BOOMING SANDS OF THE MOJAVE DESERT AND THE BASIN AND RANGE PROVINCE, CALIFORNIA*

P. K. HAFF

A. W. Wright Nuclear Structure Laboratory

Yale University, New Haven, Connecticut 06520

and

W. K. Kellogg Radiation Laboratory

California Institute of Technology, Pasadena, California 91125

*Supported in part by the National Science Foundation [PHY76-83685] — Caltech Internal Report.

ONE OF THE LIME AID PREPRINT SERIES IN NUCLEAR GEOPHYSICS AND COSMOCHEMISTRY

June 1979

The phenomenon of acoustically active desert sand dunes has been recorded since ancient times[(1)]. These dunes are usually known in the present day as booming, barking, roaring, or singing sands. The most striking example of the phenomenon is associated with the displacement, on steep slopes exceeding the angle of shear of a large area of unstable sand. As the sand moves downhill a strong and persistent vibration is set up generating a readily noticeable shaking of the surrounding (undisplaced) sand, as well as a loud and pure audible tone similar to that made by a low-flying propellor aircraft. The sand displacement may occur naturally, or be induced by the observer. A list of references to old observations together with a recent study of the phenomenon at Sand Mountain, Nevada, may be found in ref. (2, 3).

The present paper deals with the acoustic properties of sand from several sites in the Mojave Desert of California and from the Basin and Range Province of California and (in one case) western Nevada, See Fig. 1.

There are several motivations for these studies. The first was curiosity about the type of mechanism which could marshal the energy of 10^{10} cohesionless and apparently randomly distributed grains and extract from them coherent vibrational motion. The purity of the tone produced suggested the existence of a physical principle which depended only on average properties (grain size, surface friction, etc.) of a very large number of grains and which therefore might be simple and amenable to mathematical modelling and analysis.

The second motivation was a disbelief that the booming phenomenon could really be rare as has been claimed, since dune composition (quartz, feldspars), grain sizes (few hundred microns diameter), morphologies, etc. are rather similar for a large number of dunes, including ones known to boom. Could the booming mechanism really be a sharp function of one of these variables?

The third motivation grew out of the realization that regular coherent motion frequently accompanies the flow of cohesionless particulate matter [4], and that there might be a connection between the practical problems involving flow rates of such grainy material and the geological oddity of booming sand.

The following dune sites, See Fig. 1, were visited during the summer of 1978 for the purpose both of observing any booming activity directly and of collecting samples for laboratory study.

1. Kelso Dunes, (lat. 34° 48' N, Long. 115° 43' W). Located near Kelso, California, these dunes may be reached by a well-graded gravel road (Kelbaker Road) running between Interstate 40 on the south and Interstate 15 on the north. USGS 15-minute quadrangles Flynn (1956) and Kerens (1957) cover the major dune area. These dunes, which have been extensively studied by Sharp [5], have maximum heights of about 200 meters, but most of the field is composed of smaller accumulations.

The lowest hummocks are sparsely vegetated, and here the sand was noticeably damp ten centimeters below the surface. The same composing the crest of the very high dunes at the southern edge of the field was dry to the touch even 30 centimeters below the surface. The acoustical events discussed here were generated on these high dunes, while no acoustical activity was observed lower down. This is consistent with the observation [1,2,3] that high humidity or dampness can completely eliminate the booming quality, a point which we come back to below.

Acoustic vibrations of rather pure frequency could be generated in a large number of ways. For example, walking up or down the steep lee slopes produced loud wheezes (like a tuba) upon the placement of each foot. The sand was loosely packed here (see below) and the boot sunk in 10-12 centimeters at each step, while slipping somewhat downhill.

Running two or three fingers held together through the sand did not produce much effect, but a cupped hand moving swiftly produced a very audible hum. The frequency of the hum seemed to depend somewhat on the mass or the velocity of the sand moved, but since it is easier to move a small mass quickly by hand than a large mass, it was not clear which variable was the important one. Drawing ones hands together rapidly through the top level of sand produced a high pitched squeak, and a handful of sand dropped from a height of 20-30 centimeters produced a definite wheeze upon striking the dune surface. A cupped hand drawn in rapid figure-eights through the top few centimeters of sand produced a continuous buzz whose frequency depended on the position of the hand in the figure-eight cycle. Leaping off the crest of the dune and landing on two feet produced a very loud low-frequency groan lasting about a second.

The most spectacular and enduring vibrations were produced by the movement of large quantities of sand. This could be initiated by vigorous kicking at the sharp dune crest in order to dislodge a metastable surface layer on the lee slopes, or by sitting on such a slope and forcing oneself vigorously downhill by action of the hands and feet. In this way many square meters of material could be set in motion at one time. The frequency spectra discussed in conjunction with Fig. 3 below were derived from sands driven in this way.

Natural instabilities of sand accumulations on steep faces are responsible for the spontaneous sound generation reported in many localities around the world [1, 2, 6]. One such occurence was heard at the Kelso dunes, although the source was evidently some distance away and was not visible.

Sample No. 1, discussed below, was collected from the leeward slope near the top of the dune where the above acoustic activity was studied.

The leeward and windward sides of the crest were distinguished by the degree of packing of the sand grains. The lee slope material is typically inclined at a steeper angle [6], and the material there is much looser. A boot or a finger is without effort easily thrust in several centimeters, while the windward surface was packed to such a extent that only the shallowest footprints remained after treading. This general phenomenon was observed in many instances on a number of dunes. In some instances the packing is sufficiently great that a hole having vertical walls can be dug to a depth of 20-30 cm. Once the material had been transformed from this hard packed state, whose strength relies on interlocking grain networks and not cohesion due to moisture or cementing [6], to a looser state by shuffling with the hands, it gave the same sort of acoustic responses as the looser lee slope material.

2. Big Dune, (lat. 36° 39' N, long. 116° 35' W). Located south of Beatty, Nevada, this site is accessible via a good dirt road leading south from US 95. USGS quadrangle Big Dune covers the major dune area. The dune field is rather smaller than at Kelso, but the largest dunes seem nearly as high. There is only very slight vegetation on the lower dune flanks. On the highest crests, all the modes of excitation described for the Kelso dunes were also observed with a comparable audio intensity, except for spontaneous avalanching, which was absent when the dune was visited.

A feature common to all the large dunes (Kelso, Big Dune, Panamint, Death Valley), and especially noticeable at Big Dune, was the break-off of large (several sqare meter) plates of sand in the initial phases of the avalanche. The lee faces were particularly delicate at the time of the visit to Big Dune, and a stamp of the boot near the crest of the largest dunes would dislodge material for several meters further along the crest. Typically, cracks composed of straight lines, and segments of straight lines, would develop more or less perpendicularly to the crest and the intervening sand would slide downward as a single unit with rather distinct boundaries on all sides. It is emphasized that the material in motion is the typical unconsolidated lee slope material, yet it moves essentially as a single plate until slightly before coming to rest, at which time it may dissolve into a motion better described by the word "flow" than "slide".

The depth of the moving material in the plate seemed to be about 5-10 cm. These large scale plate-like motions are often, but not always, accompanied by strong, regular acoustic radiation. Although their motion may end in an indistinct sand avalanche or flow, such plate motions are distinguishable from the "tongue" shaped flows which scar many steep sand slopes and which are often generated by flow patterns more reminiscent of hydrodynamics. The flowing avalanche tongues do not seem to generate the very strong signals referred to here. The edge of the tongues, which themselves are usually less than a meter wide, are nearly parallel to the line of fall from the crest, and thus often nearly perpendicular to that crest. It may be the case that lines of weakness along such old, and perhaps buried, boundaries are the places where the plate preferentially detaches from the surrounding material.

