evaporates off the grains into the interstitial air, which, when heated during the day, expands and carries the water vapor out of the dune. At night, cold, dry air fills the granular interstices and repeats the process until the surface sand is completely dry. However, sand is a poor conductor of heat, and this temperature gradient rarely reaches more than 20 cm into the dune. Beyond that, with no mechanism to drive it anywhere, interstitial air can become completely saturated with water vapor and remain trapped for years (Bagnold, 1954c). Since booming sand tends to shear off in plates that are roughly 4 inches deep (Humphries, 1966), sounds occur in those parts of the dune which dry off the fastest. Near the leeward dune crest, the combination of smooth, well-sorted grains and the constant recirculation of interstitial air resulting from the flow of wind over the crest helps promote complete granular drying deep into the dune. Note also that although spontaneous acoustical activity normally only occurs on leeward slopes, sand from the windward side usually possesses comparable acoustical potential. Windward sand is usually not as loosely packed or steeply inclined as leeward sand, and hence does not shear spontaneously as easily, but when properly loosened up, it frequently emits sound just as readily as leeward sand (Haff, 1979). For completeness, we note that during the unusually dry conditions of summer 1994, our tests at Sand Mountain revealed booming over much of the dune's leeward sides, with the most robust emissions occurring near its base.

Wind carrying airborne sand grains across the dune crest has a greater tendency to deposit the grains closer to the top of the leeward than near its bottom. Consequently, sand accumulates faster in the upper portions of the leeward slope than in the lower portions, slowly increasing the angle that the dune's leading edge makes with the horizontal. General slumping occurs when this angle reaches ~34°, the angle of dynamic repose for dry desert sand (Bagnold, 1954d). Typically, large plate-like slabs of sand break off along clearly defined cracks near the crest. Especially in booming sand, it is possible that these cracks form in regions of more symmetrical skewness, which are typically less resistant to shear (Humphries, 1966). The plates themselves usually remain more or less intact until they get near the base of the dune, where the change to a gentler slope slows their slide (Haff, 1979).

An unusual, and as yet not fully understood aspect of booming sand is the manner in which these plates subsequently break apart. Rather than simply disintegrating into loose flow upon hitting the gentler basal slopes, the upper (trailing) portions of booming sand plates are at times seen collapsing, or telescoping, into the lower (leading) portions. Haff (1979) compares the appearance of this effect to that of a sheared deck of cards, and suggests that it may result from distinct boundaries formed between shearing and stationary grains within the plate itself. Furthermore, the free-flow of sand that finally does result from the break-up is unusually turbulent, resembling "a rush of water seen in slow motion" (Bagnold, 1954b). The connection between this flow phenomenon and the booming mechanism is as yet not fully understood. It is not clear from the literature whether this "stacking" effect and the subsequent turbulent motion occurs only when the sand is booming, and hence is the result of sound propagation through the sand, or whether it always occurs, and is the result of some unique grain packing. On the other hand, no such rippling motion has been reported by Criswell et al. (1975) and Lindsay et al. (1976), suggesting that this effect may be subtle or completely absent in some booming dunes. More detailed field observations are needed.

Piezo-Electric Properties of Quartz and the Booming Mechanism

The piezo-electric properties of quartz crystals were at one time thought to play a significant role in the booming mechanism, although as yet there has been no evidence to suggest that this may be the case with squeaking sand. It is well known that electrical polarization arises when pressure is applied to both ends of certain axes within a quartz crystal (Cady, 1946). It has been proposed that the way in which stress is applied to booming grains when sheared may cause an accumulation of these tiny piezo-electric dipoles, which would then somehow be responsible for the pronounced acoustic output of the sand (Bagnold, 1954b). Such speculation began after Lewis (1936) observed that upon slowly pouring Kalahari booming sand, grains would occasionally adhere to one another so as to form filaments as long as a half inch. An electroscope verified that these filaments did indeed exhibit electrical charge. Furthermore, if booming sand was shaken inside a glass jar, a significant number of grains were observed to adhere to the sides of the glass, where they remained for several days. The grains were also noted to cling most densely at places where the temporary surface of the sand had rested against the glass. However, this has also been observed in normal sand.

One could even extend this reasoning to explain why booming is precluded by the adsorption of very small amounts of water, which could effectively interfere with the necessary polarization of grains. Nonetheless, Lewis (1936) was able to demonstrate that grounding the sand had no effect on its acoustic output. Moreover, since booming occurs naturally in the calcium carbonate sand dunes of Hawaii and Lewis claims to have produced booming in sodium chloride crystals, this "electrical connection" should be considered tenuous at best.

