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Brontides: Natural Explosive Noises

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Historical and scientific records from various parts of the world contain many accounts of episodes of mysterious booming or explosive noises, usually described as resembling thunder or the firing of distant artillery and sometimes, but by no means always, occurring in association with perceptible seismic activity (*1-3*). Obvious causes (such as artificial explosions, thunder, or meteorite entry) can be ruled out in most cases. Some of these episodes appear to have been precursory to major earthquakes.

Summary. Episodes of explosive noises of natural origin, or brontides, have been well documented, often in association with seismic activity and in a few cases as precursors to major earthquakes. Ground-to-air acoustic transmission from shallow earthquakes can account for many of these episodes, but not for all, and other causes, such as the sudden eruption of gas from high-pressure sources in the ground may at times have been responsible. Confusion with distant thunder or artillery at times of anomalous sound propagation complicates the analysis, and more recently the greatly increased frequency of artificial explosive noises and sonic booms has tended to mask the recognition of natural brontides.

The phenomenon of natural airborne booming noises does not appear to have been much discussed in recent times, but many accounts of it were published around the turn of the century, and there is evidence that it was recognized even in ancient times. In many instances, the noises occurred at irregular intervals over a period of months or years in a particular region and there acquired a local name. Thus we have Barisal guns in the Ganges delta, *mistpoeffers* ("fog belches") off the coast of Belgium, *brontidi* ("like thunder") in the Apennines, Seneca guns in central New York State, and some 20 other names to describe a similar type of event. We agree with Talman (*1*) that "the diversity of nomenclature is evidence of independent observation . . . for if any given community had merely borrowed its ideas on the subject from its neighbors, it would have borrowed the name as well." In this article, we will refer to all such natural booming noises of unknown origin as brontides, following a common usage in the earlier scientific literature.

This historical context may be relevant to discussions of the series of mysterious airborne acoustic "booms" heard (or felt) during the winter of 1977 to 1978 by thousands of people along the East Coast of North America (*4*). According to the Naval Research Laboratory (*5*), nearly all such noises were aircraft sonic booms propagated great distances under favorable atmospheric conditions; but a more recent study for the Mitre Corporation (*3*) concluded that although some 70 percent of the booms could be attributed to supersonic aircraft, "most of the remaining 181 events are believed to have a natural origin." Whatever the explanation eventually accepted for the East Coast episode, one is not justified in automatically assuming that every occurrence of mysterious booming noises can be accounted for by artificial sources.

Association with Earthquakes

The historical record suggests occurrences of booming noises in various degrees of association with earthquakes. In any one instance it may be very difficult to deduce the physical mechanisms responsible, and there are indications that even somewhat similar occurrences may have been due to quite different physical processes. In some cases, a long series of intermittent booming noises is heard, sometimes extending over many years, but having no clear association with seismic activity. In other cases, the series includes a number of minor seismic shocks in close coincidence with some of the booming noises; or the series includes a major earthquake. Yet another type is the occurrence of extremely loud detonation-like sounds in close association with the occurrence of a major earthquake but without any preceding sequence of booms.

Such transient phenomena, known only from "ear-witness accounts," are very difficult to analyze and interpret at a later time. For that reason the brontide phenomenon seems to have been largely ignored in recent times. However, tectonic and seismic events are rare and the time between occurrences is long, and this forces one to gain as much evidence from the past as possible. A better understanding may help in the discussion of the nature of earthquakes and perhaps improve the methods of prediction.

Several natural sources of airborne booming noises are known that have an evident or suspected relationship to tectonic events. In many cases it is difficult or impossible now to identify a particular episode of brontides with one or another of the following sources, but they must be considered as candidates.

1) Direct transmission during an earthquake of seismic energy into the air. The acoustic mismatch from ground to air is great, and a rather intense seismic wave is needed to generate a very loud sound. However, it appears that a noticeable sound may be generated by a seismic disturbance that is too weak to be felt.

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2) Fracture of an exposed or near-surface rock face (rock burst).

