GROUND MOTIONS GENERATED BY UNDERGROUND NUCLEAR EXPLOSIONS

By Dean S. Carder and William K. Cloud

The U. S. Coast and Geodetic Survey measured ground effects from a number of large underground nuclear explosions of the PLUMBBOB (Rainier) and HARDTACK II series and certain other tests using high explosives. In this article some of the results of engineering interest will be discussed.

The nuclear tests under discussion were fired in massive tuff beneath the Rainier mesa of the Nevada Test Site during September 1957 and October 1958. These tests are described in the literature (Johnson et al, 1959). Their estimated yields and other pertinent data are summarized in Table I.

In Figure 1, shot locations are indicated by stars accompanied by the initials of the respective shots. The station locations during the HARDTACK II series (October 1958) are indicated by numerals, the last two digits of the official station numbers. Station 1200.14 is indicated by .14, and station 1200.01 by .01, etcetera. Figure 2 is a cross section from Station .14 on the mesa to Station .01 on the quartzite, a few miles east of the mesa. Not shown are Stations .09 on granite and 7.2a^2 on deep alluvium. Geologic structure of the area is indicated. The station layout during shot Rainier was covered in an earlier report (Carder and Cloud, 1959). The station locations shown here and in the earlier report are compromises between scientific optimum and economic feasibility.

The instruments consisted of the standard strong-motion seismographs used for years by the Survey for measuring earthquake motion (Cloud and Carder 1956). They are direct recording seismographs consisting of simply constructed compound pendulums damped by permanent magnets together with requisite timing and photo-mechanical recording apparatus. These instruments are capable of recording ground motion in the acceleration range from 0.001 g or less to 3.0 g, and transitory ground displacements of 6 inches (15 cm) or less. For this purpose two sets of seismometers are required, one set having pendulum periods substantially less than the periods of expected ground motion and the other with periods substantially greater than the ground periods. Results of earlier work served as guides to optimum gain settings of the instruments.

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Test Results

Formulas which prior to the HARDTACK II series seemed to give satisfactory results are

(1) $\log a = 0.75 \log W + 4.0 - 2 \log D$

(2) $\log A = 0.75 \log W + 4.6 - 2 \log D$ (0.3 to 3 km)

(3) $\log A = 0.75 \log W - 2.9 - \log R - 0.006 R$ (3 to 160 km)

Where a = maximum acceleration, single component (gravity)

A = maximum displacement, single amplitude, single component (centimeters)

W = TNT equivalent of explosion in tons

D = distance to explosion (feet)

R = distance to explosion (kilometers)

Figures 3 and 4 show tracings of acceleration records from the Blanca and Logan shots, and Figures 5 and 6 show traces of corresponding displacement records. Figure 7 is a plot of maximum observed accelerations with distance. The solid graphs are according to predictions. Figure 9 is a corresponding plot of maximum observed displacements and the graphs are based on predictions. The fit of observed data to predicted values is in general fair considering that predictions are extrapolations from 10 to 50 tons of HE to 19,000 tons equivalent of nuclear energy. There are discrepancies, however. For example, the Tamalpais acceleration data are a factor of 5 or 6 higher than were the predicted values and Evans displacement data from stations beyond a few miles are at least an order too low.

In the evaluation of the evidence of Figure 9, one should be aware of the physical location of each station in respect to the shot, and the geologic underground near the station. To assist with this evaluation, strong-motion data are designated by the initial of the rock upon which the station is located, or by the initial accompanied by a symbol.

The data may be interpreted as follows:

1. Ground amplitudes on deep alluvium are higher than amplitudes at like distances on granite by factors of 2 to 3.5.

2. Amplitudes on granite, quartzite, and limestone are generally consistent

with each other and generally predictable with the use of the second leg of the displacement formula (equation 3), applicable in the formula for distances from 2 to 100 miles, but in this case from 0.5 to 100 miles.

3. Amplitudes on bedded tuff are not consistent, most of the time they are high but in some cases they are comparable with data on limestone, etc.

4. Amplitudes on welded tuff are always high. This is more likely a combination of a geographic condition and the nature of the rock. The welded tuff caps the mesa containing the shots, and the stations on the mesa (welded tuff) are higher in elevation than the shots. The stations on the top and side of the mesa doubtless receive seismic energy from the shots in a more concentrated form, whereas, at the other stations there may be some loss by refraction.

5. Amplitudes at teleseismic stations are scattered but follow predicted estimates within a factor of 3. From item (2), it appears that earlier postulates which imply that amplitude falls off as the square of the distance out to 3 km was an apparancy because of the geographic position of the stations; and the condition that some of the stations were located on top of the mesa where they were in a position to receive a greater concentration of energy. If the data pertaining to a given rock unit, limestone for example, are examined more closely, it appears that amplitudes attenuate linearly with distance - with absorption. This is in accordance with the idea that elastic energy is propagated from the source in spherical wave fronts, assuming no change in frequency. Energy in this form attenuates as the square of the distance.

We have the simple formulas:

$$E \propto v^2, \quad v = \frac{2\pi}{T} A; \quad a = \frac{2\pi}{T} v$$

where v is the particle velocity during a passing wave front and E, a, T, and A are as defined elsewhere. If absorption is negligible, it follows that A would be expected to attenuate linearly with distance assuming no change in period, and aT would likewise attenuate linearly with distance. According to observation, waves associated with the maximum displacements maintain about the same period from place to place, but maximum accelerations are associated with short periods near the source, and with longer periods at relatively larger distances. Maximum accelerations and their associated periods have been combined as a product and plotted according to distance in Figure 8. The estimate of these associated periods is rough, which alone may account for the scatter of the data. Nevertheless the trend toward linear attenuation is evident.

