MASTER

AIR PRESSURE WAVES FROM MT. ST. HELENS ERUPTIONS

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ABSTRACT

Barograms from a number of National Weather Service stations were assembled for the May 18, 1980, eruption and compared to airblast wave propagations from large explosions. Wave amplitudes at 50 to 300 km distances were about what might be expected from a nuclear explosion of between 1 megaton and 10 megaton yield. Pressure-time signatures could not be resolved for the first compression phase, because of the slow paper recording speed. The 900 s negative phase duration was much too long for comparison with the negative phase of an explosion. Nevertheless, positive and negative amplitudes were about equal, as often observed at long distances from explosions. Calculations have been made for a simple finite amplitude propagation model. These show rough bounds on the source compression rate, to give the observed inaudible waves at least to 54 km distance, yet cause audibly rapid compression at Seattle, near 150 km, and beyond.

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INTRODUCTION

Weather station barograph records were obtained from twenty-one stations in the Washington-Oregon-Idaho region, operated by the National Weather Service (NWS) and Federal Aviation Administration (FAA), for the morning of May 18, 1980. Each clearly showed a pressure perturbation caused by the Mount St. Helens eruption. These were reviewed to give an estimated 5-megaton equivalent explosion yield for this volcanic eruption.

Early eyewitness reports did not include any mention of a blast wave at close ranges (10-30 km), but there were many reports of booming noises heard in Seattle, WA, (160 km) and more distant points. The compression rate was apparently too slow at short range to cause any significant structural response or noticeable sensation in humans. An explanation will be advanced for distant audibility, in that a portion of the compression wave travelled to high altitudes (possibly 50 km above sea level) where a shock front formed by finite amplitude effects. The wave was then refracted back to ground level at long ranges with audibly rapid compression rates (probably ≤ 100 ms).

STANDARD EXPLOSION YIELD SCALING

The spherical wave from a point explosion expands with peak-to-peak pressure amplitude decreasing with distance [1] as shown in Figure 1. According to explosion scaling laws, the distance to a given amplitude is proportional to the cube root of the explosion yield. Thus the curve in Figure 1, scaled to 1 Mt NE free air burst (away from any nearby reflecting surfaces), has a distance scale of ten times the scale of a standard 1 kt nuclear explosion (NE) [2]. Explosion scaling is further described in The Effects of Nuclear Weapons [3].

ATMOSPHERIC REFRACTION OF EXPLOSION WAVES

Atmospheric sound rays (perpendiculars to the wave front) are refracted and curved upward, away from ground, in layers where the sound velocity (sound speed plus directed wind component) decreases with altitude as it usually does in the troposphere (up to about 10-15 km altitude)[4]. Conversely, rays are bent downward, toward ground level, in layers where sound velocity increases with height. As a ray propagates along an upward path through a strong gradient of sound velocity, there is significant scattering and diffraction into the shadowed "silent zone", with amplitudes shown by the "strong gradient" curve in Figure 1. This curve was derived from recent experimental data observed at Cape Canaveral, Florida [5].

FIGURE 1

UPPER AIR WEATHER OBSERVATIONS

The regular teletyped NWS observation at 0500 PDT 5/18/80, from the closest balloon radiosonde upper air station at Salem, OR, showed that northward blast propagation would be strongly refracted (bent) upward away from ground, particularly above the 3 km MSL source height on Mount St. Helens. Winds were light to moderate westerlies (from 255° at 5.7 m/s at 3.6 km; 245° 11.8 m/s @ 6.1 km; 265° 34.5 m/s @ 12.2 km), that would not enhance northward propagation. A typical temperature decrease with altitude was observed (275 K at 3 km; 209 K at 11.9 km), so that north-directed sound velocity decreased from 336 m/s at the source altitude to 294 m/s near 12.2 km MSL. Thus with slower propagation aloft, a normal to the wave front (ray) would be turned up and away from the ground. Only scattered and diffracted acoustic energy (minimum propagation) would travel to ground level observing and listening points.

STRATOSPHERIC PROPAGATION

At high altitudes, near 50 km, the warm upper stratosphere [6] refracts waves back to ground level in an ensonified annular ring near 200 km range [7]. Annual cycling monsoon winds at that high altitude cause sound to be focused downwind to the east in winter, to the west in summer. Microbarograph records of atmospheric nuclear tests in Nevada were summarized to given amplitude expectations versus distance during the transitional month of May, for 1-Mt and 10-Mt NE as shown in Figure 2.