Development of Modern Friction Theories

The earliest reports of booming sands were made by desert nomads, who interpreted the noises as supernatural ghosts and demons (Curzon, 1923). Similarly unorthodox notions, such as that the soundings result from the eruption of subterranean volcanoes, persisted well into the late-nineteenth century (Carus-Wilson, 1888). At this time more serious systematic investigations into the phenomena first began. In 1889, Bolton (1889a), one of the first to extensively study the phenomena, published his model of "air-cushion" theories. He proposed that the sounds result from thin films of adsorbed gases deposited on the grains by the gradual evaporation of water. The acoustic emissions would arise from the vibration of elastic air cushions, and the volume and pitch of the emissions would be modified by the surface structure of the grains themselves and extinguished by smaller fragments and debris in the sample. Given the importance assigned to water in this model, the reader might assume that Bolton was concerned exclusively with squeaking beach sands. Booming dunes exist in extremely arid desert regions which receive essentially no rainfall for years at a time. As it turns out, most of the "musical" sand which Bolton sampled was actually squeaking beach sand (although he did use this model to explain booming sands as well, and did not seem to attach much importance to the differences between the two). However, concrete empirical evidence in support of this theory has never been produced, and the fact that tactile vibrations observed in booming sand from Sand Mountain, Nevada, (shown on Fig. 2) at atmospheric pressure are no different from those observed at 1.5 mm Hg air pressure (Criswell et al., 1975) effectively discredits an air-cushion mechanism as the cause of booming emissions. To the authors' knowledge, the last paper published in support of Bolton's air-cushion model was by Takahara (1965). It is, however, merely a reaffirmation that squeaking sand produces better acoustic emissions immediately after washing.

As was stated at the outset of this paper, it is likely that the cause of the acoustic emissions is closely related to the frictional behavior between the grains during shearing. Carus-Wilson (1891), a contemporary of Bolton, was the first to propose that intergranular frictional effects may create sound in certain types of "musical" (in fact squeaking) sands. He was, it seems, the first to correctly conclude that the grains are in general highly spherical, well-rounded, well-sorted and unusually smooth, and postulated that acoustic emissions must result from collectively "rubbing" grains which exhibit these four properties. He, nonetheless, drew criticism for not elaborating on precisely how a frictional sounding mechanism might work. Most notable among his critics was the physicist Poynting (1908), who showed that if the soundings should result only from the natural vibrations of the grains themselves, frequencies of no less than 1 megahertz could be produced. Working together, Poynting and J. J. Thomson (1922) made their own attempt to extend Carus-Wilson's reasoning by coupling it with the principles of granular dilatancy, as put forth by Reynolds (1885). Dilation is simply the expansion in volume that a granular substance undergoes when it deforms under applied shear. This principle can be rephrased by stating that fixing the volume of a granular mass precludes its deformation. A familiar example of this volume expansion is the drying out, when stepped on, of wet sand around one's foot. The pressure applied by the foot creates a deformation in the sand, causing expansion in the region immediately surrounding the place of compression. This expansion, or dilation, is large enough to cause temporary drainage from the compressed to the expanded regions.

Poynting and Thomson (1922) reasoned that if a close-packed granular substance consists of monodisperse, spherical particles, then the dilation caused by shearing should be (roughly) periodic in time. Such uniform variations in dilation, they conclude, are likely related to the uniform oscillations which produce booming and squeaking. Specifically, suppose a shearing stress is applied to one layer of such grains, causing it to slide over another layer of identical grains. Following Reynolds (1885), they reasoned that this motion requires some grains to dilate, or rise out of their interstices, move over neighboring grains, and then fall down into adjacent interstices. So long as the shearing stress remains constant, successive expansions and contractions should occur periodically. Needless to say, real grain flow is far more complex than specified in this simple model. It is unrealistic to expect that the uniform size and spherical shape of the grains is enough to ensure such highly-ordered behavior in loose aggregates. In fact, sound-producing grains are not, in general, perfectly monodisperse. Their model also implies that the frequency of emissions should depend on grain size and the rate of shear alone. This contradicts the fact that squeaking emissions are usually 5 to 10 times higher in frequency than booming emissions, even though both types of grains are usually ~300 μm in diameter. Also, if sand is already shearing in a thin layer (as in most squeaking sand), the addition of shear stress at the surface is more likely to create new shear planes parallel to the existing one rather than increasing the rate of shear at the existing plane (and hence, by the Poynting and Thomson model, increasing the frequency of emission) (Ridgeway and Scotton, 1973). Of course, not all of the added shear stress can be accommodated at new shear planes, and some increase in frequency is bound to occur. But in neither booming nor squeaking sand does frequency of emission vary linearly with rate of shear (Lewis, 1936; Bagnold, 1954b). This argument would not apply to booming sand, which shears in rather thick (~4 inches) thick layers. Lewis (1936) nonetheless found that quadrupling the rate of shear roughly doubled the frequency of emission and resulted in a pronounced increase in volume.

The Bagnold Model of Booming and Squeaking Emissions

In 1966 the British engineer and field commander R. A. Bagnold, having already done a large amount of work on granular mechanics in general, put forth the most complete attempt at explaining the booming mechanism to date. According to Bagnold, both types of acoustic emissions result from non-linear oscillations of dispersive stress along the shear plane. The idea that the cause of the sound may result from disturbances in the shear plane itself stems from experiments performed by Bagnold (1954b) in which booming was produced by shaking sand in a jar. He found that a critical amount of downward force must be applied to each stroke in order to keep the sand sounding and estimated the magnitude of this force to be approximately equal to the weight of 8-10 cm of sand; roughly the depth at which shearing planes form in booming sand. The weight of the sliding grains alone, it seems, exerts just enough force on the shear plane to sustain the oscillations.