Energy contained in seismic waves in an assumed spherical wave front at a distance of about 1 km from the Blanca shot was calculated using the initial crests recorded on the displacement records and applying the following formulas:

$$E_s\ (\text{ergs/cm}^2) = 0.5\pi^2\rho \sum VA^2/T \quad \text{and}$$
$$E\ (\text{ergs}) = 2\pi E_s R^2 \times 10^{kR}$$

Here E_s is the energy density in the wave front as it passes a station; $\underline{E}$ is the total energy in the wave front, assuming that it maintains a spherical shape from the source to the station; ρ is the rock density; $\underline{V}$ is the seismic wave speed in the rock; $\underline{A}$ is the zero to peak ground amplitude; $\underline{T}$ is the wave period; and $\underline{k}$ is an absorption factor, base 10. An additional catch-all factor which includes loss by refraction is normally applied, but since in this case it is considered unity, it was not included.

Using data from the 10 nearest C&GS stations, the calculated log E of the Blanca shot is 18.46± 0.15 which is equivalent to a magnitude 4.8 earthquake. Since the calculated yield of this shot was 19 kt, or the equivalent of $10^{20.9}$ ergs, the estimated energy in the wave front 1 km from the source is about 0.4 percent of the total yield. Much seismic energy may have been absorbed near the source, but the value given here is pertinent when comparisons with earthquakes are made.

Trajectories of particle motion during the passage of seismic waves from shot Blanca across two selected stations are shown in Figures 10 and 11. The trajectories are represented in three planes (a) the vertical plane containing the ray, (b) the horizontal plane, and (c) the vertical plane at right angles to the ray. In some cases, the initial part of the motion is shown on an enlarged scale. The selected stations are .05 on top of the mesa at a distance of approximately 5,500 feet, and station .08 on limestone at a distance of 9,460 feet.

It is believed that the initial wave at each station had part of its history in the limestone underlying the tuff in which the shots were fired. This wave is identified as P_L. It must be, and is, essentially vertical and radial. An impulse following P_L by a few tenths of a second likewise has a strong radial direction. For stations on the mesa, the direction is in phase with the initial P_L and is believed to be associated with the direct, or almost direct, wave from the source to the station through the tuff. This wave is designated P_T. It arrives at Station .05 about 0.85 sec after zero time, compared with 0.55 sec for P_L. At Station .08 the second impulse is oppositely directed from the first, that is, it is out of phase with the first arrival. It arrives about 0.25 sec later, and is believed to be a reflection of the P wave on the surface. The longer part of its path in the slow speed tuff is believed to be responsible for the delay in arrival time of 0.25 sec. It is designated pP meaning a P wave from the source to the surface near the source and then reflected as a P wave to the station. This wave has comparatively high energy and is believed responsible in part for the confusion in identifying some first arrivals as positive upward at distant points. The corresponding S_L, ST, and sS arrivals are indicated on the illustrations.

RESPONSE SPECTRUM ANALYSIS OF RECORDS FROM EVENTS BLANCA AND LOGAN

By William K. Cloud

A response spectrum is defined as the envelope of maximum relative velocities obtained by a series of oscillators when subjected to known accelerations. As pointed out by Hudson in 1956 (Reference 1), such spectrums are useful not only for the determination of structural responses in particular cases of ground motion, but also for investigating the general character of ground motion.

Within the past 20 years, records from a number of earthquakes, and several quarry blasts, have been subjected to response spectrum analysis (References 2, 3, 4, 5, 6). Event Blanca (19 kilotons) and Logan (5 kilotons) offered an excellent opportunity to make similar analyses of records from underground nuclear explosions.

Relative maximum velocity spectrums from 11 radial component acceleration records of these two events were run on a Mark II Electric Analog Spectrum Analyzer, described by Caughey, Hudson, and Powell elsewhere in the Proceedings of this Conference.

Ten of the resultant spectrums are shown in Figures 12 to 21. For interpretation of earthquake spectrums Benioff (Reference 7) and Housner (Reference 8) suggest use of "Response Spectrum Intensity" defined as the area under the relative velocity response curve between oscillator periods of 0.1 and 2.5 sec and thus a measure of an average spectrum value over the range of periods of structural interest. With slight modification, the suggested method has been used for interpretation of the nuclear detonation spectrums. Results are given in terms of the average maximum velocity for the oscillator period range 0.1 to 2.0 sec rather than in terms of area.

At first glance spectrums in Figures 12 to 21 show considerable variation. However, when average maximum velocities for 10 percent damped oscillators are plotted against station distance from detonation (Figure 22), attenuation appears reasonably uniform. Data from Station 1200.07 are exceptions for which there is no immediate explanation.

Disregarding the exceptions, Figure 22 suggests the possibility of developing an empirical formula relating seismic energy to average maximum spectrum velocity and to distance. Assume a formula of the following type:

$E = KVD^n$ Where D = slant distance to nuclear detonation (feet)

V = average maximum spectrum velocity at distance "D" (feet/sec). (Period range 0.1 to 2.0 sec, 10 per cent critical damping.)