Another series of linear features is sometimes visible at the upper edge of a sliding plate as it comes to rest. As a plate halts the upper portions slide somewhat further (1 cm) than the lower portions, but in a series of discrete layers, like a card deck being sheared. This suggests that there may be sharp boundaries between sliding and static material, even though the material is cohesionless and unconsolidated.

Sample No. 2 was collected on the highest and most active portion of the dune, and Sample No. 3 from a low associated hummock of coarser sand, which could be made to wheeze by hand only.

3. Eureka Dune, (lat. 37° 6' N, Long. 117° 40' W). Located near the south end of Eureka Valley, at the western edge of the Last Chance Range, in California, this site is accessible via a signed dirt road leading off of the main Eureka Valley road (gravel). USGS quadrangle Last Chance Range covers the main dune area.

Eureka Dune is a very impressive formation, being more or less a single isolated structure, but attaining a height similar to that of the highest crests in the much more extensive Kelso field. (Other nearby sand deposits built up on spurs extending into the valley from the Saline Mountains on the west were not investigated at this time). As with all the other large dunes investigated, the lower portions were sparsely vegetated, while the upper portions, beyond the level of capillary action[(7)], are devoid of macroscopic plant life.

The high crests of Eureka Dune demonstrated all the booming properties observed at Kelso, although the acoustic intensity did not appear to be quite so great. Sample No. 4 was collected on the highest booming crest, and Sample No. 5 from some lower shoulders where the average grain size was considerably larger. It was not possible to generate booming sounds in the field at this latter location.

4. Panamint Dunes, (lat. 36° 28' N, long. 117° 27' W). Located in the north end of Panamint Valley, these dunes may be approached by an indistinct dirt mining road leading north from California route 190. USGS quadrangle Panamint Butte covers the region. Access to the dunes from the road is by foot several kilometers across the valley floor and up a large alluvial fan. The dunes proper are considerably lower than those at Kelso and cover a rather smaller area. To the south extends an extensive, but sparsely vegetated, plain of coarse sand only occasionally built up into very small hummocks. The sand here was silent. Sample No. 7 was collected in this region.

The dune crests exhibited moderate acoustic activity. Although sand avalanches could be easily started on the steepest slopes, they produced no significant booming. However, forced displacement of sand by the boot, and shearing and compression produced by drawing the open hands rapidly together elicited easily audible vibrations. Material collected in this region constitutes Sample No. 6.

5. Death Valley Dunes, (lat. 36° 37' N, long. 117° 7' W). Located several kilometers southeast of Stovepipe Wells, these dunes are easily accessible from California route 190. USGS quadrangle Stovepipe Wells covers the main dune area. These dunes are more extensively vegetated than those dunes discussed above, and the vegetation in spots grows nearer to the crests. This was the only site of dunes of great height for which no acoustical activity could be generated, in any manner, in the field. Sample No. 8 was collected near the top of the highest crest. Sample No. 9, consisting of predominately very fine particles, was collected from small drifts off the shoulder of California 190 near the large dune location.

6. Saline Dunes (lat. 36° 46' N, long. 117° 51' W). Located in the western portion of Saline Valley, California, these dunes are accessible from the main north-south Saline Valley road (gravel). USGS quadrangle Waucoba Wash covers the main dune area. These dunes are smaller in height than those found in any of the above sites. The dunes were sparsely covered with vegetation,

including the crests, and no significant booming could be induced by any of the techniques discussed earlier. Sample No. 10 was collected from the top of a small dune on the western edge of the field.

7. Olancha Sand Drift, (lat. 36° 18' N, long. 117° 58' W). Sample No. 11 was collected from some small east-west running drifts, ~1 meter high, on the south side of California route 190, near the turn off to Dirty Socks Hot Mineral Spring. These are much smaller than and are to be distinguished from the larger dunes located several kilometers further south. In the field, the sand here could not be made to produce any booming sounds. USGS quadrangle Keeler covers the area.

8. Will Rogers Beach, (lat. 34° 2' N, long. 118° 33' W). As a comparison, some beach sand, Sample No. 12, was collected from Will Rogers Beach State Park, California. USGS quadrangle Topanga covers the area. The sand does not have any booming properties.

9. Newport Beach, (lat. 33° 36' N, Long 117° 55' W). A second comparison, Sample No. 13, was collected from the beach at Newport Beach, California. USGS quadrangle Newport Beach covers the area. The sand could not be made to boom in any manner.

With all these methods of inducing sound, one may wish to have a definition of booming sand. It seems not unreasonable to expect that if the mechanism for one mode of excitation is understood, then the others will also be understood, even though the frequencies and amplitudes differ considerably among them. It is after all the same kind of particles rubbing together in all cases. Specifically we would like to include in our definition of booming some reference to those methods of excitations which involve relatively small volumes of sand, since this allows simple and more controlled tests to be performed in the laboratory. If all possible tests produce audible vibrations, the sand is clearly booming. We adopt the point of view here that even if only some tests produce pronounced vibrations, the sand is still booming. There can be many reasons for only partially positive results in a series of tests. For example, the slope of the flank of a dune crest may be insufficient to produce a sustained avalanche, or recent rainfall or high humidity may have temporarily eliminated all sounds which might have otherwise been found in the field. Tests designed for the laboratory are not expected to be so subject to factors which really have no intimate connection with the booming mechanism itself.

In this connection there are two simple qualitative tests which can indicate the presence or absence of coherent vibrations of a sand mass. The first is based on the observation that a known booming sand (say Kelso) can produce easily detectable vibrations when placed in a container (glass beaker, stainless steel beaker, plastic bottle, plastic bag, etc.) and shaken back and forth. The vibration seems to be associated mainly with the collision of the moving mass with a wall of the container, and thus a suitable amount of empty space must be allowed in order for the sand to slosh against the sides.

It proved convenient to use a medium sized glass beaker filled about one quarter full of sand. The beaker is shaken sideways with an amplitude of perhaps 5 cm at a rate of ~5HZ. For booming sands a vibration may be felt in the fingers at each endpoint of the motion. The frequency of the vibration is evidently greater than 5 Hz, and I would estimate it to be more like several hundred Hertz. (For other modes of excitation, some spectra are given below). This procedure is referred to below as the "beaker test" and serves as a quick and rough indication of the presence or absence of acoustic activity. For a strongly booming sand like Kelso, the vibrations are strong enough to produce an easily audible sound, while for others vibrations can be sensed only through the fingers, or are absent entirely.

The second simple diagnostic test involved forced compression and shearing of a small (7 cm^3) inverted cone of sand by a suitable plunger. The sand is prepared by filling a funnel with the requisite amount of sand while its open end rests on a suitable smooth surface. The funnel is then slowly lifted, allowing the sand to form a small cone. Compression, from the top, is conveniently performed with the bottom of a small hand held glass beaker, although other objects, such as a large rubber or neoprene stopper, work equally well. Booming sands produce high pitched (squeaking) tones (~1000 Hz) when compressed and sheared in this manner with plunger velocities on the order of 1 m/sec. This procedure is referred to as the "compression test".