Bagnold introduced the concept of "dilatation," $1/\lambda$, of a granular substance, and defined it to be the ratio of the mean intergranular surface-to-surface separation, s, to mean grain diameter, D. This ratio is qualitatively identical to the "dilation" of Reynolds, but is easier to work with mathematically. Since for most natural packing densities, dilatation, as defined above, is far smaller than unity, its inverse, the linear concentration $\lambda = D/s$, is generally used. In the limit of closest possible packing densities, the linear concentration approaches infinity. Bagnold showed that most granular materials remain fairly rigid for linear concentrations down to $\lambda = \lambda_2 \approx 17$, the point at which dilatation becomes just large enough to allow general slumping. Granular materials with $\lambda < 17$ begin to take on the properties of a fluidized bed of particles. The system behaves as a non-Newtonian fluid for small mean intergranular separation, that is resistance to shear exists at zero shear rate. Below some linear concentration, $\lambda_3 \approx 14$, the grains are too disperse to effectively transmit intergranular stress. The system then becomes a Newtonian fluid, losing all resistance to shear.

Piling up sand to above its dynamic friction angle results in the shearing of a thin layer of grains near the surface of the sand. A repulsive stress in the plane of shear ($\lambda \approx 17$) results from the successive collisions of flowing grains upon stationary grains. Of particular interest is the stress component normal to the plane of shear, which is responsible for sustaining the dilation in the first place. In steady-state equilibrium flow, this component is equal and opposite to the normal component of the compressive stress due to the weight of the shearing grains under gravity. However, Bagnold argues, should the shearing grains attain a relative interfacial velocity in excess of the system's preferred velocity, without internal distortions occurring in the shearing layer, the shearing grains could begin vibrating collectively. He reasons that a large, sudden increase in dispersive stress must be created to compensate for the increase in velocity. This creates dilation throughout the entire sliding layer, raising it slightly up off the plane of shear. The dispersive stress itself in turn quickly decreases in magnitude as dilation increases, and the sliding grains soon collapse under their own weight back into the bulk sand. This compacts the original $\lambda \approx 17$ slip face into a denser ($\lambda > 17$) packing, creating a new $\lambda \approx 17$ slip plane slightly closer to the surface of the sand. This process repeats so long as the grains are shearing. The expression

$$f = \sqrt{\frac{\lambda_3 g}{8D}}$$

was derived for the frequency at which this saltation should occur, where g is the local gravitational acceleration. The Appendix summarizes the derivation of this relation for f.

Although elegant, this analysis does not completely describe a booming event. In the first place, a booming sample with a mean grain size of 300 μm should, according to Bagnold, boom at a frequency of ~ 240 Hz; well outside the range of Korizo, Libya (50-100 Hz) and Sand Mountain (50-80 Hz). Equally problematic is that only one frequency is predicted. It is not clear how four or five separate modes of ground vibration, all with different axes of vibration, could be created simultaneously from a single, saltating layer of grains. Consideration of the low-frequency (1-10 Hz) beats that typically accompany prolonged flows, and of the frequency modulation that occurs by varying the rate of shear, is also notably absent from Bagnold's analysis. Grain size may be one component that fixes the frequency range for a given sample of booming sand, but there must be other factors that Bagnold fails to take into account. Furthermore, other experimental results (Leach and Rubin, 1990; Leach and Chartrand, 1994) indicate that the frequency of emission for a given size fraction of booming sand seems to decrease linearly with increasing grain size, rather than decrease with the square root of grain size as proposed by Bagnold.

Bagnold applies a similar line of reasoning in explaining squeaking, the primary difference being that here a compressive stress gives rise to the sound, rather than a general slumping shear. This makes sense, since acoustic emissions in squeaking sand are most naturally created by a quick, sharp compression, like when walking on it, rather than by general shearing like avalanching in dune environments. Bagnold proposes that dispersive stress should again be created in the shear planes in a similar way as in booming sand. However, since compression subjects the grains in the shear plane to K times more acceleration than they would experience during slumping, the emission frequency should be $\sqrt{K}$ times higher. The constant K varies among different types of granular systems and depends on, among other things, the area of sand compressed and the maximal angle of repose of the sand (Terzaghi, 1943). The frequencies emitted by squeaking sand seem to fit Bagnold's model better than those of booming sand (Lindsay et al., 1976).