3) Sudden venting of high-pressure gas from deep below through fissures in the ground. Events of this type are known to occur in connection with so-called mud volcanoes and may well occur in other areas where the geological identification of the exit point is more difficult. Such gas emergence from an enormous overpressure is very effective as a source of sound; even very small amounts released by minor tectonic events may result in loud and sharp reports.

4) Electrostatic ignition of combustible gases that have emerged from below. This can lead to unstable burning or explosive events, and again it is well known in regions of mud volcanoes but may be much more widespread.

The types of events in categories 2, 3, and 4 can occur without any significant seismic disturbance, but many instances are also known where they have evidently been triggered by an earthquake.

It has long been suspected that some brontides are manifestations of unfelt or feeble earthquakes (*2*). Richter (*6*) suggested that even weak earthquakes can transfer energy of audible frequency and intensity from the ground to the air. But very little observational or theoretical work was done until recently, when Hill *et al.* (*7*) succeeded in recording an audible rumbling sound (~ 20 decibels above the threshold of hearing) at around 60 hertz produced by an earthquake of magnitude 2.8 in California. The primary (P) wave, which was apparently heard but not felt, was followed 2.2 seconds later by a secondary (S) wave (of larger amplitude but lower frequency), which was felt but not heard. Here the instrumental detection confirms a pattern often reported: a faint booming or rumbling sound noted seconds before a minor earthquake. Since the transmission of sound in air is very slow compared with that in the ground, the source of the airborne sound must then be close to the observer. Since in many cases the earthquake extended over regions of many kilometers, the sound must have had a local origin for each observer, and the direct transmission then seems the most likely explanation. The most frequent description, in terms of "distant thunder," implies that the noise was not very loud; a predominantly upward-directed low-frequency sound wave, such as the seismic signal might produce, would provide virtually no directional clues for an observer. For the P wave of an earthquake to be heard but not felt, the source region of the seismic slip should be small enough for the frequency of the intensity peak (the so-called corner frequency) to be audible. Furthermore, the hypocenter must be relatively shallow and the propagation path must be well consolidated so that the audible frequencies can reach the surface with little attenuation (*8*).

The analysis by Hill *et al.* established that seismic vibrations near the threshold of human detection could indeed produce faint but audible sounds. A question then arises concerning the loudness of a boom that can be produced by an earthquake too faint to be felt. Can one expect an earthquake for which even the S wave cannot be felt to result not only in an audible, but even in a loud boom?

Audible Detection Threshold

In general, the maximum sound pressure, p, measured in air during an earthquake will be due to the integrated effect of acoustic radiation from an extended surface area of the ground around the observer (*9*). For our purposes, however, it is sufficiently accurate to assume simple one-dimensional acoustic transmission from the ground to the air. If we let p_1 be the incident seismic wave pressure in the ground and p_2 be the transmitted acoustic wave pressure in the air (both relative to ambient pressures) and let $\rho_1 c_1$ and $\rho_2 c_2$ be, respectively, the acoustic impedances of the ground and of the air (where ρ is density and c is sound velocity), then continuity at the interface between incident, reflected, and transmitted waves (*10*) gives

$$p_2 = 2\,\frac{\rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}\,p_1 \approx 2\,\frac{\rho_2 c_2}{\rho_1 c_1}\,p_1 = 2\rho_2 c_2 v_1$$

where v_1 is the velocity of the particle displacement in the incident seismic wave. Assuming that the latter is sinusoidal with frequency f, and taking root-mean-square values for pressure, velocity, and accelerations, we can write

$$p_2 \approx 2\,\frac{\rho_2 c_2 a_1}{\omega}$$

where a_1 is seismic root-mean-square acceleration and $\omega = 2\pi f$. In decibels, p_2 translates to $L = 96.6 + 20 \log (a_1/f)$, where a_1 and f are in cgs units, and 0 dB corresponds to the standard pressure of 0.0002 dyne per square centimeter.