E = total seismic energy (ergs)

K and n = constants

The slope of the lines in Figure 22 indicates that $n = 1.78$. Corresponding values of $\underline{V}$ and $\underline{D}$ read from the Blanca line in Figure 22, combined with Carder's value for seismic energy of Blanca ($10^{18.4}$ ergs), gives a value for $\underline{K}$ of $10^{12}/2.4$. Substitution gives

$$E = \frac{10^{12} V D^{1.78}}{2.4}$$

A comparison of seismic energies calculated by the formula and by other methods for Logan and four earthquakes is shown in Table 2. Many additional strong-motion records from underground detonations or earthquakes are needed to judge whether or not the formula has merit. The order difference between energy calculated by the formula and given by seismologists for two of the earthquakes is certainly not encouraging. However, in both cases the formula value does back up observation. Engineers noted that, considering magnitude ratings, effects on structures were below average for the Hebgen Lake shock; above average for the Port Hueneme shock.

For comparison with spectrums from the nuclear detonations, two earthquake spectrums are shown in Figure 23. A verbal communication from Dr. Don Tocher, University of California seismologist, placed the epicenter of the earthquake approximately 4.9 miles from the Hollister station and gave the magnitude as 5.0. Average maximum velocities (10 per cent critical damping) for the oscillator period range 0.1 to 2.0 sec were: N 81° W component, 0.290 ft/sec; N 01° E component, 0.203 ft/sec. Modified Mercalli scale intensity at Hollister was VI.

Tentative conclusions may be drawn from comparing the data:

a) Although there is some dissimilarity between the earthquake and detonation spectrums this dissimilarity is no greater than between the two earthquake spectrums from the same stations or between spectrums of the same detonation at different stations.

b) Buildings at distances somewhere between 2.4 and 3.0 miles from the Blanca detonation and 1.6 and 1.9 miles from the Logan detonation would have been subjected to similar ground effects as the building at Hollister located 4.9 miles from the epicenter of the 19 January 1960 earthquake. In this connection it is of interest to quote from a report by observers stationed 2.75 miles from the Blanca detonation:

"Immediately following zero time as indicated by the countdown a sharp light reflection, somewhat resembling a light flash in appearance, was observed for several hundred yards along the profile of the mesa as the initial shock wave passed through the earth's surface. This was followed by a severe earth tremor, resulting in an up-and-down motion similar in appearance to water wave action. Vehicles were observed to rock or bounce on their springs. This severe tremor lasted approximately 3 seconds, after which it subsided to a gentle rolling movement which persisted approximately 10 seconds."

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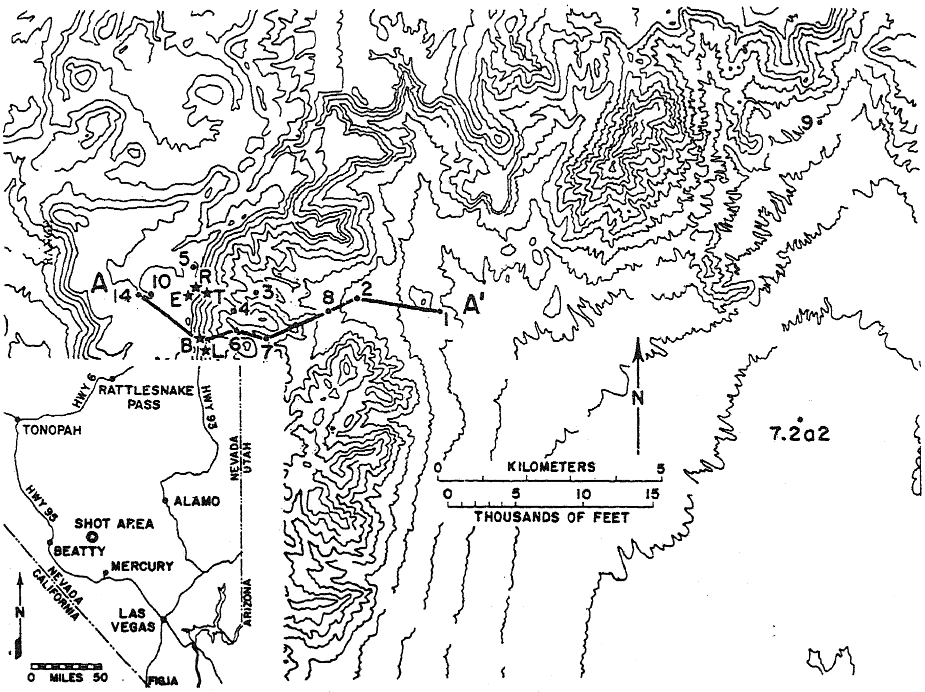
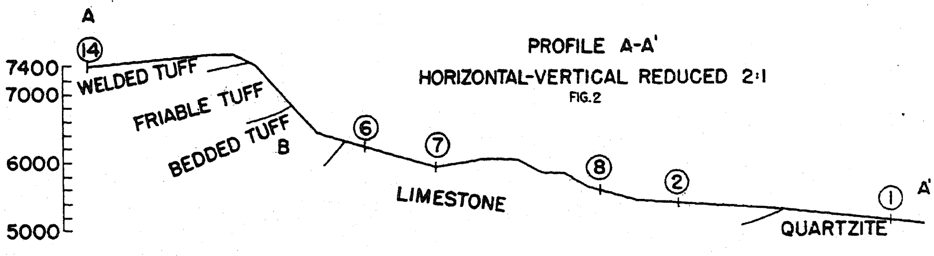


Figure 1. Location of strong-motion seismograph stations.