Comparisons Between Booming and Squeaking Sands

There are many qualitative differences between booming and squeaking emissions. For instance, squeaking emissions almost always produce only a single fundamental frequency of vibration. The multiple-band phenomena observed in large booming events almost never occurs. Conversely, squeaking sand often produces four or five harmonic overtones (Takahara, 1973), while at most only one harmonic of the fundamental tone has been observed in booming sand (Criswell et al., 1975). Understandably, a consensus that squeaking sand never booms and that booming sand never squeaks has arisen in the literature (Criswell et al., 1975; Lindsay et al., 1976; Bagnold, 1954b) We too were unsuccessful in getting booming sand to squeak. A closer look at the older literature may nonetheless suggest otherwise. For instance, in 1889 Bolton (1889b) writes:

> "The sand of the Hawaiian islands possesses the acoustic properties of both classes of places [beaches and deserts]; it gives out the same notes as that of Jebel Nagous [an Egyptian booming dune] when rolling down the slope, and it yields a peculiar hoot-like sound when struck together in a bag, like the sands of Eigg, Manchester, Mass., and other sea-beaches [squeaking sand]."

More recently, Haff (1979) has also been able to produce similar high-frequency squeaking using booming sand from the Kelso dunes, both *in situ* on the dune as well as in a laboratory. The fundamental frequencies of these vibrations are close to 1200 Hz, implying that compression of booming sand doesn't just amplify high-order harmonic frequencies of low-frequency fundamental tones (e.g., 50-300 Hz). This provides some support for Bagnold's theory, which implies that the only difference between the two modes of emission are compressional versus shear-induced slumping. Subtle differences do exist between booming sand that squeaks and genuine squeaking sand, however. For instance, frequency analysis by Haff clearly shows that multiple fundamental frequencies are still present in squeaking emissions from booming sand. It is further interesting to note that *all* desert sands Haff sampled were able to produce some type of squeaking emission when compressed vertically in a container. Bolton (1889a), on the other hand, noted that the sand of Jebel Nakus, an Egyptian booming dune, could not produce such "squeaks" when compressed. It is possible that since Bolton was working *in situ*, adequate pressure might not have been applied. Moreover, Haff found that silent beach sand does not necessarily squeak when compressed. Most likely, the occurrence of squeaking in sand corresponds very directly with grain shape and morphology. Most silent desert sand grains tend to be more spherical, rounded and polished than silent beach sands (Lindsay et al., 1976). It would be interesting to see if table salt, which Lewis (1936) claims can be made to boom, could also be made to squeak. We have observed some booming after sieving silent sand.

The back-beach booming dunes of Hawaii, which differ from most other booming dunes in a number of fundamental ways, provide an interesting case study. In the first place, they are composed primarily of calcium carbonate grains from sea shells, and are thought to be the only naturally-occurring booming sands not made out of quartz. The grains themselves are unusually large (~460 μm) and the frequency range of their emissions appears to be wider than that of most other booming sands, although the latter point has yet to be precisely determined (Lindsay et al., 1976). Also, they are the only non-desert booming dunes and seem to exhibit a slightly higher tolerance for water exposure than do other booming dunes (Haff, 1986). Nonetheless, the loose packing and the rough surface profile of back beach dunes may be what keeps them from squeaking. More comprehensive investigations of the Hawaiian dunes are needed.

The speculative idea that booming and squeaking are produced by the same mechanism, the output of which is modulated either by certain intrinsic grain parameters or by the method of shearing used to produce the sounds, is appealing and warrants further investigation. We choose here to remain with convention and treat the two types of emission as if they were produced by two distinct sounding mechanisms.

The Importance of Shearing

It seems unlikely that booming and squeaking sand grains, which both exhibit mean grain diameters of ~300 μm and appear somewhat similar in electron micrographs, could produce such substantially different modes of acoustic emission simply on the basis of some intrinsic grain parameter. Instead, the way the sand is sheared probably determines the frequency of emission, especially in booming sands. Increasing the rate of shear seems to increase its frequency of emission. Quickly compressing the booming sand vertically, thus creating a very high rate of shear, reportedly produces emissions which resemble genuine squeaking.

While the two modes of acoustic output from sand may be inherently connected and mostly governed by the method of shearing, the actual onset of acoustical activity in a sand sample probably is controlled by certain intrinsic grain parameters. The most critical parameter that governs the ability of sand to boom seems to be a high shear resistance. Both varieties of sound-producing sand possess a large fraction of smooth grains, and booming sand grains smaller than ~200 μm tend to be very smooth. In addition, squeaking sand is typically well-sorted. Monodisperse glass spheres, which exhibit a lower shear resistance than any type of sand, cannot boom, and squeak only under somewhat contrived experimental conditions. A highly-sorted collection of smooth, well-rounded spherical grains is thus not a sufficient condition for sound-production in sand.

Conclusions

In summary, important physical properties that distinguish booming sands from their silent counterparts are: high surface smoothness and high-resistance to shear. Other factors that contribute are the roundedness, the sphericity of the grains and differing roughness between the larger grains in the sample. Booming occurs best at very low humidity, since humidity creates a fluid surface coating that acts like a lubricant and lowers the shear resistance. Humidity also increases the cohesion between grains. Booming is enhanced when the grains are loosely packed, since a very tight packing will preclude shearing. Effects due to collective or resonant motion are also considered to be important. However, these collective effects are still not well understood, in spite of research work on collective motion in granular materials and related systems (see, e.g., Bretz et al.,1992; Benza et al., 1993; Jaeger and Nagel, 1992; Liu and Nagel, 1993; Bideau and Hansen, 1993; Satake and Jenkins, 1988). How these ingredients mix together to produce booming is still an open problem. The actual mechanism has been the subject of speculation for centuries and still remains unresolved.