Before proceeding further, we take the opportunity to mention the important influence of adsorbed water vapor upon the acoustic performance of the sand. It is reported [1, 2] that recent rainfall or high humidity effectively silence the sound emission from dunes which are otherwise known to boom. Dry sand returned to the laboratory in sealed plastic bags retains its sound generating property for months, at least, if kept sealed, but quickly (hours or days) loses this property (measured by beaker or compression tests) when exposed to the laboratory atmosphere. The property can be fully restored by heating and stirring the sand in a shallow pyrex dish over a open gas flame until the evident surface caking produced by evaporated and subsequently recondensed moisture has disappeared. The sound emission characteristics can be eliminated and restored at will by sequentially moistening and drying the sample. For example, five drops of water in 1 liter of fresh Kelso sand essentially eliminated the strong vibrations initially evident upon shaking the sand in a 1 gallon plastic water jug. Placement of several grams of anhydrous $CaCl_2$, wrapped in cheesecloth, in the sealed jug led, in a few days, to a partial restoration of the vibrations. Heating restored it completely. In the beaker and compression tests described below, unless otherwise indicated, the sand samples were preheated and allowed to cool to a temperature tolerable to the hand just prior to testing.

Since the sand mean grain size and grain size distribution may be important determining characteristics of acoustic activity, we sorted the thirteen samples mentioned above into the bins 0-104 μm, 104-175 μm, 175-246 μm, 246-351 μm, 351-589 μm, and ≥ 589 μm, and investigated the properties of each size fraction separately. Table I gives the mass fraction in each bin, for each sample. Fig. 2 shows a raw data histogram of mass fraction versus diameter. Note that bin sizes are not all the same.

There is evidently no common feature of the grain size distribution which is critical for *in situ* booming. Thus the strongly booming sites (Samples No. 1, 2, 4, and 6) are all deficient in the 0-104 μm bin. However, Sample No. 8 (Death Valley, dune) has a distribution essentially identical to Sample No. 2 (Big Dune, high crest), yet the Death Valley dunes were silent. The beach sands, Nos. 12 and 13, are also markedly deficient in the finest grain sizes, yet they are completely silent. It is not necessary that the sands be particularly well sorted: for example, the coarser Big Dune material, Sample No. 3, is moderately active *in situ*, while the fairly well sorted Newport sands, Sample No. 13, are silent.

These conclusions depend upon the assumption that other factors in the dune environment are uniform or constant from site to site. It is difficult to check this assumption. As far as is known, there was no rainfall in any of the locations visited immediately prior to sample collection. However, the Death Valley dunes, for example, tended to be vegetated over a larger fraction of their height than those at Big Dune, and a noticeable caking or cohesion of sand particles was observed on the middle elevation flanks, although not the crests themselves. Even in the absence of rainfall it may happen that a significant amount of water resides in the latter dunes, even at the higher elevations, due to (a) enhanced capillary action associated with a higher ground water level and/or (b) a greater hygroscopic tendency due to salt accumulation in the dune. Salt accumulation in the interdune beds upon which the dune itself rests were more pronounced at Death Valley than at the other sites, except for Olancha, where the sand was also silent.

The silent beach sands would not be expected to be dry *in situ*, of course, and in addition they may be contaminated with sodium chloride and other salts.

Arguments of this type support the idea that the occurence of booming in a particular dune field or other sand formation depends upon the simultaneous presence of a number of environmental factors. Thus spectacular booming could be a fairly unusual occurence even though the structure at the grain level is quite uniform for many dunes. In the laboratory, where the environment (mainly moisture content) is more fully controlled than in the field, we would expect booming to be a more common occurence.

With the various grain size fractions in hand a number of tests were performed to attempt to elicit acoustic emission. For sand from several sites, including both *in situ* booming and silent sands, compression tests were run on each fraction. For the remaining samples, the compression test was applied to the abundant (and generally active) 175-246 μm fraction. The results are summarized in Table II.

From this Table it is clear that all *in situ* booming sands have at least one very active size fraction as determined by the compression test. All the *in situ* silent dune deposits have some at least moderately active size fractions. Even the Olancha (Sample No. 11) and Death Valley roadway (Sample No. 9) sands, which were not secured from well developed dune crests, showed modest acoustic responses. Thus all samples collected from eolian deposits showed some activity in either the abundant 104-175 μm or 175-246 μm fractions. Only the beach sands (Sample No. 12 and 13) emitted no clear tones under any circumstances.

Scanning electron microscope analyses of grain shapes and textures are not yet completed. However, Criswell [2] found that grain surface texture was an important factor in determining acoustic activity. We anticipate [8, 9] finding characteristic differences between the marine (Samples 12, 13) and the eolian samples. Some preliminary results indicate that the Death Valley dune sand, Sample 8, which was silent in the field, is composed of grains of more irregular shape than those found in the other desert deposits studied here.

The quality of the tone produced by activated sand is shown in Figs. 3-4. In Fig. 3, a tape recording of Kelso dune sand,made to slide in the field by a person forcing himself downslope on his haunches,is analyzed into its Fourier coefficients. The peak is at 92.8 Hz, and has a full width at half maximum of approximately 4 Hz. The peak position and width are not absolutely stable in time, as illustrated by Fig. 4, which shows a Fourier analysis of the same Kelso sliding event, but at a different time. The peak has shifted to 96.8 Hz, and the shape is somewhat different, although the full width at half maximum remains about the same. A small feature has meanwhile appeared at 147.2 Hz. It is not clear whether this is due to the action of the sand, or is an artifact of the excitation method. Although an attempt was made to keep the environment as silent as possible, except for the emission from the sand, there was a certain amount of noise inevitably generated by the person driving the sand downhill. Nevertheless, these figures give a fairly clear idea of the purity and stability of the sound generated on the sand slopes themselves.

The compression tests generated sounds of a much higher frequency. As discussed above, when small quantities of sand were rapidly sheared and compressed on the dune itself, a higher pitched note was sounded than when larger quantities of sand were moved more slowly. In the compression test, a small amount of sand ($\sim 7\ cm^3$) is compressed and sheared very rapidly, and the high pitch of the note is qualitatively consistent with observations on the dune. As the sound emission mechanism has not been established, it cannot be said for certain at this point whether mass or velocity, if either, is the determining characteristic. However, it seems likely that the differences in velocity are responsible for the change of frequency, with a change in mass (or area) merely affecting the efficiency of the coupling of the sand vibration to the air vibration.

Figs. 5-7 show Fourier coefficients for compression tests conducted on 175-246 μm fractions of Kelso (Sample No. 1, booming), Saline (Sample No. 10, silent), and Will Rogers (Sample No. 12, silent) sand. The sound emission in each case lasted only about 0.1 sec and peaks shown were taken from near the maximum peak height.

The Kelso sand, from Sample No. 1, Fig. 5, produced a major peak at 1224 Hz, with a series of associated features ranging down in frequency to around 1160 Hz. The low frequency range below about 300 Hz shows background noise not associated with the sand (pumps, air conditioning) and appears in all three traces.

The Saline sand, from Sample No. 10, Fig. 6, produced a major peak at 964 Hz. It is not known if the several subsidiary peaks (e.g., 430 Hz, 1370 Hz) with frequencies greater than ~ 300 Hz constitute background noise or not. In any case, this sample also concentrates output in a narrow band around a thousand Hertz.

Fig. 7 shows the response of the Will Rogers beach sand, Sample No. 12. It is totally unlike the previous two examples. Although large peaks are present, there is no concentration of emission confined to a small range of frequencies. The audible impression given by the shear corresponding to this event is an indistinct and slurred hissing, as compared to the musical squeaks elicited from the Kelso and Saline sands.

These tests were run on carefully heated and dried sand samples. The Will Rogers sample had been rinsed in distilled water first to remove as much salt and loose organic matter as possible. As mentioned above, however, high humidity at the dune site, or moist sand, effectively eliminate the booming quality. In view of the apparent importance of the grain surface in determining the acoustic properties, it is not surprising that various modifications of the surface may affect the booming property, perhaps removing it altogether. We are thus led to consider briefly how addition of liquid or finely divided solid impurities can alter the acoustic output as measured by the beaker or compression tests.