Using the equation above, we show in Fig. 1 the acoustic air pressure produced by a seismic vibration of given acceleration (lines labeled in units of the gravitational acceleration, g) as a function of frequency. From measurements of the threshold acceleration for human tactile detection of ground vibration (*11*), we plot (dotted line) the *corresponding* sound pressure transmitted from the ground to the air. Also plotted (heavy line) is the human audible and infrasound detection threshold (*12*). We note that for ground vibrations with $f \lesssim 17$ Hz, there is a range of accelerations (or equivalent amplitudes) for which the vibrations can be felt but not heard; for $f \gtrsim 17$ Hz, there is a range for which they can be heard but not felt (that is, above the audible but below the vibration thresholds). The observation of Hill *et al.* (circle with error bar) falls within the latter range.

Figure 1 shows in addition the audible threshold curve for homing pigeons, as recently determined by Kreithen and Quine (*13*). Homing pigeons have an extraordinary infrasound detection threshold some 40 dB below that of humans, which probably allows them to sense the occurrence of certain extremely faint seismic tremors that remain both unfelt and unheard by humans. Detection of foreshock infrasounds may in part explain the apparent ability of birds (and perhaps some other animals) to sense impending earthquakes. We believe, however, that most of the widely reported anomalous behavior of animals before earthquakes (*14*) is due to the sense of smell; a growing body of evidence (*15*) indicates that deep-seated gas at high pressure is emitted before many earthquakes and this may drive the overlying soil-entrapped gases into the atmosphere, causing alarm among animals with sensitive olfactory organs (*16*). Infrasound detectable by birds may also be produced by this latter process.

In attempting to determine whether loud brontides can in fact be produced by seismic ground-to-air transmission, a difficulty arises in evaluating the subjective impressions of what constitutes a "loud" noise. In many accounts of brontides, witnesses compare the quality and intensity of the sounds to thunder, so we shall attempt to use thunder as a rough calibration. Measurements of the acoustic intensity and frequency range of thunder are surprisingly few (*17*), but we estimate that most thunder sounds as perceived by observers on the ground fall within the ellipse in Fig. 1. The lower bound on their intensity is probably determined by refraction shadowing for thunder originating beyond a critical distance, the upper bound by the average breakdown voltage for normal thunder and the exclusion from our sample of any extremely close strikes.

It is clear from Fig. 1 that sounds as loud as very close thunder, or even louder sounds (such as 120 dB at 40 Hz), might well be produced by violent earthquakes, in which the ground acceleration is typically in the range 0.1 to 1*g*. Many of the loud booms reported as having occurred during intense earthquakes may well have been produced in this way, with atmospheric refraction perhaps accounting for the apparent aerial origin of these sounds.

Considering the question of brontides in the absence of perceptible earth tremors, we note that since the locus of sounds generated by unfelt earthquakes must lie below the curve corresponding to the human vibration threshold in Fig. 1, and since this curve intersects the lower part of the elliptical locus of normal thunder, the data would appear to rule out the possibility that unfelt earthquakes can generate sounds as loud as very close thunder. This conclusion is perhaps strengthened by the possibility that the plotted vibration threshold data are systematically on the high side. An earlier set of vibration detection data obtained under more rigorous conditions (*18*) gives a more sensitive threshold that would be plotted some 20 dB below the dotted curve in Fig. 1; this implies that an unfelt earthquake can generate only very faint sounds. However, a laboratory environment is not a good approximation to the conditions under which people will first notice the occurrence of a minor earthquake. If we accept the vibration threshold curve as shown in Fig. 1, then the data admit the possibility that feeble earthquakes can be detected more readily in some cases by sounds than by vibrations. From this discussion it does not seem very likely that a sound described as very loud, being presumably more than 50 dB above threshold, could be produced by earthquakes whose P waves are not felt or by earthquakes so weak that even the S wave is not felt.

