totoxicity of certain OSC (*3, 5*), can be prevented by the presence of serum lipoproteins during exposure of the cells to OSC. Since OSC reportedly possess angiotoxic properties and are suspected of being atherogenic (*14*), the modulating and possibly protective effects displayed by serum lipoproteins toward the entry of OSC into cell membranes and the consequent OSC-induced derangements of cell membrane structure and function may provide a useful model for further study.

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## Natural Explosive Noises

Gold and Soter (*1*) speculate that gas escaping from fractures in the earth is responsible for many unexplained explosive, booming noises. They cite the occurrence of heard but unfelt events prior to and following some major earthquakes as evidence for escaping gas, evidence on which they have erected the hypothesis that large amounts of methane might be found in the lower crust or upper mantle (*2*). In this comment I present evidence that earthquakes too weak to be felt frequently produce loud booming noises, examine the mechanism by which escaping gas can generate loud booming sounds, and critically review some accounts cited by Gold and Soter as supporting their interpretation.

Field observations show that earthquakes too small to be felt sometimes produce loud booming noises. During aftershock studies near the Mojave Desert town of Landers, California (*3*), and in the vicinity of Mammoth Lakes, California (*4*), booming sounds from earthquakes as small as magnitude 1 were transmitted from large bedrock outcrops. Had those conducting the studies not been equipped with seismographs, most of the booming sounds heard would not have been recognized as associated with individual earthquakes. In neither case were signs of escaping gas mentioned by any of the geologists, seismologists, visitors, or residents in the epicentral area.

Perceptions of observers other than seismologists show that unfelt earthquakes can be heard. Earthquakes near Fontana, California (8 January 1980), and Berkeley, California (6 April 1980), were, according to newspaper and police reports, heard rather than felt. In both cases, many citizens telephoned local authorities to report hearing an explosion. In neither case was evidence of an explosive-like discharge of gas reported.

Airwaves associated with the great 1964 Alaska earthquake were recorded on microbarographs thousands of kilometers from the source. Bolt (*5*) demonstrated that a significant part of this signal traveled as an airwave from the epicentral region. Mikumo (*6*) showed that the barograph records, which were distinct from records of large atmospheric explosions, were consistent with the hypothesis that the source of the pressure waves was a sudden vertical displacement of a large area of the earth's crust.

Unless strong evidence to the contrary exists, there is no need to invoke different physical processes for a single phenomenon. Direct transmission of seismic energy from ground to air, sometimes by earthquakes too small to be felt, is clearly adequate to explain booming noises. I will now consider whether gas, high-pressure or combustible, is a good candidate for generating loud booming noises.

Recent events in Kansas and Oklahoma demonstrate what can occur when gas escapes geologic media (*7, 8*). Combustible gas broke through flaws in rock formations, throwing mud and water more than 10 m into the air. Although the gas concentrations were well within explosive limits, the gas did not ignite spontaneously, and no unusual noises were generated. Mud volcanoes and craters were formed and will long mark the sites of these gas eruptions.

High-pressure gas emissions most likely cannot generate loud, low-frequency booms without leaving evidence. Pressure levels for gas in subterranean openings cannot exceed the least principal stress or the cracks will propagate as hydraulic fractures. Weight of overburden thus constrains the allowable pressure for gas at rest in fractures to less than about 300 bars per kilometer of depth. While this value may suggest that explosive, audible discharge of gas is plausible, serious objections must be considered.

It is difficult to conceive of a fractured


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formation porous enough yet impermeable enough to contain high-pressure gas sufficient to produce a loud boom. Most boreholes encounter some water, and the velocity of high-pressure gas through this water is restricted by the viscosity of the water and turbulence in the fractures. Permeability of fractured rocks is too high to permit long-term entrapment of high-pressure gas. The examples cited by Gold and Soter, known to produce loud booms, are restricted to mud volcanoes and geysers. These manifestations, which leave highly visible evidence of their presence, involve high flow rates driven by two-phase fluid-gas instabilities that permit high pressures to coexist with high permeabilities.