Many avenues of investigation remain open. Determination of the mineral composition of the grains, particularly at the granular surface, has only recently been attempted[1]. Shearometer analysis and X-ray studies of mass density fluctuations during shear would also be of interest. Examination of the possible piezo-electric properties of booming sands, alluded to earlier, has also been minimal, as have been attempts to create synthetic booming grains. A good understanding of sound-production in loose aggregates might help our understanding of grain flow in general.

---

[1] See, for instance, Leach and Chartrand (1994). Takahara (1973) does present a small table of percent weight by mass analysis of the chemical composition of squeaking grains.

Appendix

Derivation of the Equation for the Frequency of Vibration of Booming Sand

In 1906, Einstein (1906) considered the effect of solid grains, immersed in a fluid, on the shear resistance of that fluid. Half a century later, Bagnold (1954a, 1966) considered a regime that was apparently neglected at the border between hydrodynamics and rheology, namely the case of a Newtonian fluid with a high concentration of large solid spheres. In this appendix, we summarize Bagnold's derivation of the equation for the frequency of vibration that occurs during a booming event.

First consider the slumping, under the force of gravity, of dry sand that has been piled up to its critical angle of repose. Grain flow occurs along a well-defined front and proceeds with a constant velocity. One would like to be able to express this terminal velocity as a simple function of such variables as the mean grain size and the depth of flow. Bagnold's equation for the frequency of vibration that occurs during a booming event is derived from the analysis of the terminal velocity of the flowing front.

Two different experiments were conducted by Bagnold to arrive at his result. In the first, a collection of uniformly-sized spheres was placed into an immersing fluid. The spatial distribution of spheres was kept uniform by experimenting under "gravity-free" conditions, where the density of the grains, σ, was balanced against the density of the immersing fluid, ρ. In order for uniform shear strain to be applied to all the spheres, the spheres were sheared inside the annular space between two concentric drums. This allowed for the accurate measurement of the intergranular stresses and strains that occur during shearing. In the second set of experiments, these results were extrapolated to model the dynamics of dry sand avalanches, where the grains are not uniform in size, nor is the interstitial fluid (air) of the same density as the grains.

We now turn out attention to the theoretical considerations involved in the first experiment (Bagnold, 1954a). Suppose that we have a collection of uniformly-sized spheres, with diameter D. Clearly, in the closed-packed limit, the distance that separates the centers of two adjacent spheres is D. Recall that the linear concentration, $\lambda = D/s$, is defined to be the ratio of the mean grain diameter D to the mean intergranular separation s. For the case of equal spheres, λ approaches infinity since s is very small. Also, the volume fraction C of space occupied by the grains becomes $C_0 = \pi / 3\sqrt{2} \approx 0.74$ for the case of close-packed equal-sized spheres.

Next consider what happens when the spheres are uniformly dispersed, so that the mean distance separating two adjacent centers becomes bD, where $b > 1$ (see Figure 3a). In this case, the mean intergranular separation s, as measured from the surface of the grains, is larger than the s of the close-packed equal sphere arrangement

$$b = \frac{s}{D} + 1 \ . \tag{1}$$

This result can be expressed in terms of the volume fraction C

$$C = \frac{C_0}{b^3} = \frac{C_0}{(\lambda^{-1} + 1)^3}. \tag{2}$$

The smaller λ is, the easier it is to induce shearing. In general, shearing becomes possible for values of $\lambda \leq 17$. Moreover, Bagnold made the following assumptions about the flow of spheres and the shear that occurs:

(i) The spheres are in a uniform state of shear strain, $\nabla(dU/dy) \approx 0$; and the mean relative velocity between the spheres and the interstitial fluid is zero everywhere (see Figure 3a). $U(y)$ is the velocity field of the granular material whose average motion is along the "downhill" x-direction.

(ii) Frictional losses maintain a constant kinetic energy per unit volume of the system.

(iii) In addition to the general drift in the x-direction, the spheres also make small oscillations in all three directions.

Now, consider oscillations produced by a sequence of small jumps or saltations as the spheres of one layer jump over the neighboring sphere layer. Since the "gravity-free" conditions in principle provide a uniform spatial distribution of spheres, the spheres can be treated as being arranged into sheets lying parallel to the $x-z$ plane, with one plane shearing across the top of the layer immediately below it (see Figure 3b). Let us designate the top layer as B, and the bottom layer as A. Then the mean relative velocity of a sphere in layer B with respect to plane A is $\delta U = kbD(dU/dy)$, where k is a constant that varies from $1/\sqrt{2}$ to $\sqrt{2/3}$ depending on geometry (Bagnold, 1966). In this model, the spheres in plane A can be thought of as constituting a rigid plane, across which the spheres in layer B saltate at the differential velocity δU.