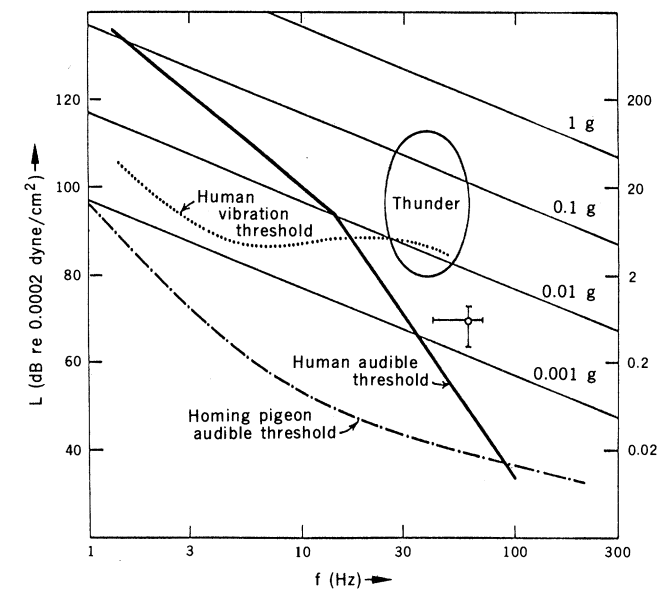

Fig. 1. Sound intensity (in decibels or acoustic pressure) transmitted from the ground to the air by seismic vibrations of different accelerations (parallel lines) as a function of wave frequency. Superimposed are curves for the sound intensity in air transmitted by ground motion at the threshold of human vibration sensitivity (*11*), the human audible threshold (*12*), the homing pigeon audible threshold (*13*), and the locus of common thunder (*17*); the circle with error bars represents the sound recorded during a magnitude 2.8 California earthquake (*7*). The human audible and "vibration" threshold curves cross at ~ 17 Hz.

Sources of Brontides

Reports of brontides that may be difficult to explain by direct transmission of seismic waves to the air are plentiful. Episodes such as the *mistpoeffers* on the Belgian coast or the Barisal guns in the Ganges delta occurred in areas of deep alluvial sediments that would absorb heavily in the audible frequency range. It seems improbable that hundreds of small quakes would all occur in the intensity range in which they could be detected by sound but not be felt. Many episodes of this type, where long series of booms are reported over a period of years, seem to be associated with bodies of water, the sounds seeming to come from a great distance across an open ocean or a large lake. For example, the *mistpoeffers* seemed to come from out in the North Sea (*19*), the Barisal guns from out in the Bay of Bengal (*20*), the Seneca guns from over Lake Seneca. It is possible, of course, that some or all of these episodes have nothing to do with earthquakes. Under certain atmospheric conditions, for example, sounds can be heard at distances greater than 100 km from their source, leaving an intervening shadow zone of silence. Businger (*21*) suggested that the *mistpoeffers* may have been due to such anomalous propagation of distant thunder or artillery fire, and it is difficult to rule out this possibility.

Thus, in most cases where there is no known relationship with earthquakes, anomalous propagation of thunder, artillery fire, or other sounds must be considered. In fact, the association of the *mistpoeffers* with still, foggy days suggests that temperature inversions may have enhanced the propagation of sound across the water, perhaps from artillery exercises near the British coast.

For the case of the Seneca guns, a sporadic sequence of booms lasting many years, it seems strange that no conventional noise sources could be identified if any were, in fact, responsible. The Barisal guns, another well-documented series of booms, heard over many years near the coast of the Bay of Bengal and also as far as 300 km inland in the delta region, may represent a similar type of phenomenon. But here there is a suggestion of an association with the great Assam earthquake of 12 June 1897; the frequency of booming noises is reported to have increased in the days before the quake and to have subsided markedly thereafter (*22*).

All this may be coincidental, but in this case no alternative explanation unrelated to tectonic events seems very likely. Distant thunder would be readily identified by the seasonal nature. Artillery fire from ships at sea is unlikely to have been so common, or to provide an explanation for the reports from far inland. In this, as in some other cases, the possibility has to be considered that high-pressure gas venting was responsible.