The sound ring at 200 km is assumed to reflect quite efficiently and strike again near 400 km. Minimum amplitudes, recorded near 120 km would be reflected to 240 km, etc. Indicated averages, shown by the dashed curve, represent best estimates, based not only on May observations but on the annual cyclic pattern for each station. The range of actual May observations shows that severely atypical propagations occasionally occur. Comparison with Figure 1 shows that ozonosphere propagations should scatter around the gradient curve, within an order of magnitude.

According to W. L. Donn, Lamont Observatory, Palisades, NY, their continuous atmospheric infrasonic measurements showed that the transition to summertime stratospheric easterly winds occurred before May 18. We do not, however, have any historical explosion records that would indicate just how this wind shift affects northward propagation.

TOLEDO, WASHINGTON BAROGRAM

The closest National Weather Service (NWS) barogram, shown in Figure 3, came from an FAA Flight Service Station at the Toledo, WA, airport (54 km). It shows a 373 Pa compression "spike". Recording paper speed was only 2.7 mm per hour so no time resolution was possible for this compression wave. The 13-minute negative phase duration was much too long for a megaton-class explosion yield, as was the hour-long second compression phase. Thus, these waves must have been caused by some phenomenon other than a single point explosion.

FIGURE 2

MAY OZONOSPHERE PROPAGATIONS FROM NEVADA TESTS.

BAROGRAM, TOLEDO, WA, MAY 18, 1980.

FIGURE 3.

Nevertheless, wave overpressures and peak-to-peak amplitudes from the 21 stations are listed in Table I, along with distances and bearings, and are used for estimates of an equivalent explosion yield. The geometric average of positive and negative phase amplitudes were nearly equal, consistent with experience at large distances from explosions. Thus it should cause no bias in interpretation to use peak-to-peak amplitudes. Amplitudes were used to avoid errors in estimating an unperturbed background pressure level from a thick pen trace, as needed for overpressure determination. In other words, peak-to-peak values are probably more representative than overpressures, for records of this type.

OTHER WEATHER STATION BAROGRAPH DATA

Figure 4 shows peak-to-peak amplitudes versus distance for the NWS barograph records that are listed in Table I. Data points are labeled by station number. They are connected by lines where general azimuthal direction was maintained. Minimum propagation was directed southward along the Portland and Eugene azimuths. Moderate propagation traveled toward the northeast and east. Strongest propagations appeared along the Toledo to Quillayute (northwest) and Seattle to Bellingham (north) lines. There is no indication of any significant sound ring near 200 km, unless it may have struck near Eugene in the south, or at the long distances of Spokane and Lewiston in the east sector.

TABLE I

Mount St. Helens 5/18 Eruption Signals on National Weather

Service Microbarographs

	<u>R (km)</u>	<u>Bearing(°)</u>	<u>p(Pa)</u>	<u>Pk(Pa)</u>	<u>Remarks</u>
Yakima, WA	125	069	141	318	
Wenatchee, WA	195	042	[106]	203	positive phase not copied clearly, value estimated.
Spokane, WA	371	063	73	125	
Lewiston, ID	370	085	74	138	
Walla Walla, WA	277	092	74	127	
Pendleton, OR	248	104	32	91	
Dallesport, WA	99	132	138	283	
Eugene, OR	250	198	26	78	
Corvallis, OR	199	204	91	136	
Roseburg, OR	348	195	31	63	
Salem, OR	158	203	99	162	
Portland, OR	76	206	[131]	[253]	no positive phase, pen stuck(?) estimated from values 121 Pa negative phase.
Astoria, OR	117	270	164	262	
Hoquiam, WA	153	306	205	[395]	negative phase copy poor, estimated amplitude.
Toledo, WA	54	307	373	767	
Quillayute, WA	256	321	129	194	
Olympia, WA	102	330	235	459	
Bellingham, WA	300	366	133	198	
Seattle, SEA-TAC	140	356	188	365	
Seattle WSFO	161	357	146	276	
Stampede Pass, WA	130	024	167	331	

FIGURE 4

Comparison in Figure 5 shows that these barograph amplitudes were somewhat higher than expectations for 1 Mt NE, possibly nearer to the averaged expectation for 10 Mt NE.

Considering the uncertainties in atmospheric propagation, "explosion" source geometry and characteristics, and the coarseness of barograph measurement, it appears that the equivalent explosion yield of the Mount St. Helens eruption was a "few" megatons.