A. Kelso 175-246 μm fraction plus ~1% by volume of the same fraction, but ground into a fine powder. The compression test gives a definite loud squeak, while the beaker test gives only the faintest of tactile vibrations. The result of the beaker test is very different from that for untreated Kelso sand, where the vibrations are very pronounced.

B. Kelso 175-246 μm fraction plus ~1% by volume powdered talc. The compression test gives a pronounced squeak while the beaker test yields only faint vibrations. These results are very similar to those of part A.

C. Kelso 175-246 μm fraction plus ~1% by volume powdered iron. The compression elicited no definite squeak, while faint but definite vibrations were present in the beaker test.

D. When any of the Kelso fractions, or the unsorted Kelso sand, was treated with green India ink (such grains were used as markers to examine flow patterns under shear) and allowed to dry, the compression test produced nothing at all resembling a tone. It was not, however, possible to dry this sand by heating in the usual way as high temperatures caused the ink to decompose. If dyed grains are utilized in an attempt to study the flow pattern of moving sand, therefore, one must be aware that the frictional properties of the grains, and thus possibly the flow itself, can be substantially modified.

E. Using a non-standard volume (30 cm^3) of unsorted Kelso sand, which in the compression test can produce a very loud squeak, the effect of moisture was investigated. One drop of distilled water thoroughly mixed with the sand was sufficient to render the sample totally inactive in both the compression and beaker tests.

F. To a similar volume (30 cm^3) of unsorted Kelso sand was added 0.3 cm^3 finely powdered aluminum. The compression test produced a loud squeak and the beaker test a moderate tactile vibration which was just audible. Addition of 1.0 cm^3 of Al to this same sample produced the following results: compression test; not so loud, but a definite tone was present; beaker test; no vibrations. Addition of 1.0 cm^3 more Al (Al 8% of total sample by volume prior to mixing) resulted in the compression test giving no sound. The beaker test remained negative.

These results give some indication of the sensitivity of the booming mechanism to grain surface conditions. As a controlled method of exciting the grain system was not available at the time when these observations were made, it is not possible to draw detailed conclusions from the above data beyond the fact that such surface sensitivity is indeed present. Note that both insulating and conducting impurities produced effects, to varying degrees. There is some indication that the response to the compression test, at least where solid particulates were added, is less sensitive to impurities. This is consistent with the fact that intergrain forces are likely to be considerably higher in the compression test, than in the beaker test, so that ball bearing or lubrication effects involving finely divided material are less likely to be important. That is, impurity particles get pushed out of the way, or mashed flat enough, that grain surfaces may still rub together.

Finally, there are a couple of further observations which might be helpful in illuminating the mechanisms responsible for acoustic emission. First, a stainless steel chamber through whose walls the vibration of freshly dried Kelso sand were clearly felt at atmospheric pressure upon shaking, was evacuated slowly. The intensity and quality of the tactile vibration appeared to be independent of the pressure inside the vessel. This confirms earlier observations [2,10], and rules out the role of trapped intergrain air in the booming mechanism. In most vibrational problems in physics we look for a feature of the system which will allow storage of potential energy, and the compressibility of air internal to the sand mass had seemed a possibility. But this is not the case.

Another interesting quality of granular material is connected with the property known as dilatation. If sand is piled up loosely, say by pouring from a beaker onto a horizontal surface to form a heap, or into another beaker or container, the sand mass so formed is generally not at its minimum volume. Agitation of the mass produces a marked decrease in volume. For example, the Kelso 175-246 μm fraction undergoes a volume shrinkage of about 10%. The Will Rogers 175-246 μm fraction, from Sample No. 12, shrinks by about 11%. Other sands investigated had similar dilatation factors. Thus there is the possibility of a slumping sand deposit alternately shifting a part of its energy between kinetic energy of motion and potential energy stored in a state of increased volume. Variations of this idea have been discussed by Poynting and Thomson [11] and by Bagnold [12]. Whether or not it is possible for the grain system to reach the high volume, high potential energy state is another question which depends in detail upon the nature of the grain-grain interaction (including friction).

REFERENCES

1. Curzon, Marquess of Kedleston, Tales of Travel, Hodder and Stoughton, London, 1923.

2. D.R. Criswell, J.R. Lindsay, and D. L. Reasoner; Seismic and Acoustic Emissions of a Booming Dune, J. Geophys. Res. 80 (1975) 4963-4974

3. J.F. Lindsay, D.R. Criswell, T.L. Criswell, and B.S. Criswell; Sound Producing Dune and Beach Sands, Geo. Soc. Am. Bull. 87 (1976) 463-473.

4. C. Brennen, private communication.

5. R.P. Sharp, Kelso Dunes, Mojave Desert, California, Geo. Soc. Am. Bull. 77 (1966) 1045-1073.

6. R.A. Bagnold, The Physics of Blown Sand and Desert Dunes, Chapman and Hall, London, 1973.

7. Bruce Pavlik, private communication.

8. D. Krinsley, P.E. Biscaye, and K.K. Turekian, J. Sed. Petrology 43 (1973) 251-257.

9. D. H. Krinsley and J.J. Doornkamp; Atlas of Quartz Sand Surface Textures, Cambridge University Press, 1973.

10. A. D. Lewis; Roaring Sands of the Kalahari Desert, S. African J. Geogr. 19 (1936) 33-49.

11. J. P. Poynting and J.J. Thomson; Text Book of Physics (Sound), Ch. Griffen, London, 1904.

12. R.A. Bagnold; The Shearing and Dilatation of Dry Sand and the "Singing" Mechanism, Proc. Roy. Soc. 295A (1966) 210-232.

TABLE I

Percent by weight of the indicated size fraction for thirteen samples. Sample No. 1, Kelso (booming); No. 2, Big Dune (high, booming); No. 3, Big Dune (low, booming); No. 4, Eureka (booming); No. 5, Eureka (silent); No. 6, Panamint (booming); No. 7, Panamint (silent); No. 8, Death Valley (dune, silent); No. 9, Death Valley (fines, silent); No. 10, Saline (silent); No. 11, Olancha (silent); No. 12, Will Rogers (silent); No. 13, Newport (silent).

Diameter µm	Sample # 1	2	3	4	5	6	7	8	9	10	11	12	13
<104	2	0	0	0	8	1	5	0	43	88	0	0	0
104-175	9	10	11	10	15	21	18	9	49	13	4	2	9
175-246	46	27	15	60	11	53	11	25	2	18	33	11	36
246-351	43	47	19	29	19	25	11	50	0	49	62	35	50
351-589	1	17	40	0	45	1	35	16	0	11	1	36	4
>589	0	0	15	0	2	0	20	0	5	0	0	15	0

TABLE II

Response of the indicated samples and grain size fractions to the compression test.