PROFILE A-A'
HORIZONTAL-VERTICAL REDUCED 2:1
FIG.2

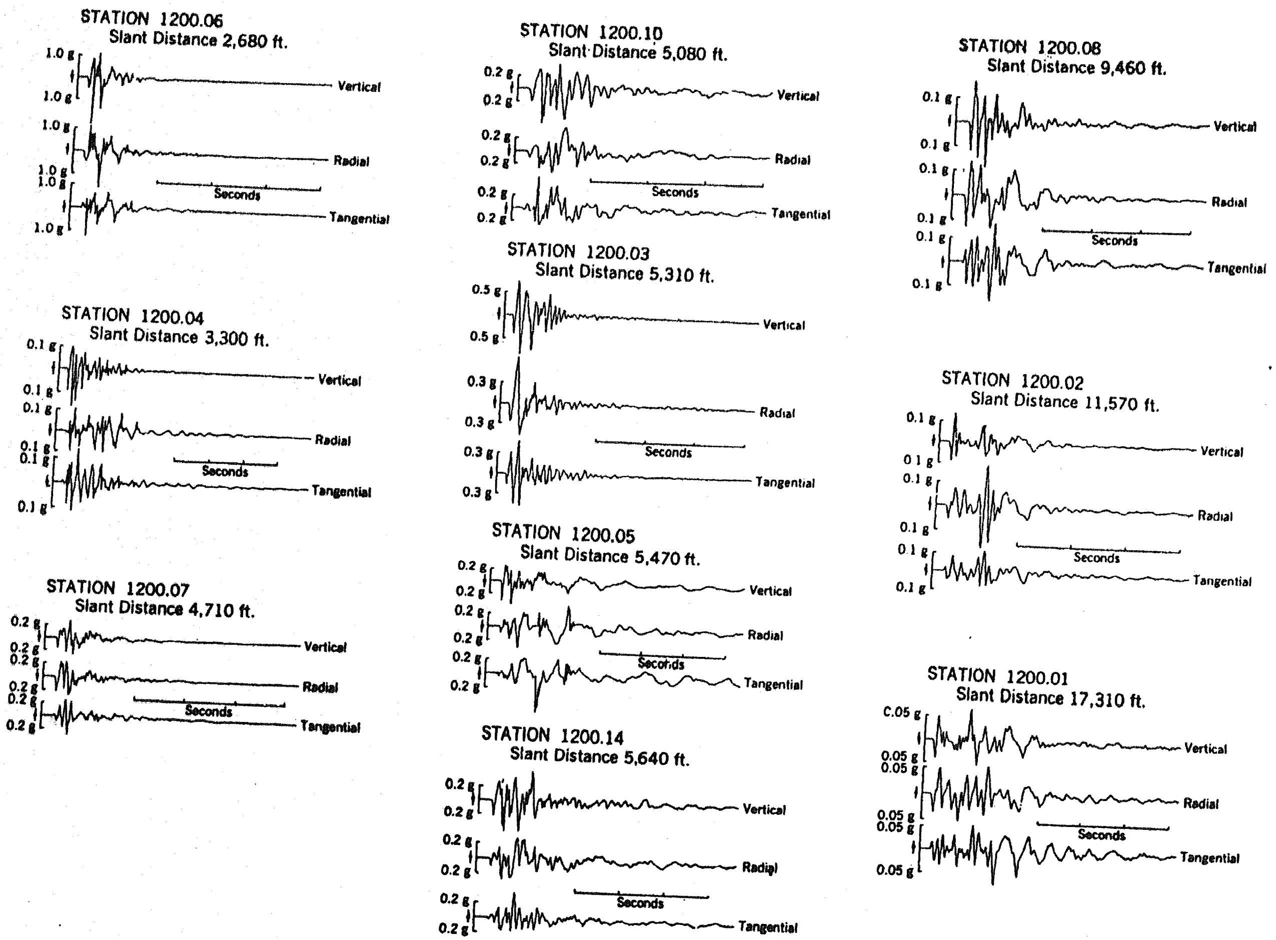


Figure 3--Tracings of acceleration records, Blanca Shot. The direction of the arrows indicate initial ground motion up, radially away from zero, and tangentially to the left when facing zero.