Suppose that on average, any given sphere in layer B makes $f(\lambda)\,\delta U/s$ collisions per unit time with layer A. The number of spheres in a unit area of the B plane is $(bD)^{-2}$, and with each collision a sphere in layer B will experience a change in momentum $2m\delta U\cos\alpha$ in the y-direction (the angle α is determined by collision conditions, and will be discussed in more detail shortly). This implies that a net repulsive pressure P_y should exist between the two layers, with magnitude

$$P_y = (bD)^{-2}\frac{f(\lambda)\delta U}{s}2m\delta U\cos\alpha\ , \tag{3}$$

$$P_y\ = r\sigma\lambda f(\lambda)D^2\left(\frac{dU}{dY}\right)^2\cos\alpha, \tag{4}$$

with

$$r = \frac{2mk^2}{\sigma D^3}. \tag{5}$$

Also, there is a corresponding tangential shear stress T_{xy} given by

$$T_{xy}\ = P_y\tan\alpha. \tag{6}$$

Indeed, Bagnold's experiment found that, at sufficiently high speeds, both T_{xy} and P_y become proportional to $\left(dU/dy\right)^2$. The only unknowns in the above equations are $f(\lambda)$ and α. Bagnold's experiment (Bagnold, 1966) with uniform spheres sheared inside a rotating double-cylinder found that in the case where the spheres are sufficiently far apart for the material as a whole to take on the properties of a Newtonian liquid, $\lambda < 12$, $f(\lambda) \approx \lambda$, $\tan\alpha \approx 0.32$ and $r = 0.042$. Thus for $\lambda < 12$, we can write

$$P = 0.042\sigma\lambda^2 D^2\left(\frac{dU}{dy}\right)^2\cos\alpha. \tag{7}$$

At this point, there is no *a priori* reason to suppose that these results should be applicable to dry sand avalanches, since silicon dioxide does not have the same density as air, nor are grains of sand uniform in size or shape. Nevertheless, let us now make the appropriate substitutions and try to derive a general expression for the terminal velocity of flow using known grain parameters. On any $y =$ constant plane below the upper, free surface of the sand, the applied shear stress is:

$$T_{xy} = \sigma g \sin\beta \int_y^0 C(y')\,dy', \tag{8}$$

with β being the angle of incline and C the volume fraction (Eq. (2)). Since air has a very low viscosity, we can apply the above results, and equate expressions (7) and (8). Thus

$$r\sigma\lambda f(\lambda) D^2 \left(\frac{dU}{dy}\right)^2 \sin\alpha = \sigma g \sin\beta \int_y^0 C(y')\,dy', \tag{9}$$

which implies that

$$\frac{dU}{dy} = \left(\frac{g\sin\beta}{r\sin\alpha}\right)^{1/2} \frac{\left[\int_y^0 C(y')\,dy'\right]^{1/2}}{\lambda D}\ . \tag{10}$$

Making the reasonable assumption that C is roughly uniform through the depth of the flow, and that it has a value of $C = 0.6$ (obtained empirically by Bagnold), the integral in Equation (10) reduces to

$$\int_y^0 C\,dy' = 0.6|y|. \tag{11}$$

Finally, taking $\lambda = 17$ at the shear plane, and $r\sin\alpha = 0.076$, equation (10) then reduces to:

$$\frac{dU}{dy} = 0.165(g\sin\beta)^{1/2}\,\frac{y^{1/2}}{D}\ . \tag{12}$$

Thus,

$$U = \frac{2}{3}(0.165)(g\sin\beta)^{1/2}\frac{y_0^{3/2}}{D}, \tag{13}$$

where y_0 is the overall depth of the flow and $y = y_0$ refers to the top surface.

We can further simplify the above expression by making the following assumptions about the flow: for the relatively high concentrations that we are working with here, the relative interfacial velocity U at any shear surface can be substituted for the expression $D(dU/dy)$. This simplifies the expression for the pressure:

$$P = r\alpha\sigma\lambda^2 U^2 \cos\alpha \ . \tag{14}$$

Also, for slow continuing shear, we can take $\lambda \approx 17$ for the local linear concentration, giving:

$$U_c = \frac{1}{17}\sqrt{\frac{P}{r\sigma\cos\alpha}} \ . \tag{15}$$

Having performed the 1954 experiments, Bagnold next needed to verify that these results for U and P apply to actual sand avalanches, and not just in the ideal case of uniform spheres in a rotating drum (1966). In order to verify these results, he performed a bull-dozing experiment in which a heap of sand was pushed, at a constant depth h_0 below the surface, by a push plate. The results he obtained indicated that the above equation for terminal velocity of flow also holds for dry sand shearing.

In order to explain the frequency of emission that occurs in a booming dune, first consider the force Q, which is the normal compressive stress on the shear surface due to the weight of the sand above it. In equilibrium, any increase in U in excess of U_c requires a dilatation increase at the shear surface, so that λ falls to some value smaller than 17.

If the velocity of flow does momentarily exceed the terminal velocity, then P will briefly exceed Q, and the sand mass is accelerated slightly upward. However, the upward stress P decreases rapidly as the dilatation increases. The sand would then collapse back under the weight of gravity, decreasing the dilatation, and again causing P to temporarily exceed Q.