Sample/Size Fraction (μm)	Response to Compression Test
Kelso (booming #1)	
- unsorted	Faint squeak; Beaker - audible vibration
175-246	Loud; Beaker - easily audible vibration
Big Dune (high, booming #2)	
175-246	Loud
Big Dune(low, booming #3)	
175-246	Loud
Eureka (high, booming #4)	
- unsorted	Rather faint squeak; Beaker - moderate vibration.
<104	Insufficient material
104-175	Loud
175-246	Loud
246-351	Fainter than above, but definite
351-589	Insufficient material
>589	Insufficient material
Eureka (low, silent #5)	
- unsorted	Faint
<104	Loud
104--175	Loud
175-246	Loud
246-351	Very faint or absent
351-589	Very faint or absent
>589	Very faint or absent
Panamint (high, booming #6)	
175-246	Loud

Table II

Sample/Size Fraction (μm)	Response to Compression Test
Panamint (low, silent #7)	
175-246	Fairly Loud
Death Valley (high, silent #8)	
175-246	Fairly Loud
Death Valley (roadway #9)	
104-175	Very modest squeak
Saline (silent #10)	
<104	Silent. Cakes slightly upon compression
104-175	Fairly loud
175-246	Fairly loud
246-351	Fainter, but definite
351-589	Fainter, but definite
>589	Insufficient material
Olancha (silent #11)	
<104	Insufficient material
104-175	Fairly loud
175-246	Fainter but definite
246-351	Fainter but definite
351-589	Insufficient material
>589	Insufficient material
Will Rogers (silent #12)*	
<104	Insufficient material
104-175	Silent
175-246	Very faint or absent
246-351	Silent
351-589	Very faint or absent
>589	Too rocky to test

* (rinsed in distilled water)

Table II

Sample/Size Fraction (μm)	Response to Compression Test
Newport (silent #13)*	
175-246	Very faint or absent

* (unrinsed)

FIGURE CAPTIONS

Fig. 1. Map of southern California and part of Nevada showing (x-marks) collection sites for samples discussed in the text.

Fig. 2. Histograms showing weight percentage for indicated size fractions of each sample. We caution that bin sizes are unequal.

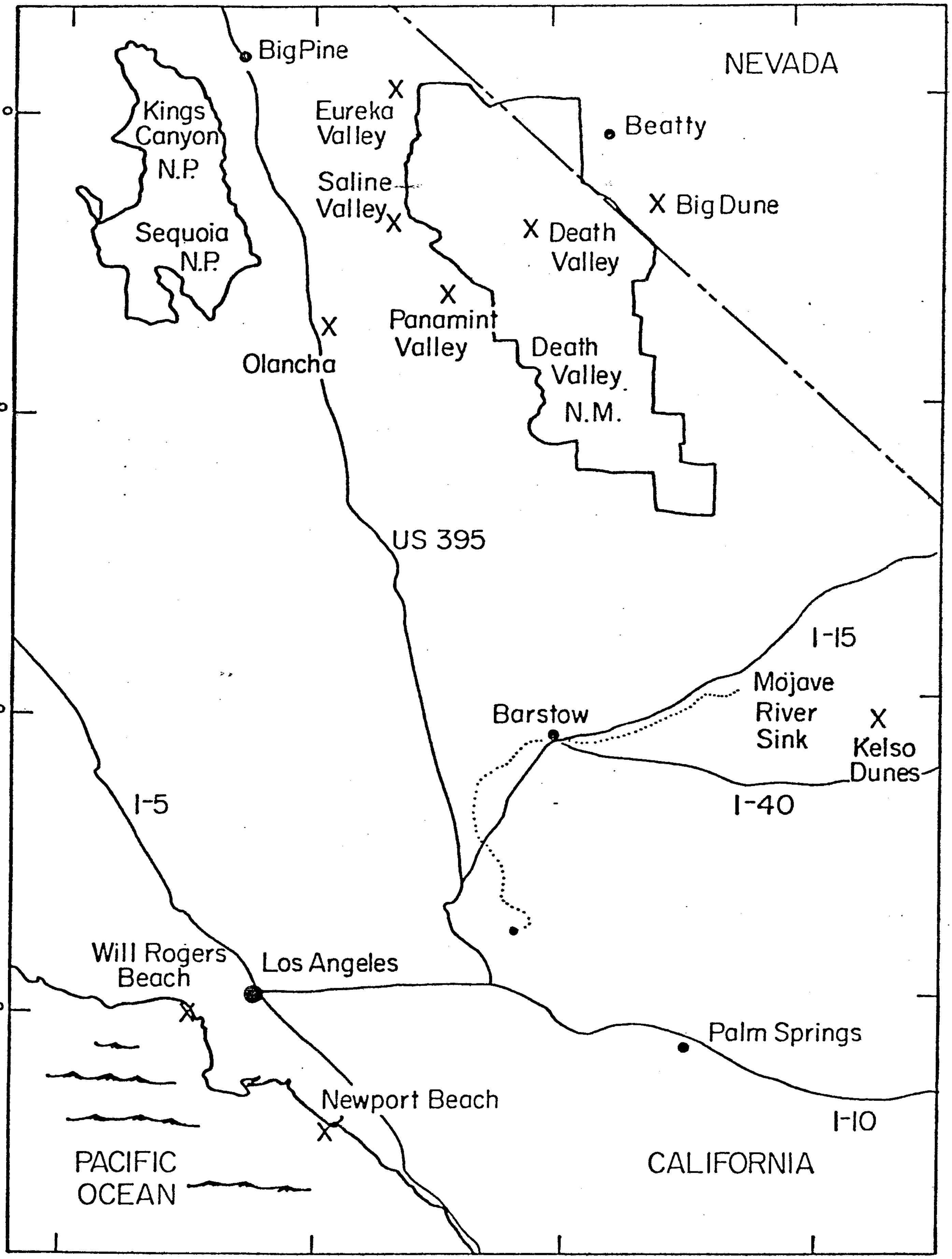
Fig. 3. Fourier components of induced Kelso booming event. Peak is at 92.8 Hz.

Fig. 4. Same as Fig. 3, but a few seconds later. Main peak is at 96.8 Hz, and subsidiary peak is at 147 Hz.

Fig. 5. Fourier components for compression test of Kelso sample (175-246 μm fraction).

Fig. 6. Same as in Fig. 5, but for Saline Sample.

Fig. 7. Same as in Fig. 5, but for Will Rogers sample.



NEVADA
Big Pine
Kings Canyon N.P.
Sequoia N.P.
Eureka Valley
Beatty
Saline Valley
Big Dune
Death Valley
Panamint Valley
Olancha
Death Valley N.M.
37°
36°
35°
34°
US 395
I-15
Mojave River Sink
Barstow
Kelso Dunes
I-40
I-5
Will Rogers Beach
Los Angeles
Palm Springs
Newport Beach
I-10
PACIFIC OCEAN
CALIFORNIA
119°
118°
117°
116°