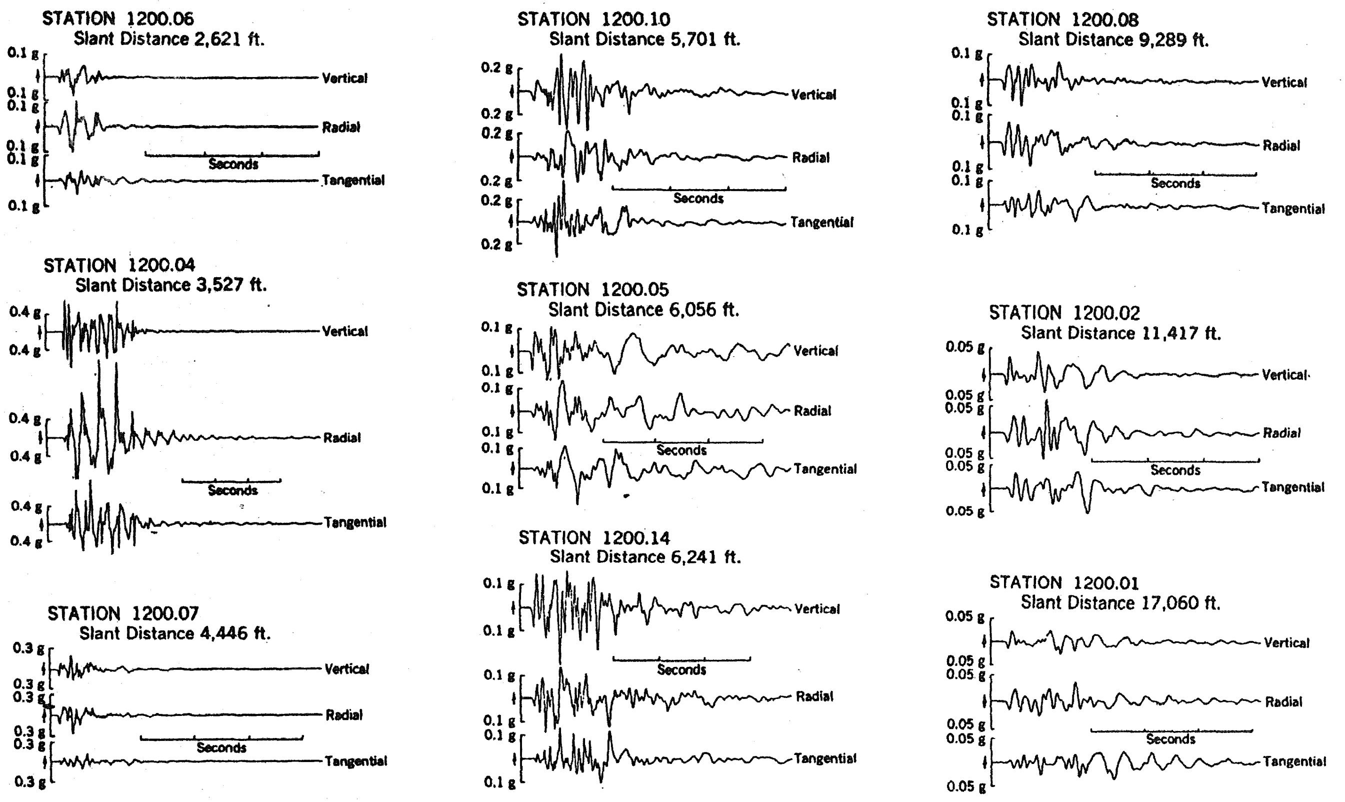


Figure 4--Tracings of acceleration records, Logan Shot. The direction of the arrows indicate initial ground motion up, radially away from zero, and tangentially to the left when facing zero.

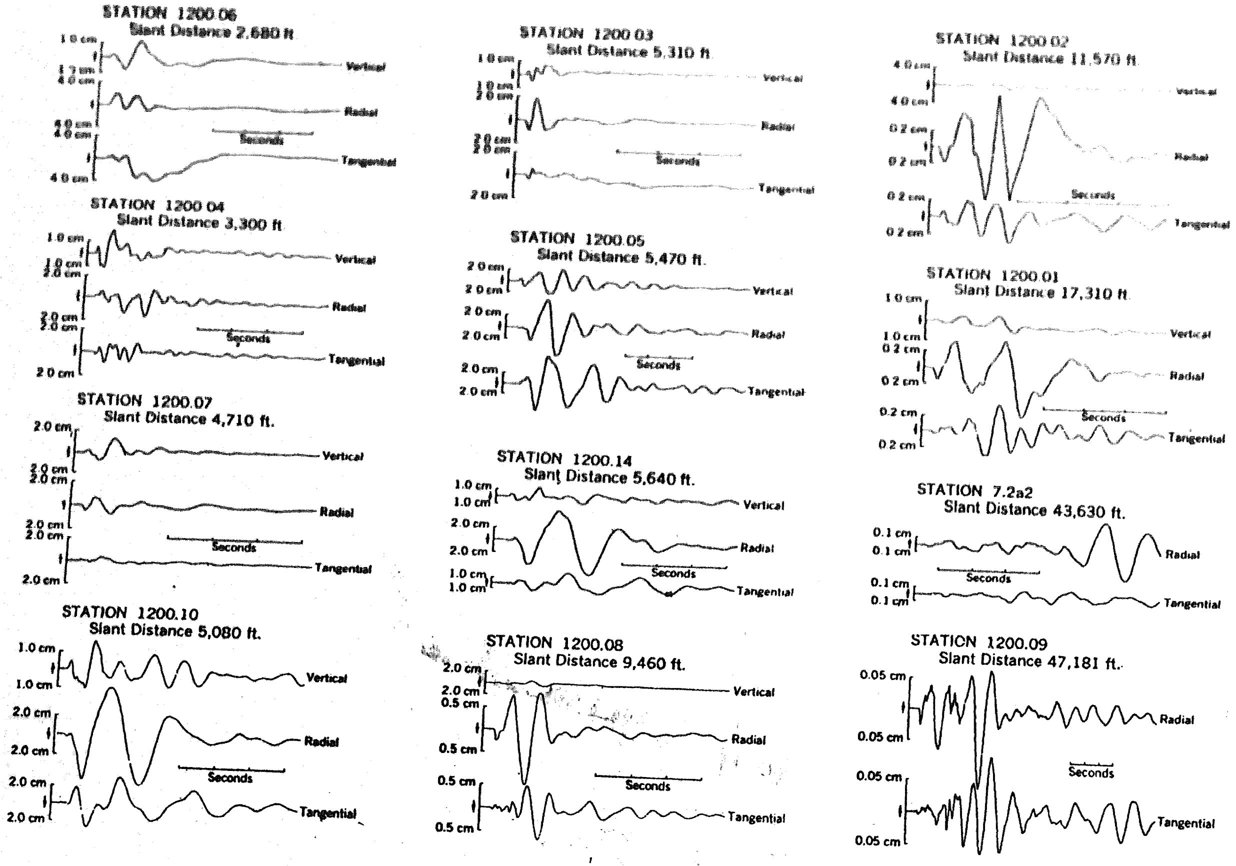


Figure 5--Tracings of displacement records, Blanca Shot. The direction of the arrows indicate initial ground motion up, radially away from zero, and tangentially to the left when facing zero.