There are now several lines of observational evidence strongly suggesting a role for the eruption of high-pressure (and sometimes combustible) gas in connection with seismic activity (*15*), and we cannot rule out the suggestion (*23*) that such a mechanism may also account for some of the brontide episodes. This might occur either by the physical impact of high-pressure gas from below the ground bursting into the atmosphere, or in some cases by its chemical explosion (if combustible methane or hydrogen is involved) due to ignition in the air. There is, in fact, a natural phenomenon that is known to produce explosive sounds in the atmosphere by both these means. We refer to the mud volcanoes, which are vents through which natural gas, mostly methane, is sporadically erupted, building up in the process mud mounds or even enormous mountains of sediment (*24*). Numerous outbursts of mud volcanoes have been attended by booming noises and sometimes flames (*25*). The gas is electrostatically self-igniting, as was first understood by Mallet (*26*) in his study of the mud volcanoes of Burma.

Massive escape of gases should not be thought of as limited to mud volcanoes (*27*). In the presence of near-surface mud, the location of the gas vent will become a permanently recognizable feature, and it is at such places that the phenomenon has been studied. But in the absence of mud, the eruption of similar amounts of gas would have left little visible record. One may suppose, therefore, that many other gas seeps or eruptions have occurred without attracting the attention of geologists. Were such an eruption of gas (with or without ignition) to lead to an explosive sound, it would be difficult to identify the source. In a few cases, reports of flames accompanying the noises lend support to a gas eruption explanation. For example, loud explosive noises and eruptions of flames were reported as issuing from Wantastiquet Mountain in New Hampshire on several occasions during the 18th century (*28*), and detonations with flashes were frequently reported from Lake Bosumtwi in Ghana during the last century, leaving the lake covered with dead fish (*29*).

Many brontide episodes appear to have had some relation to tectonic events, but are not clearly attributable to ground-to-air transmission of sound. There is, for example, the series of detonation-like sounds on the Adriatic island of Meleda (Mljet) heard between 1822 and 1825. A partial record of this episode lists 30 perceptible shocks, all but 3 accompanied by audible booming noises, plus 71 booming noises unaccompanied by shocks (*30*). The shocks were mostly weak, although some caused small landslides and cracked masonry. Yet some of the noises were apparently quite loud, described as sounding like "a cannon of rather large caliber fired at a distance of a few hundred paces." The account indicates that it was the booming noises rather than the shocks that were mainly responsible for general alarm among the population, causing many inhabitants to flee to the mainland. Another example of an episode of loud booming noises and only minor tremors occurred in 1874 in the mountains of western North Carolina (*31*), preceding the brontide episode in neighboring western South Carolina, discussed below, by about 10 years.

Precursory Brontide Episodes

The type of brontide episode that is of the greatest interest involves booming noises that are apparently precursors of major earthquakes. At times these may have been due to direct transmission by unfelt foreshocks for which, in the absence of sensitive local seismographs, the human ear has been the best available detector. In some cases, however, the descriptions of loud noises without identified shocks, or with only minor tremors, place this interpretation in some doubt, and gas releases may have been involved.

Examples of precursory brontide episodes include one preceding the Charleston (South Carolina) earthquake of 1886. For at least 18 months before that earthquake there were heard scores of dull booming noises, many accompanied by shocks, near the town of Ninety-Six in western South Carolina; these continued to be experienced there for several months after the earthquake (*32*). Reports of these explosive sounds were even published 3 months before the great earthquake (*33*). And in Summerville, near the epicenter of the Charleston earthquake, loud explosive noises and light earth shocks were experienced several days before the earthquake (*34*), and dull booming noises, sometimes accompanying the aftershocks, continued to be noted there for more than 1 year afterwards (*35*).

Another example is given by the San Francisco earthquake of 18 April 1906. According to one investigator (*36*), "heavy detonations and rumblings were heard near the base of Mount Tamalpais, Marin County, during the winter months and previous to the great earthquake which destroyed San Francisco," and these continued to be heard in Marin, Sonoma, and Mendocino counties, sometimes in association with the aftershocks, as late as 1908. And for a more recent example of such a precursory episode, Toksöz *et al.* (*37*), in their account of the East Anatolian earthquake of 1976, report that "noises resembling thunder were heard several times during the week preceding the quake," although "there were no foreshocks felt along the fault zone before the main shock."