Figure 1

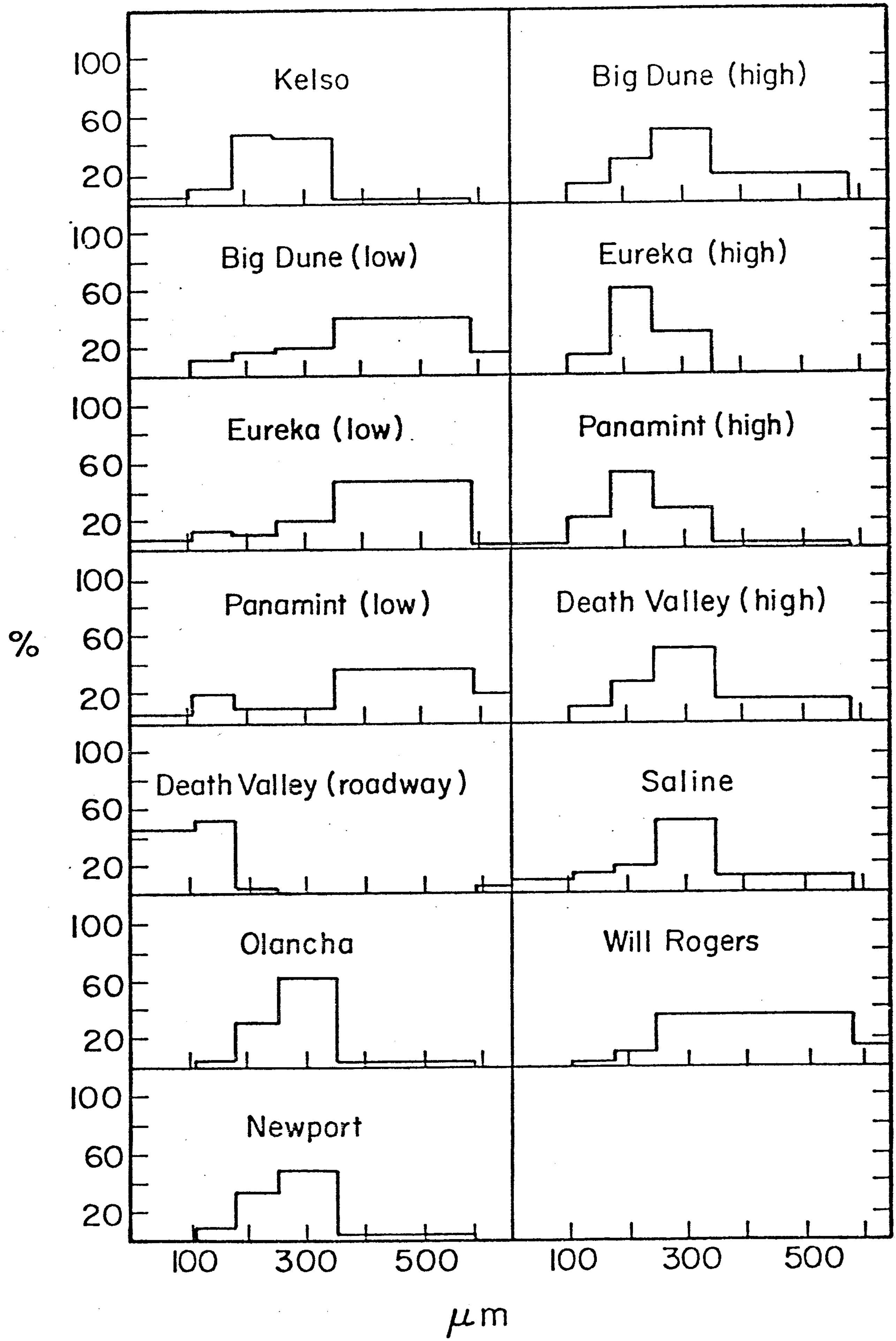

Kelso
Big Dune (high)
Big Dune (low)
Eureka (high)
Eureka (low)
Panamint (high)
Panamint (low)
Death Valley (high)
Death Valley (roadway)
Saline
Olancha
Will Rogers
Newport
%
100
60
20
100
300
500
μm

Figure 2

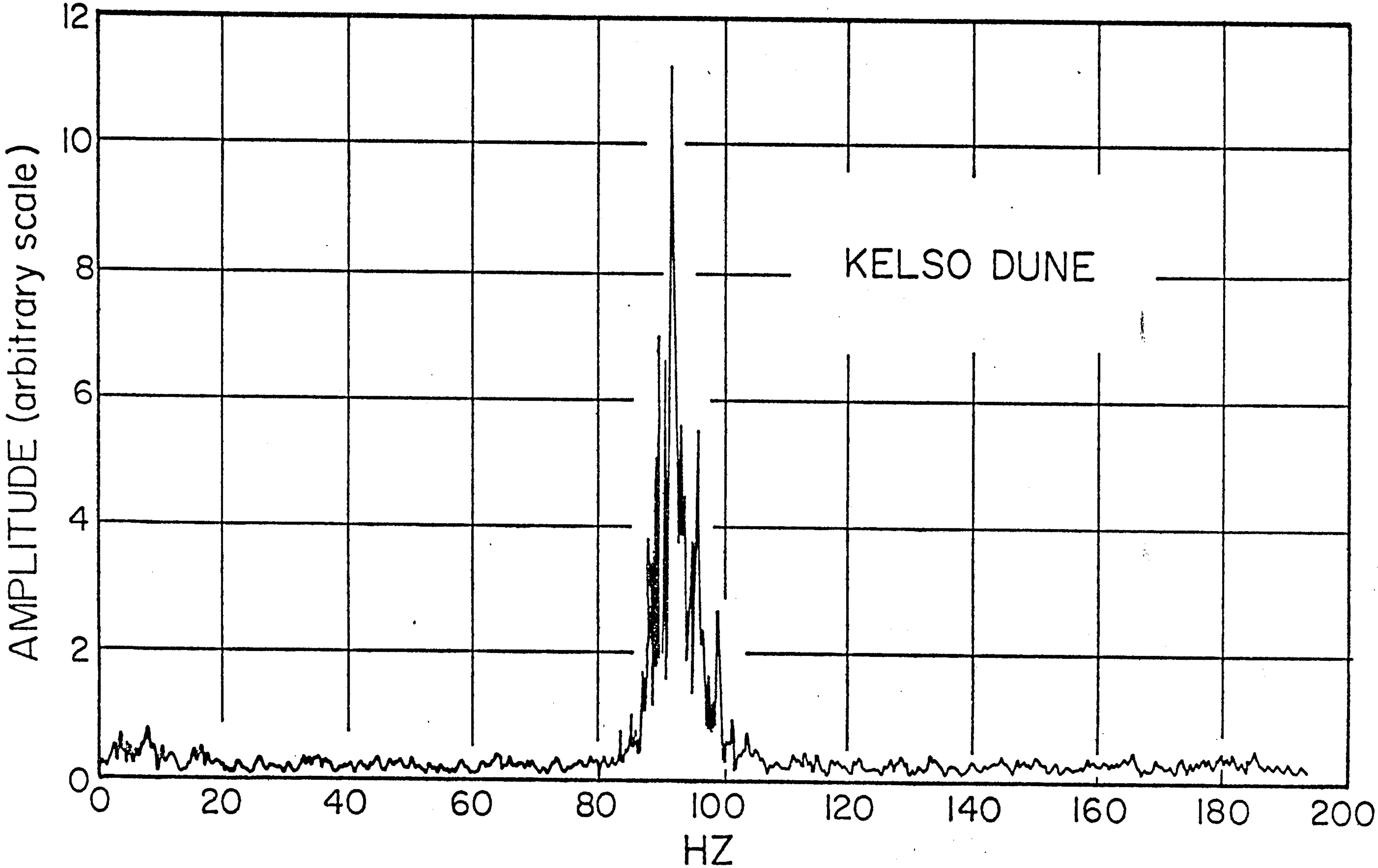

KELSO DUNE
AMPLITUDE (arbitrary scale)
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
180
200
HZ