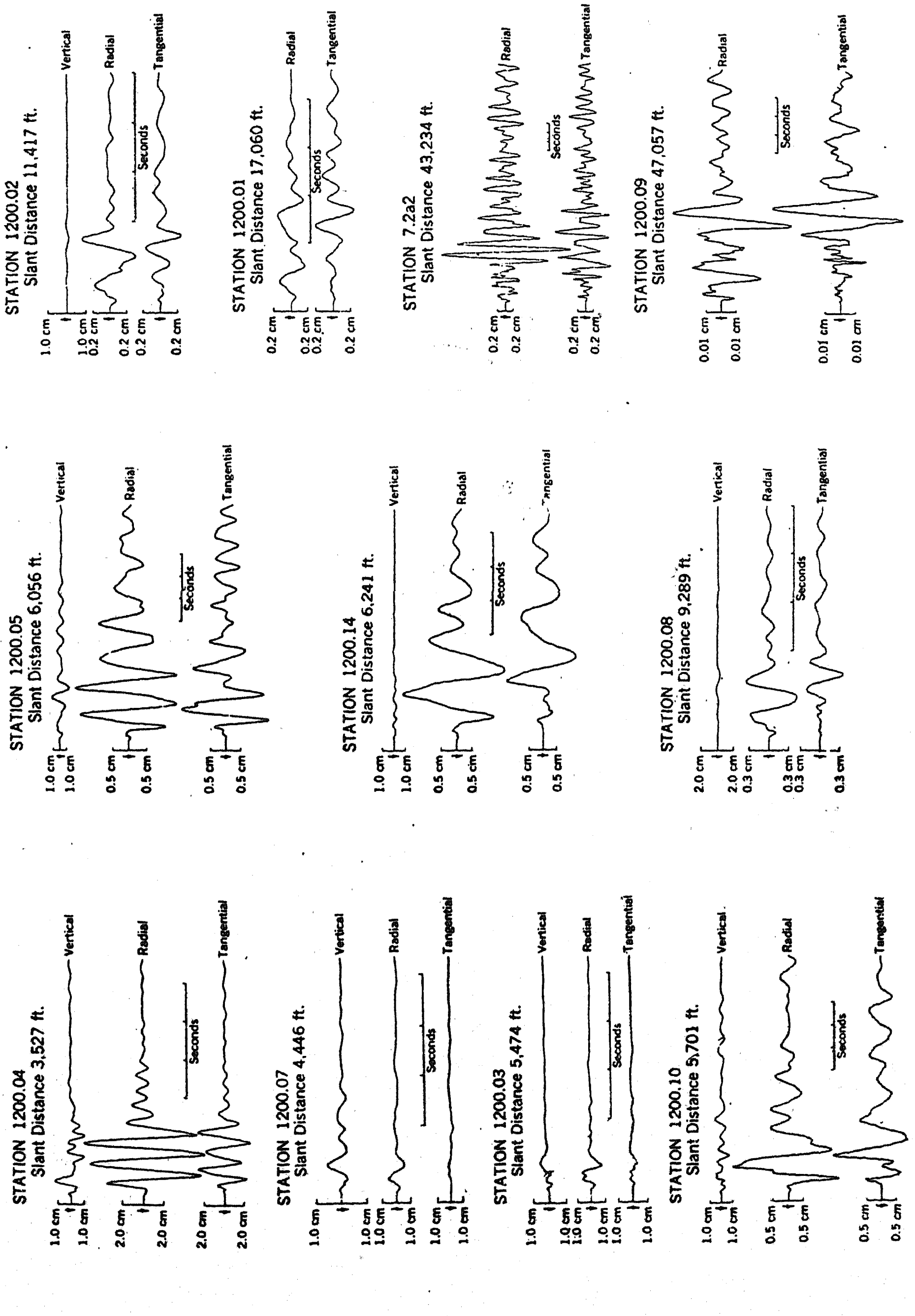


Figure 6--Tracings of displacement records, Logan Shot. The direction of the arrows indicate initial ground motion up, radially away from zero, and tangentially to the left when facing zero.