If the mass of flowing sand is m, then it would be subject to the oscillating force $mg - P$, which would create oscillations in the normal direction. Also the minimum mean local dilatation at the shear surface, at which oscillations could still occur, is $D / \lambda_{\min}$.

The stress P is only effective when the dilatation, λ, is near its minimum, because the contact faces (of the sliding planes) just clear one another and since P very rapidly varies with λ. Thus, the rise and fall of the overburden through the distance $D / \lambda_{\min}$ will be an almost free-fall. Hence, the minimum frequency of oscillation is given by

$$f = \sqrt{\frac{g\lambda_{\min}}{8D}} .$$

This expression provides an estimate of the vibration frequency that occurs during a booming event. Using $\lambda_{\min} \approx 14$ and $D \approx 300$ µm, this expression then predicts that $f \approx$ 240 Hertz, which is in the observed range of values for booming acoustic emissions during an avalanche.

References

Bagnold, R. A., 1954a, "Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid Under Shear," *Proceedings of the Royal Society,* **255A,** 49.

Bagnold, R. A., 1954b, in *Physics of Blown Sand and Desert Dunes,* (London, Methuen), pp. 247 - 267.

Bagnold, R. A., 1954c, *ibid.,* pp. 236 - 246.

Bagnold, R. A., 1954d, pp. 188 - 207.

Bagnold, R. A., 1966, "The Shearing and Dilatation of Dry Sand and the 'Singing' Mechanism," *Proceedings of the Royal Society* **295A**, 219.

Benza, V. G., F. Nori and O. Pla, 1993, "Mean Field Theory of Sandpile Avalanches," *Physical Review E* **48**, 4095.

Bideau, D. and A. Hansen, eds., 1993, *Disorder and Granular Media*, (North-Holland, Amsterdam).

Bolton, H. C., 1889A, "Researches on Sonorous Sand in the Peninsula of Sinai," *Proceedings of the American Association for the Advancement of Science* **38**, 137.

Bolton, H. C., 1889B, "Researches on Musical Sand in the Hawaiian Islands and in California," *Transactions of the New York Academy of Sciences* **10**, 28.

Bretz, M., J. Cunningham, P. Kurczynski and F. Nori, 1992, "Imaging of Avalanches in Granular Materials," *Physical Review Letters* **69**, 2431.

Brown, A. E., W. A. Campbell, D. A. Robson and E. R. Thomas, 1961, "Musical Sand: The Singing Sands of the Seashore Part I," *Proceedings of University of Durham Philosophical Society* **13** (No. 21), 217.

Brown, A. E., W. A. Campbell, J. M. Jones and E. R. Thomas, 1965, "Musical Sand: The Singing Sands of the Seashore Part II," *Proceedings of the University of Newcastle Upon Tyne Philosophical Society* **1** (No. 1), 1.

Cady, W. G., 1946, in *Piezoelectricity: An Introduction to the Theory and Applications of Electrochemical Phenomena in Crystals* (McGraw-Hill, New York), pp. 1-8.

Carus-Wilson, C., 1888, "Musical Sand," *Bournemouth Society of Natural Science* .

Carus-Wilson, C., 1891, "The Production of Musical Notes from Non-Musical Sands," *Nature* **44**, 322.

Carus-Wilson, C., 1915, *Nature* **95,** 90.

Clarke, J. A. R. C., 1973, "Singing Sands," *New Scientist* **59**, 222.

Criswell D.R., J. F. Lindsay, and D. L. Reasoner, 1975, "Seismic and Acoustic Emissions of a Booming Dune," *Journal of Geophysical Research* **80**, 4963.

Curzon, G. N., Marquess of Kedleston, 1923, in *Tales of Travel* (George H. Doran, New York), pp. 315-398.

Darwin, C., 1889, *Voyage of H. M. S. Beagle Around the World* (Murray, London).

Dunnebier, F. K. and G. H. Sutton, 1974, “Thermal Moonquakes,” *Journal of Geophysical Research* **79**, 4351.

Einstein, A., 1906, “Zur Theorie der Brownschen Bewegung” *Ann. Phys. Leipzig,* (4), **19**, 371.

Folk, R. L., and W. C. Ward, 1957, “Brazos River Bar: A Study in the Significance of Grain Size Parameters,” *Journal of Sedimentary Petrology* **27** (No. 1), 3.

Haff, P. K., 1979, unpublished, “Booming Dunes of the Mojave Desert and the Basin and Range Province,” *Internal Report: PHY76-83685* (California Institute of Technology, Pasadena, CA).

Haff, P. K., 1986, “Booming Dunes,” *American Scientist* **74**, 376.

Hashimoto, M., 1951, “Some Properties of Singing Sand,” *Proceedings of the First Japan National Congress for Applied Mechanics,* 261.

Herbert, F., 1984, *Dune*, (New York, Putnam).

Ho, M. M. K. and W. J. Burwash, 1969, “Vertical Vibration of a Rigid Foundation Resting on Sand,” *Vibration Effects of Earthquakes on Soils and Foundations, ASTM STP 450,* American Society for Testing and Materials **450**, 197.