Figure 3

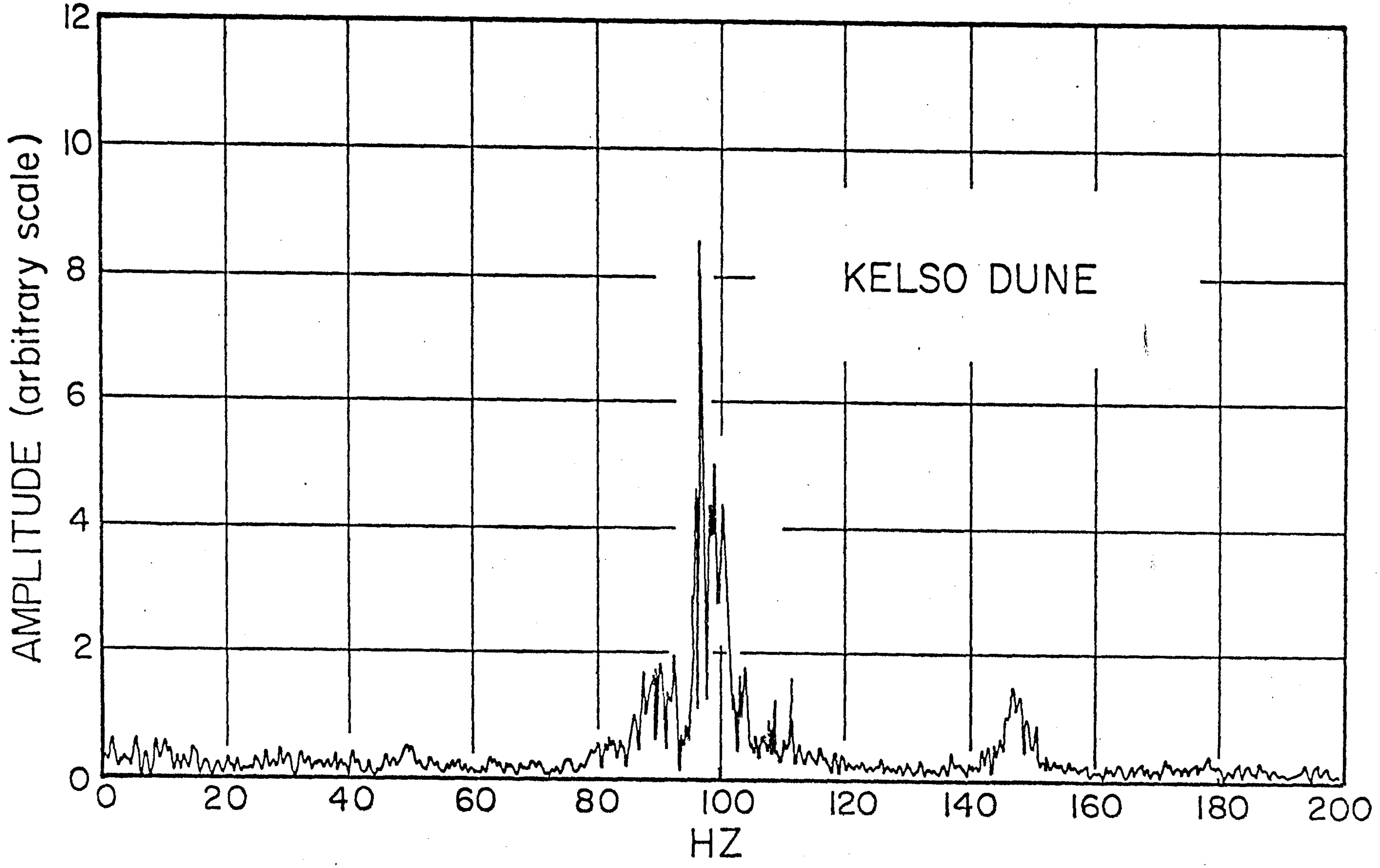

KELSO DUNE
AMPLITUDE (arbitrary scale)
HZ
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
160
180
200

Figure 4

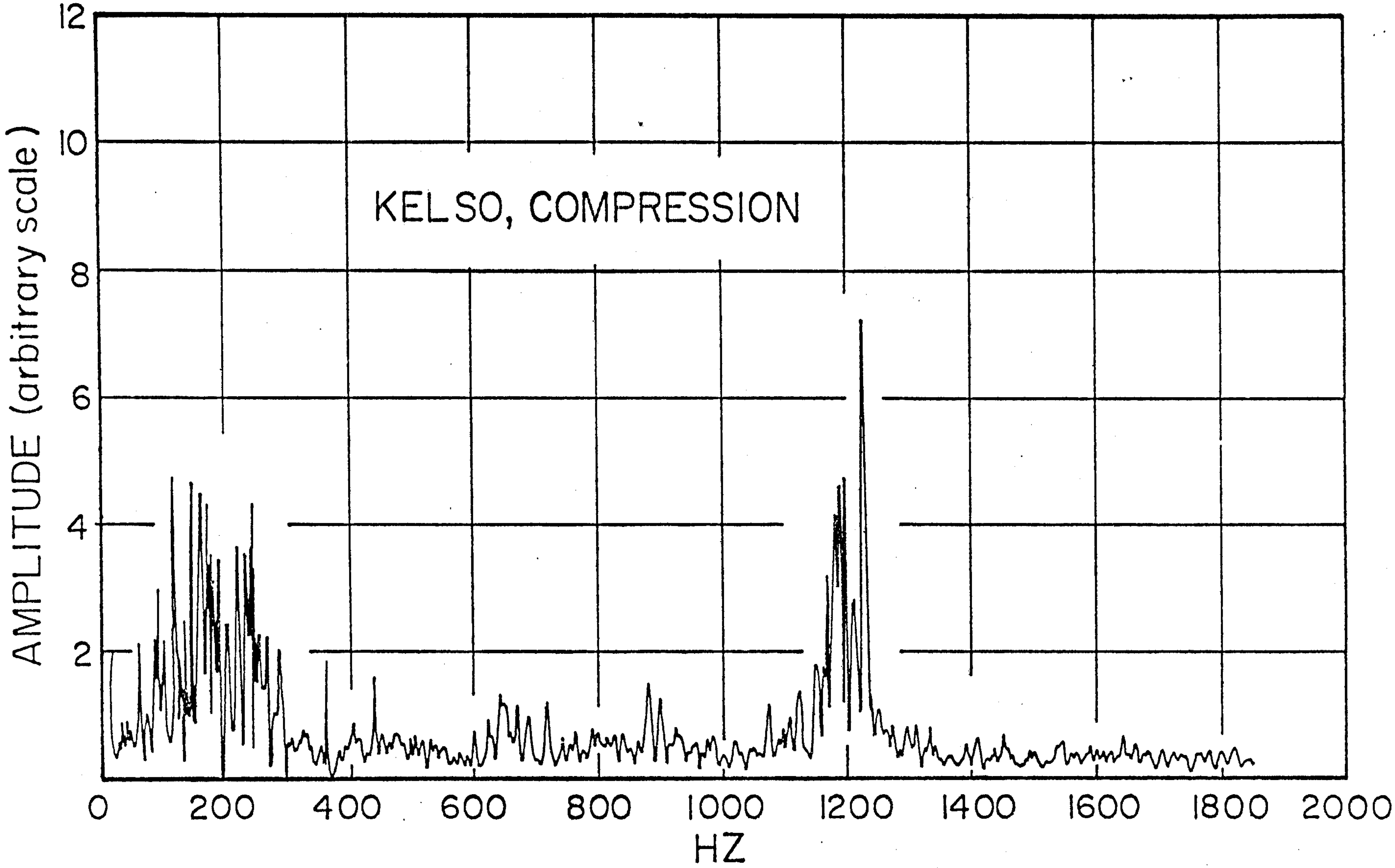

KELSO, COMPRESSION
AMPLITUDE (arbitrary scale)
12
10
8
6
4
2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
HZ