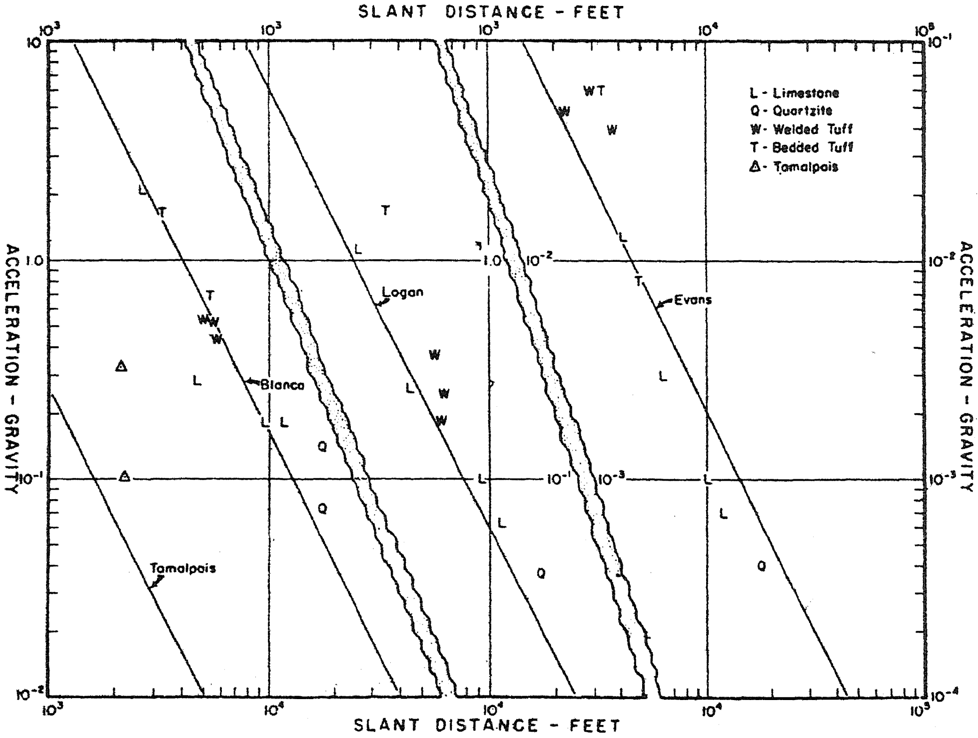


Figure 7--Attenuation of ground acceleration with distance.

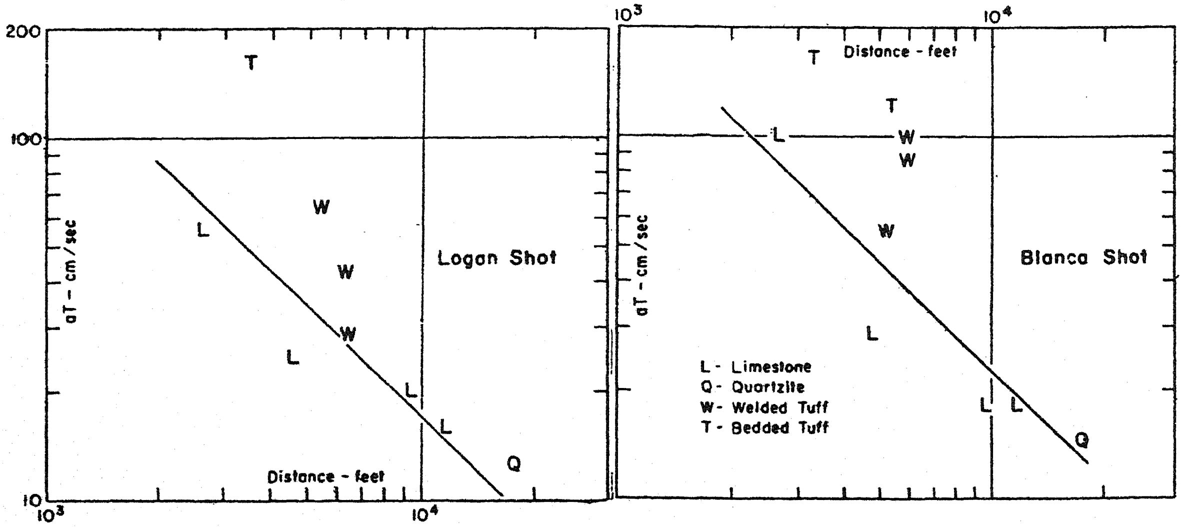


Figure 8--Attenuation of the product of acceleration and corresponding period with distance.