Explosives generate loud booming noises by supersonic compression of gas, the shock wave caused by high overpressures during rapid oxidation of the explosive mixture. If a gas mixture is confined, overpressures can build up to the point that a supersonic shock wave results when the confining structure suddenly fails. Combustion of unconfined gas does not produce the needed supersonic shock wave. Ignition of gas in semiconfined circumstances generates sounds whose tones are governed by the configuration of the confining vessel—such as the "pop" heard when gas is ignited in a test tube or the boom heard when a match is used to check the level of fuel in a gas tank. Geologic structures seldom include open pipes conducive to producing audible tones from air or gas flow. Notable exceptions are mud volcanoes and geysers, which have organ-pipe–like vents in which sudden pressure changes can generate audible signals. However, mud volcanoes and geysers are easily recognized in the field by even inexperienced observers.

A number of the sources cited by Gold and Soter as evidence for gas eruptions leave something to be desired. For example, the events at Lake Bosumtwi, Ghana (*9*), were not witnessed by the author but were "partly of a legendary nature," had "apparently not [occurred] within recent years," and were "never observed by any European." One native chief even explained the mysterious lights as caused by thieves (robbing other people's nets at night) who used fire to frighten superstitious natives.

Eruptions of flames from Wantastiquet Mountain, New Hampshire, were also not witnessed by the authors cited and should be considered as possibly legendary. None of the three persons reporting loud explosive noises and eruptions of flames had witnessed the flames (*10, 11*). Reverend Dwight's account (*10*) of a trip in 1798 associated a loud noise 23 years earlier with the finding of "a hole, forced through the mountain by a blast" shortly after the boom was heard.

However, in a letter dated 1783, Daniel Jones (*11*) wrote, "the last explosion that I recollect happened about 5 or 6 years ago, the noise resembling that of an earthquake, and the earth trembled considerably where I was, about 4 or 5 miles from the mountain." The noise Dwight investigated was apparently a "felt" earthquake which wrought no change in the mysterious pits that he referred to. The descriptions of material in and around the pits on the mountain bring to mind slaglike remains of attempts to smelt ore in situ. Reports of flame on the mountain, as well as the pits and holes found there, were many (50?) years old when the earliest of these letters (*11*) was written. The fused rocks and sand, cinders, and possibly saltpeter found in and around a crater in an otherwise granite formation (*11*) suggest that any flames seen were the result of mining activities.

Oldham's (*12*) account of the Barisal guns and sounds associated with the great Assam earthquake of 1897 explicitly rejects an explosive gas hypothesis as "too vague . . . till some definite indication is given." Apparently, despite the numerous loud booming noises before and after the earthquake, no evidence of gas eruptions was noted. Another interesting observation was that sounds were heard, though not felt, by miners working underground more than 300 km from the epicentral area. Were gaseous eruptions responsible for these sounds, the miners, who dealt with the threat of explosions, rock bursts, and gas pockets on a daily basis, might have contributed some additional material to Oldham's report.

Virtually every episode of precursory brontide activity cited by Gold and Soter is more easily explained by unfelt foreshocks than by gas eruptions. This does not mean that gas eruptions and booming noises may not occur simultaneously. But coincidental observations of gas eruptions and booming noises do not require that the former cause the latter. The numerous booming sounds heard in conjunction with small earthquakes and for which no evidence of gas eruptions was found supports the opinion that surface vibrations rather than gas emissions are responsible for many otherwise mysterious booming sounds.

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Our article explicitly points out that many faint audible booming sounds may indeed be produced by direct ground-to-air transmission from unfelt earthquakes. The frequency range of interest (about 20 to 100 Hz) is at the low end of the human auditory range but much above the range used normally in seismology, since waves of such frequencies are rapidly attenuated in the ground. One can expect such direct generation of booming noises only in cases where a fracture in rock occurs close to the surface or is separated from the surface only by a short transmission path in consolidated rock free of alluvial cover. However, there is a limit to the loudness of a sound that can be produced in this way by an earthquake too weak to be felt.

From some of the accounts it appears that brontides may be as loud as nearby thunder. We found that direct ground-to-air transmission of such a sound (at 40 Hz) would require a ground acceleration of about $0.1g$, an order of magnitude larger than the human vibration detection threshold. Furthermore, some of the reports are from regions unsuitable for low-loss transmission (for instance, the Barisal guns of the alluvial Ganges delta area). It thus appears that an additional mechanism, perhaps involving high-pressure gas, may be required to explain some of the brontides.