Figure 5

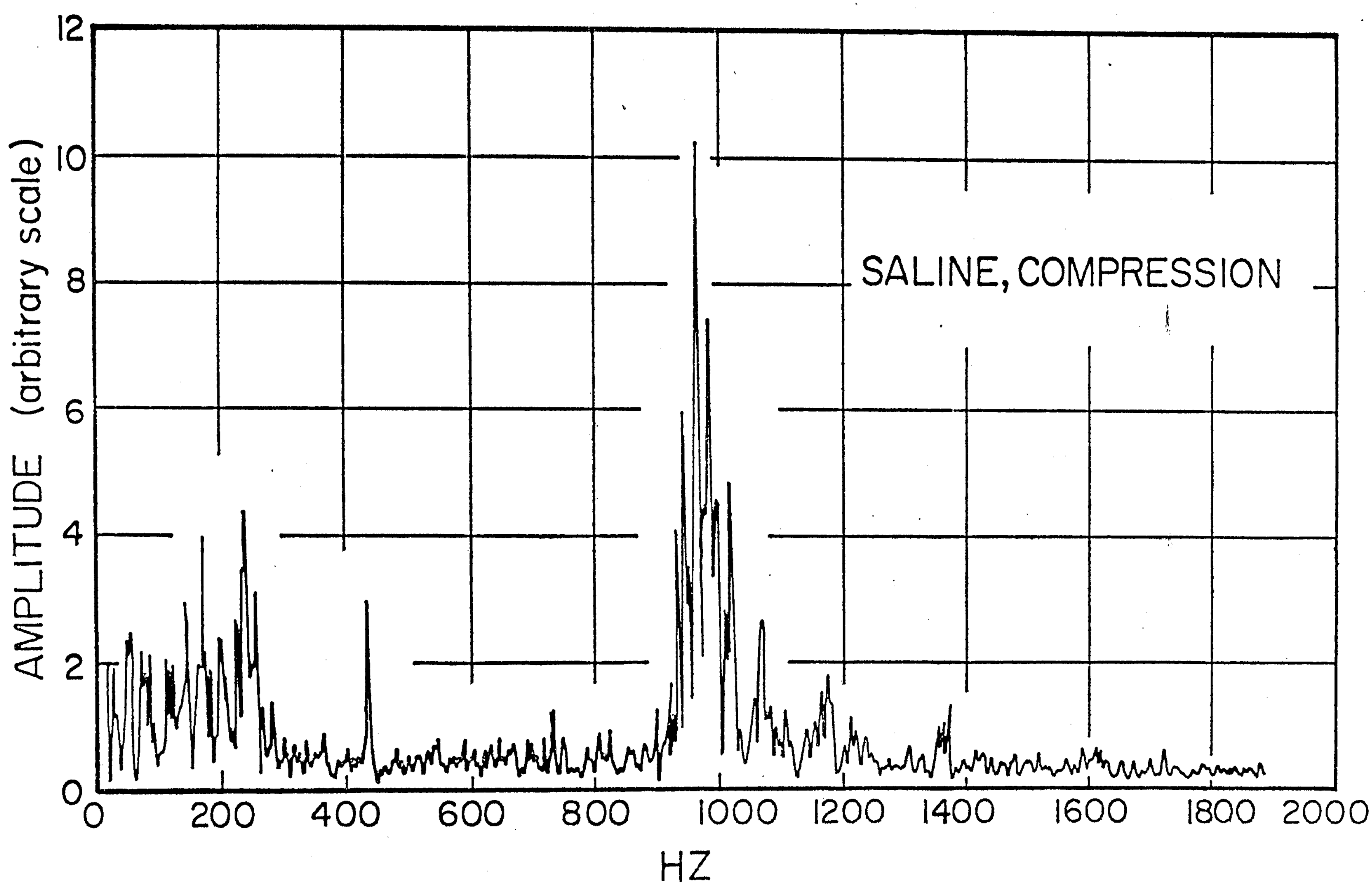

AMPLITUDE (arbitrary scale)
0
2
4
6
8
10
12
SALINE, COMPRESSION
0
200
400
600
800
1000
1200
1400
1600
1800
2000
HZ

Figure 6

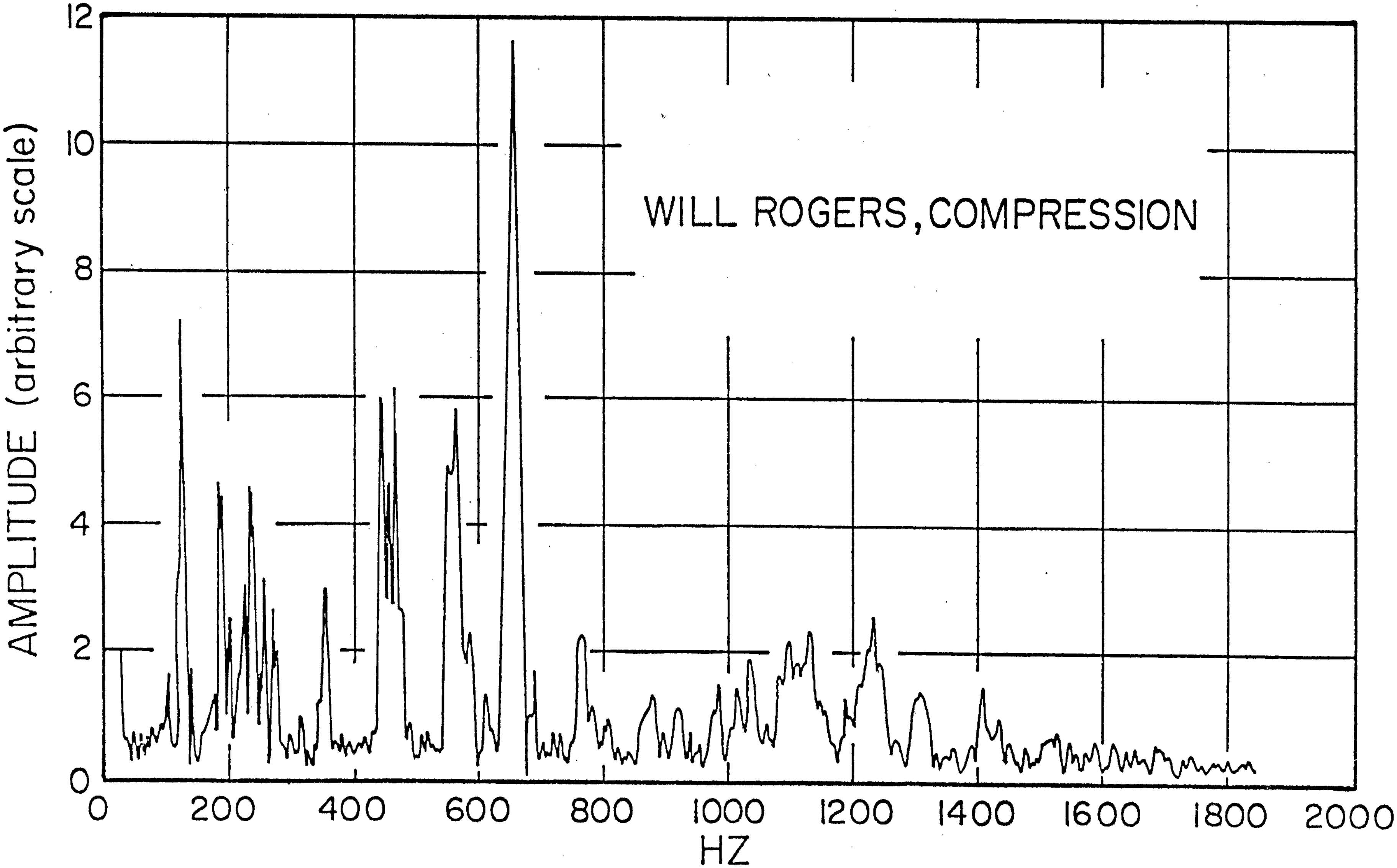

AMPLITUDE (arbitrary scale)
0
2
4
6
8
10
12
WILL ROGERS, COMPRESSION
0
200
400
600
800
1000
1200
1400
1600
1800
2000
HZ

Figure 7