Brontides accompanying major earthquakes but without a precursory series may be represented by the New Zealand earthquake of 1929. "Tremendous booming sounds" were heard more than 200 km from the epicenter, resembling "heavy rumblings, detonations, boiler explosions, and naval gun practice," which "appeared to come from a bank of clouds . . . in the general direction of the epicenter, and continued for about an hour" (*38*); that is, long after the quake. Another example is given by the great Assam earthquake of 1950; Kingdon-Ward (*39*), who was near the epicenter, said that immediately after the shocks, "from high up in the sky to the northwest (as it seemed) came a succession of short, sharp explosions—five or six—clear and loud, each quite distinct, like 'ack-ack' shells bursting." Booming sounds were heard as far as 750 km from the epicenter during this earthquake (*40*).

Such brontide events accompanying violent earthquakes may be due to a number of causes, including direct ground-to-air transmission, rock bursts, and landslides. Gas eruption may be indicated as a cause if the time relation with the shocks cannot account for the booms. Furthermore, the gas emission explanation is made probable in some instances by the range of other phenomena reported that demand a violent and sudden increase of the ground pore-fluid pressure. There are numerous reports of flames from the ground during major earthquakes (*15*), implying not only the release of combustible gases but also their spontaneous ignition. Loud roaring and hissing noises, as well as fountains of mud, water, and sand, have also been observed in many cases (*41*).

The relative absence of reports of brontide events in recent times may be ascribed to masking by the greatly increased frequency of explosive noises of artificial origin (most recently by supersonic aircraft booms). But in the light of the information that such noises of natural origin exist, and that they have a possible relationship to earthquakes, the occurrence anywhere of unexplained episodes of booming noises should be investigated and not be ascribed automatically to an artificial origin.

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25. See, for example, H. L. Chhibber, *The Geology of Burma* (Macmillan, London, 1934), p. 50. A possible association between the Barisal guns and eruptions of the mud volcanoes on the Burma coast was suggested by J. H. Rainey [*Proc. Asiatic Soc. Bengal* **1890**, 8 (1890)]. It should be noted that those mud volcanoes, some 800 km from the epicenter, erupted explosively on the day of the great Assam earthquake of 1897 and on the following day [Oldham (*22*, p. 41)]. This may simply have been due to destabilization by the long-period seismic waves, but it is conceivable that both the earthquake and the eruptions were triggered by the movement of deep-seated gas into an enormous area. For more on the connection between mud volcano eruptions and earthquakes, see J. Coggins [*Rec. Geol. Surv. India* **37**, 278 (1937)].
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Space-Filling Models of Kinase Clefts and Conformation Changes

Comparison of the surface structures of kinase enzymes implicates closing clefts in their mechanism.

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By finding similarities in the structures of different enzymes that perform the same function, one may discover general principles governing their catalytic mechanism. In this article we consider some of the structural similarities that exist among the kinase enzymes. For those kinases that have been studied crystallographically, the investigators in each case have reported a striking structural feature; the enzymes contain two lobes separated by a cleft (*1-6*). Evidence from various techniques suggests a second generalization; kinases undergo conformational changes in solution on binding substrate ligands. For example, magnetic resonance studies on arginine kinase (*7*), small angle scattering on pyruvate kinase (*8*) and hexokinase (*9*), kinetic studies of CH_3S-blocked creatine kinase (*10*), and changes in tryptophan fluorescence in hexokinase (*11*) all indicate substrate-induced conformational changes. It is clear from crystallographic studies that for hexokinase these two structural generalizations—a clefted shape and a conformational change—are functionally related (*9, 12*). The conformational change that occurs when glucose binds consists of a large relative motion of the two lobes resulting in a closing of the cleft.

A similarity has been noted in the secondary structure of several kinases (*2, 4, 6*), which is thought to be related to the binding of nucleotides. This structural

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