Stierman, on the contrary, appears to believe that direct ground-to-air acoustic transmission from weak foreshocks accounts for all booming noises. He maintains that "there is no need to invoke different physical processes for a single phenomenon." It is not clear how he knows that we are, in fact, dealing with a single phenomenon. Some investigators are not so sure. The Chinese seismologists who briefed Wallace and Ta-liang Teng (*1*) on the sounds beginning a few months before the Sungpan-Pingwu earthquakes of 1976 said "many of the sounds were clearly not related to foreshocks, because good data from seismic records showed the absence of foreshocks at the time of the sounds. On one occasion, several seismologists . . . were watching a seismograph when they heard sounds they believed to be earthquake sounds. The instrument did not record an event when they heard the sounds, but a minute or so afterward, the arrival of P waves was recorded."

As evidence for the absence of gas, Stierman describes booming sounds heard in the Mojave Desert and Mammoth Lakes, California, at the time of weak earthquakes and says that "in neither case were signs of escaping gas mentioned." Both sites are near outcrops of crystalline bedrock so that direct acoustic transmission is possible without gas escaping. Even if gas was involved in these cases, its escape through small fissures in the bedrock would not have to leave any obvious evidence.

It is not clear why Stierman cites the barometric waves detected thousands of kilometers from the great 1964 Alaskan earthquake. Such waves, with periods much longer than 1 second, propagate with little loss much farther than audible brontides. There is no question that they were caused by energy transfer from ground to air. But they were due to a single, relatively slow vertical displacement, not to high-frequency seismic vibration. And there is little doubt that the earthquake that generated them was felt.

Stierman's discussion of underground gas being at each level limited to the lithostatic pressure applies only to the static containment situation, not to the case of interest here, namely an eruption. In the latter case there would be a level at which containment suddenly fails, and the pressure there would constitute the source pressure of the gas escaping into fissures and through those into the atmosphere. If this occurs at a depth of some kilometers we are dealing with pressures in the range of kilobars, and the ascending stream will become a shock wave (similar to the case of shock tubes, where a driver gas is released into a lower pressure domain). This shock emerging from one or many exit cracks will generate an atmospheric booming noise.

The quantity of gas required to make a loud booming noise in this way is small, and direct observation of the exit points would therefore be rare. We estimate that a shock wave due to only a few kilograms of gas emerging from such a high-pressure source would be as loud as a stick of dynamite exploding. Most such small events would go unobserved visually. Yet in several cases of earthquakes involving brontides, evidence for possible gas vents was later found (funnel-shaped craters and so on), and in at least one case a visual identification of the source was made during the event (*2*).

We find no reason why the presence of mud underground should favor the generation of booming sounds—more likely the opposite. Yet the mud volcano eruptions are often noisy and sometimes produce loud explosions even without ignition. The observation that combustible gases sometimes emerge without explosive noises or ignition is not an argument against these occurring on other occasions. In any event, there is abundant observational evidence that spontaneous ignition often occurs, the most famous examples being the mud volcanoes of Burma and the Caucasus. With ignition, there may be an even louder noise than would otherwise occur. Unconfined gases can indeed achieve sonic velocity in an explosion; for pure methane this requires too large a volume for the circumstances of brontides, but with an admixture of hydrogen the flame propagation speeds are high and quite small quantities will "pop."

Stierman examines three of the particular brontide episodes for which he is able to find circumstances admitting doubt, ignoring the other 15 mentioned in our article. Almost any individual description of an anomalous phenomenon given by a nonscientist can be picked apart; it is the similarity among a large number of independent accounts that must be considered in judging the probability that the general phenomenon is real. If we had to rely on only a few accounts, we too might doubt that gas emission is the cause of any brontides.

But our hypothesis that gases, sometimes combustible, emerge from the lower crust or upper mantle in connection with seismic activity is based on many kinds of observations, by no means just on earthquake-related booming noises (*3*). Among these effects reported in many cases as preceding or accompanying earthquakes are radon gas increases at the surface; sulfurous smells; "dry" fogs; bubbling in rivers, lakes, or the sea; flames from the ground; noises that include hissing as well as booming; mud volcano eruptions; and strange behavior of animals. The most recent description of a wide range of such phenomena is given in an account of the Sungpan-Pingwu earthquakes of 1976 (*1*).

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