AUDIBILITY PATTERN

None of the close observers of this eruption reported any audible explosion, although there were many reports of rumbles heard as far away as Seattle and Victoria. At first it was assumed that nearby spectators were simply overwhelmed by eruption phenomena and failed to include in their reports any observations about an airblast wave. When it was firmly established that the 373 Pa compression wave at Toledo was indeed inaudible, and there were no building rattles nor window damages (recorded 400 Pa peak-to-peak amplitudes from Nevada atmosphere nuclear tests caused broken windows in Las Vegas, NV, and St. George, UT), it was concluded that the compression was too slow to be heard or cause any noticeable structural response.

Figure 6 shows some of the audibility reports assembled by Clara Fairfield of the Oregon Museum of Science and Industry, along with our own interview results. The wave was not generally heard as far north as Tacoma, yet it was generally heard at greater distances, even to Bowron Lake, BC, at 785 km distance.

THEORETICAL AND OBSERVED SIGNAL AMPLITUDE COMPARISON.

FIGURE 5.

AUDIBILITY PATTERN OF 5/18/80 ERUPTION.

FIGURE 6.

Some, but not all, heard the blast in Spokane, while it was easily heard in Kalispell and Glacier Park. The wave was not heard in Pullman, WA, Moscow, ID, or Pendleton, OR, yet it was heard as far east as Butte, MT. South, and beyond Salem and Albany, OR, the rumble was heard nearly to Reno, NV. Along the Oregon Coast, Mrs. Fairfield detailed a sharp boundary of audibility in the 15 km between Netarts Bay and Manzanita.

FINITE AMPLITUDE WAVE PROPAGATION

Calculations have been made with a simple model of finite amplitude propagation to show rough bounds on the source compression rate that would not cause an audible wave at Toledo, yet would cause an audibly sharp compression at Seattle.

In a simple linear compression wave, with a pressure-time signature as shown in Figure 7, the start of compression travels at sound speed, c , in the ambient air. A perturbation at peak compression travels faster, in a medium with higher pressure, and, as a result of the adiabatic process, a higher temperature. This "shock" speed, s , is conveniently expressed [8] by

$$s = c \sqrt{1 + \frac{(1+\gamma)}{2\gamma} \cdot \frac{\Delta p}{p}} \quad (1)$$

where shock strength (in atmospheres) is shown by the over-pressure (Δp) to ambient pressure (p) ratio, while γ is the ratio of specific heats for air,

$$\gamma = C_p/C_v \approx 1.4. \quad (2)$$

PRESSURE-TIME SIGNATURE, LINEAR COMPRESSION WAVE.

FIGURE 7

One result of Eq. (1) is the prediction that any finite overpressure wave (linear acoustics assumes infinitesimal amplitudes) will "shock-up", and any sinusoidal oscillation will become a saw-tooth signal. Viscous attenuation prevents this from actually happening to ordinary low-amplitude acoustic waves. On the other hand, with a single strong compression propagated into a medium of decreasing ambient pressure, the shock strength increase with time may cause the peak overpressure to catch up with the compression start and form a shock front with compression rise time $\tau = 0$. In an increment of range or distance, dR , the compression rise time, τ , is reduced by the difference of propagation times of the two waves (of zero and finite overpressure)

$$d\tau = \left(\frac{1}{s} - \frac{1}{c}\right)dR, \quad (3)$$

so that rise time is reduced to zero from an initial rise time, τ_0 at distance, R_0 , when

$$\tau_0 = \int_{R_0}^R \left(\frac{1}{c} - \frac{1}{s}\right)dR. \quad (4)$$

Variables in Eq. (4) may all be reduced to functions of altitude, z , by specifying an overpressure-distance relationship along a propagation path in (R, z) coordinates, and assuming horizontal uniformity of the atmosphere in which air temperature and pressure vary only with altitude.

A simplifying assumption was made that the wave expanded spherically from the source. Although clearly invalid at short ranges from the Mount St. Helens eruption, this assumption seems

reasonable for long range calculations. The slow-compression wave is further assumed to propagate adiabatically, without loss of energy, rather than as an explosion shock. Net wave energy, E , is then expressed [4], by the proportionality

$$E \sim \frac{(\Delta P)^2 R^2}{\rho c} , \quad (5)$$

for air density, ρ . It was further assumed that the compression phase duration (t_+ in Figure 7) was unchanged--at least until a shock was formed. In result of adiabatic propagation,

$$\frac{\Delta P R}{\sqrt{p/\sqrt{T}}} = \frac{\Delta P_1 R_1}{\sqrt{p_1/\sqrt{T_1}}} \quad (6)$$

where sound speed depends on the square root of temperature, $c \sim T^{1/2}$, and $\rho \sim p/T$. The right hand portion of Eq. (6) may be evaluated for any specific inaudible observation, such as was made at Toledo. Then overpressures may be determined for points (R, z) along the propagation path. No analytic solution is known for Eq. (4), that includes all the various height-dependent variables, so numerical evaluations were made for several appropriate propagation paths shown in Figure 8. The direct ray path to Toledo from an assumed source at 3 km altitude is also shown.