Humphries, D. W., 1966, “The Booming Sand of Korizo, Sahara, and the Squeaking Sand of Gower, S. Wales: A Comparison of the Fundamental Characteristics of Two Musical Sands,” *Sedimentology* **6**, 135.

Jaeger, H. M. and S. R. Nagel, 1992, “Physics of the Granular State,” *Science* **255**, 1523.

Jianjun, Q., B. Sun, W. Zhang, Y. Wang and G. Kang, “Surface Texture of Quartz Grain in booming sand and its acoustic significance,” *Chinese Science Bulletin*, **40**, 1719 (1995).

Leach, M. F. and G. A. Rubin, 1990, “The Acoustics of Booming Sand,” *Progress in Acoustic Emission V, The Japanese Society for NDI,* 239.

Leach, M. F. and H. J. Chartrand, 1994, “Recent Progress in the Development of Musical Sand”, *Progress in Acoustical Emission VII, The Japanese Society for NDI*, 499.

Lewis, A. D., 1936, “Roaring Sands of the Kalahari Desert,” *South African Geographical Society* **19**, 33.

Liu C.-h. and S. R. Nagel, 1993, “Sound in Granular Media,” *Phys. Rev. B* **48**, 15646.

Lindsay, J.F., D. R. Criswell, T. L. Criswell and R. S. Criswell, 1976, "Sound-Producing Dune and Beach Sand," *Geological Society of America Bulletin* **87**, 463.

Miwa, S. and T. Okazaki, 1995, "Sound of Booming Dunes in China and America," *Sand Dune Research* **42**, p. 20 (in Japanese).

Miwa, S., T. Okazaki and M. Kimura, 1995, "Sound Producing Properties of Singing Sand," *The Science and Engineering Review of Doshisha University* **36**, 67.

Nori, F., P. Sholtz and M. Bretz, 1996, "Sound-Producing Sand," *Scientific American*, in press.

Polo, M., 1295, edited by T. Wright, 1968, *The Travels of Marco Polo, The Venetian,* (AMS Press, New York) p. 101.

Powers, M. C., 1953, "A New Roundedness Scale for Sedimentary Particles," *Journal of Sedimentary Petrology* **23** (No. 2), 117.

Poynting, J. H., 1908, "Musical Sands," *Nature* **77,** 248.

Poynting, J. H. and J. J. Thomson, 1922, in *Text-Book of Physics: Sound* (Charles Griffin, London), p. 134.

Reynolds, O., 1885, "On the Dilatancy of Media Composed of Rigid Particles in Contact," *London, Edinburgh and Dublin Philosophical Magazine and Journal of Science* **20** (No. 127), 469.

Richardson, W. D., 1919, "The Singing Sands of Lake Michigan," *Science* **50**, 493.

Ridgway K. and J. B. Scotton, 1973, "Whistling Sand Beaches in the British Isles," *Sedimentology* **20**, 263.

Satake, M. and J. T. Jenkins, editors., 1988, *Micromechanics of Granular Materails* (Elsevier, Amsterdam).

Sharp, R. P., 1966, "Kelso Dunes, Mojave Desert, California," *Geological Society of America Bulletin* **77**, 1045.

Takahara, H., 1965, "Frequency Analysis of Squeaking Sand," *Journal of the Acoustical Society of America* **39** (No. 2), 402.

Takahara, H., 1973, "Sounding Mechanism of Singing Sand," *Journal of the Acoustical Society of America* **53** (No. 2), 634.

Terzaghi, K., 1943, *Theoretical Soil Mechanics* (Wiley, New York), p. 118.

Wu, T. H., 1971, *Soil Mechanics* (Allyn and Bacon, Boston), p. 272.

Fig. 1. A composite diagram (from top left to right) of normal beach (top left), squeaking beach (top right) and booming desert (bottom) sand grains using low-magnification electron microscopy. Samples were collected from Lake Huron at Bay City, MI (top left), Lake Michigan at Ludington, MI (top right) and Sand Mountain, NV (bottom). The sample in the bottom right panel was sieved and consists of grains smaller than ~200 μm. All micrographs were made on the 100 μm length scale. These photos suggest that the normal beach sand is poorly polished and irregular in shape, while the squeaking sand is more polished. Occasional scour marks appear on both types of beach sands, but not on booming sand. While squeaking grains are by and large rounded, booming sand contains a variety of erosional grain states as shown in the bottom left panel, including many smaller, well-polished, well-rounded grains, as seen in the bottom right micrograph. The top-right grain in the bottom left panel is highly unusual in booming sand.

Fig. 2. Sand Mountain, near Fallon, Nevada. Other booming dunes in the western United States include: Big Dune, near Beatty, Nevada; the Kelso Dunes, near Kelso, California; and Eureka Dune, located at the western edge of Last Chance Ridge in California.

Fig. 3. (a) Schematic diagram of two layers, A and B, of grains moving along the "downhill" $x-$direction. The average intergranular separation s, and the average distance between two adjacent centers, bD, are indicated. (b) Schematic illustration of a granular flow and its velocity profile.