ACOUSTIC RAY PATHS AND TRAVEL TIME DIFFERENCES FOR ACOUSTIC AND SHOCK WAVES. (SHOCK STRENGTH DEFINED AT $P = 400$ PA AT $R = 54$ KM.)

FIGURE 8

Calculations for sound and shock travel times were made at 1-km increments of the horizontal coordinate along each of the paths in Figure 8. Net travel time differences for various paths are shown beneath the figure. Results were found to be only weakly dependent on assumed details of atmospheric temperature and pressure structure and propagation path. The important input is the assumed source strength, characterized by the peak overpressure observation at the Toledo distance.

CALCULATED RESULTS

According to the results of simplified calculations for shock formation along atmospheric propagation paths, the Mount St. Helens eruption caused a slow compression wave with a duration of more than 1.3 seconds. Any shorter duration at the source, with the strength indicated by the Toledo, WA barogram, would have caused a shock front formation by the time the wave reached Toledo, along with a strong audible blast and a good likelihood for window damages.

On the other hand, the source compression wave probably had a rise time of less than about 5 seconds, in order to allow an audible shock wave formation by the time of arrival at Seattle, WA.

The problem remains of defining the source mechanism that was responsible for causing the air compression wave that was recorded following this eruption.

It is clear that this source was not an explosion in the normal sense (for nuclear or chemical high explosives), with an extremely rapid energy release [1] and a resultant easily heard, fast compression shock wave formation at short ranges.

MICROBAROGRAPH MONITORING

In hopes of getting pressure records with a better time resolution, in event of another nearby explosive eruption, Sandia National Laboratories placed several microbarograph systems in the area. This equipment has been used for many years to record explosion test airblast waves. Recording is currently at 1 mm/second paper speed. At Toledo, WA, the operating set range provides a capability for indicating wave amplitudes from 20 Pa to 4 kPa. At more distant stations, the amplitude range is switched for 6 Pa to 1200 Pa. During summer months distant sets were operated at Astoria, OR, Hoquiam, and Quillayute, WA. For winter, distant sets have been located at Yakima and Hanford, WA.

The only readable wave signature so far obtained was from Toledo for the June 12 eruption. This occurred while the equipment was being installed and checked out, so there is a question about timing. Nevertheless, it appears that there was a 40 Pa compression wave with a 12-second duration at 2108 PDT.

Our equipment was not designed for such long time continuous recording, so there have been problems in keeping it running. We are testing a modern digital magnetic tape

recorder and data logger that contains a memory circuit which can be scanned for signals before permanent recording. This should save a lot of paper, if it performs to specification.

SUMMARY

Weather station barograph records show pressure wave amplitudes from the 5/18/80 eruption that are comparable to what would have resulted from a "few" megaton nuclear explosion.

The peculiar pattern of reports of sounds and no-sounds has been explained. The wave began with a very slow compression that was inaudible for about 100 km or more. Part of this wave travelled to high, 50 km altitudes where its strength caused a shock to form in the low pressure ambient air. This shock was easily heard when it was refracted back to ground level.

Three to four microbarographs are now being operated at 50 to 200 km distances from Mount St. Helens, to allow better time resolution of waves from any future large eruptions.

ACKNOWLEDGEMENTS

Special thanks go to Sue Keiffer, USGS, for asking our opinions about the magnitude of this volcanic eruption. Besides using data from cited reports of W. L. Donn, Lamont Observatory, and Clara Fairfield, Oregon Museum of Science and Technology, the bulk of our data came from the NOAA-National Weather Service. This was arranged by George Miller, of the NWS Western Region, Salt Lake City, UT. He also coordinated our microbarograph installation and operations at Astoria, Quillayute, and Yakima. Dale Realph, FAA, Seattle, WA, arranged for our microbarography at Toledo and Hoquiam, and Lloyd Gifford, of Battelle-Pacific Northwest Laboratories, arranged our recording at Hanford. We most appreciate the interest and cooperation shown by the dozens of NWS and FAA people in furnishing barogram copies and particularly in nursing our ailing recording equipment.

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