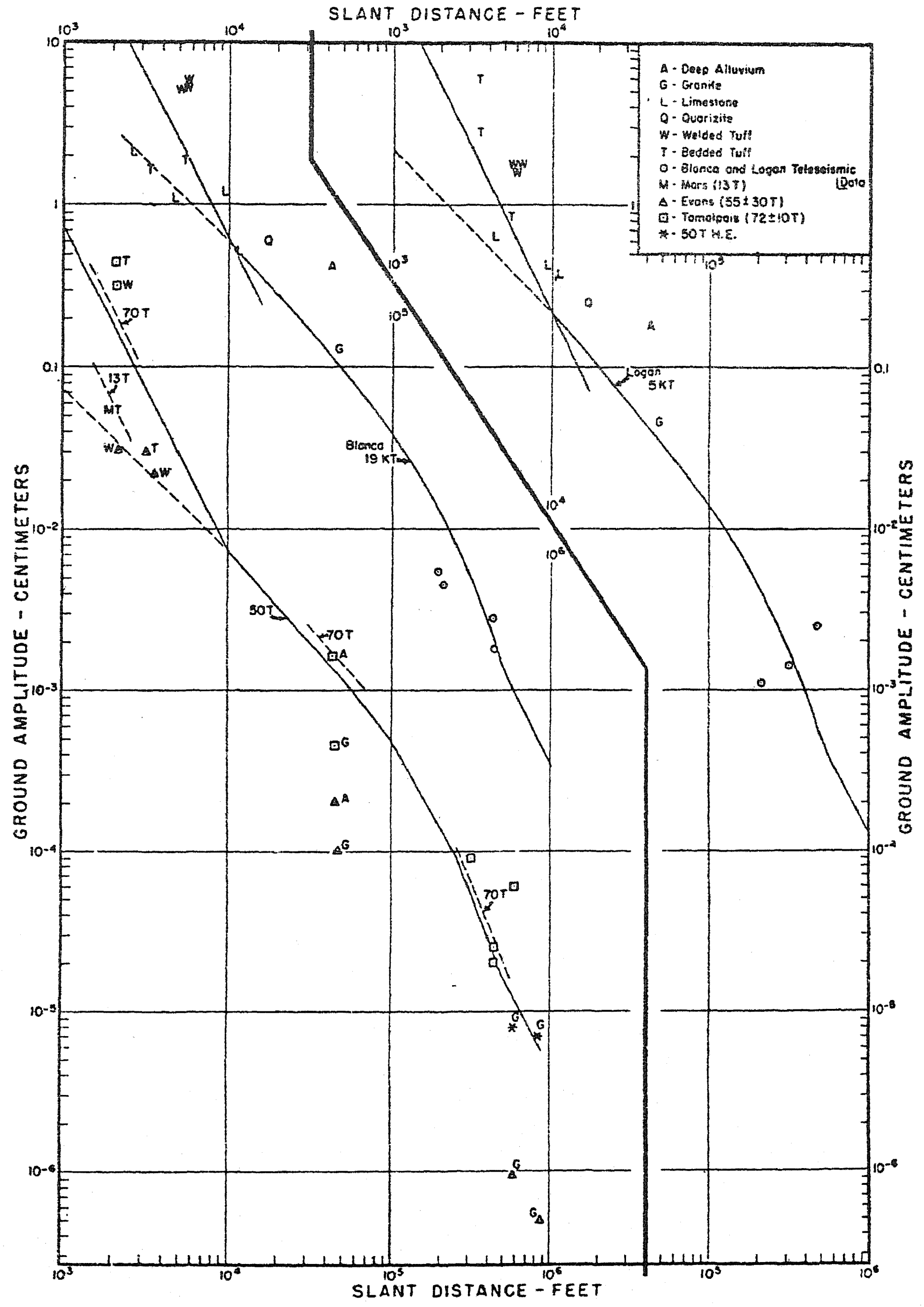


Figure 9--Attenuation of ground displacement with distance.

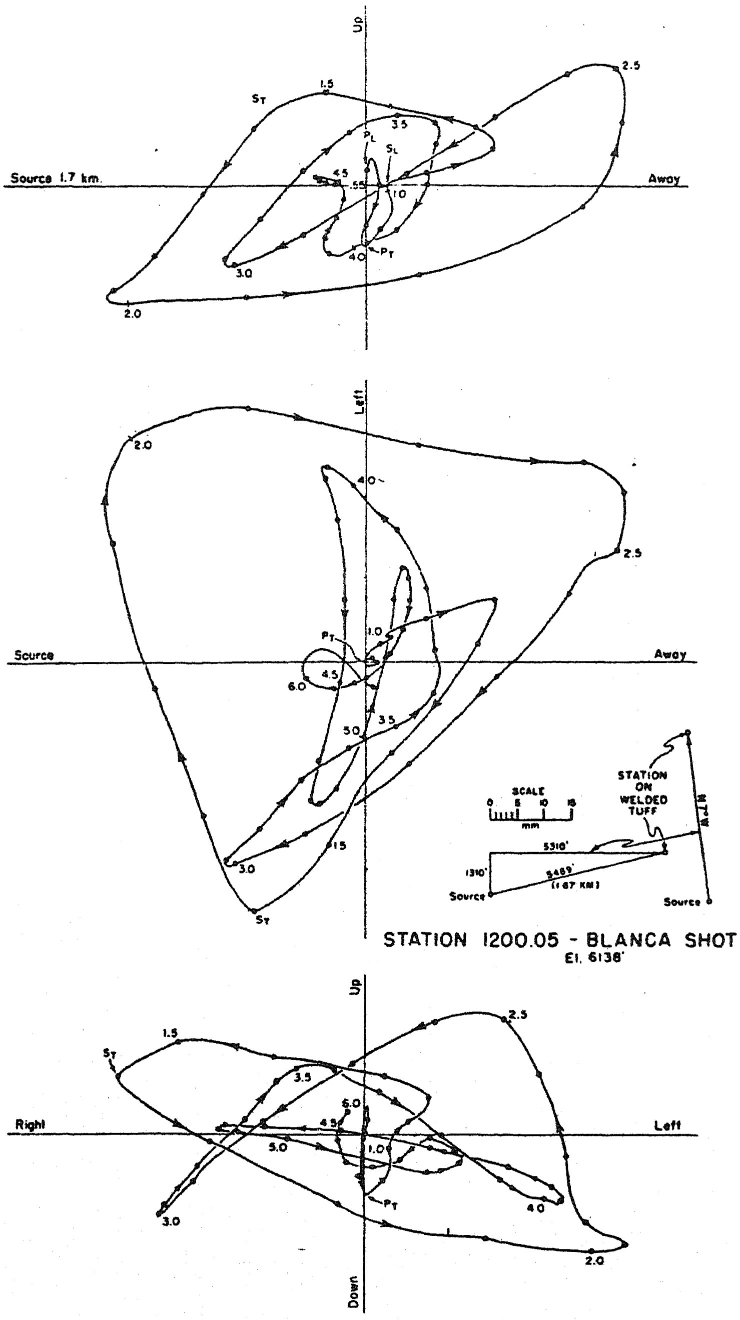
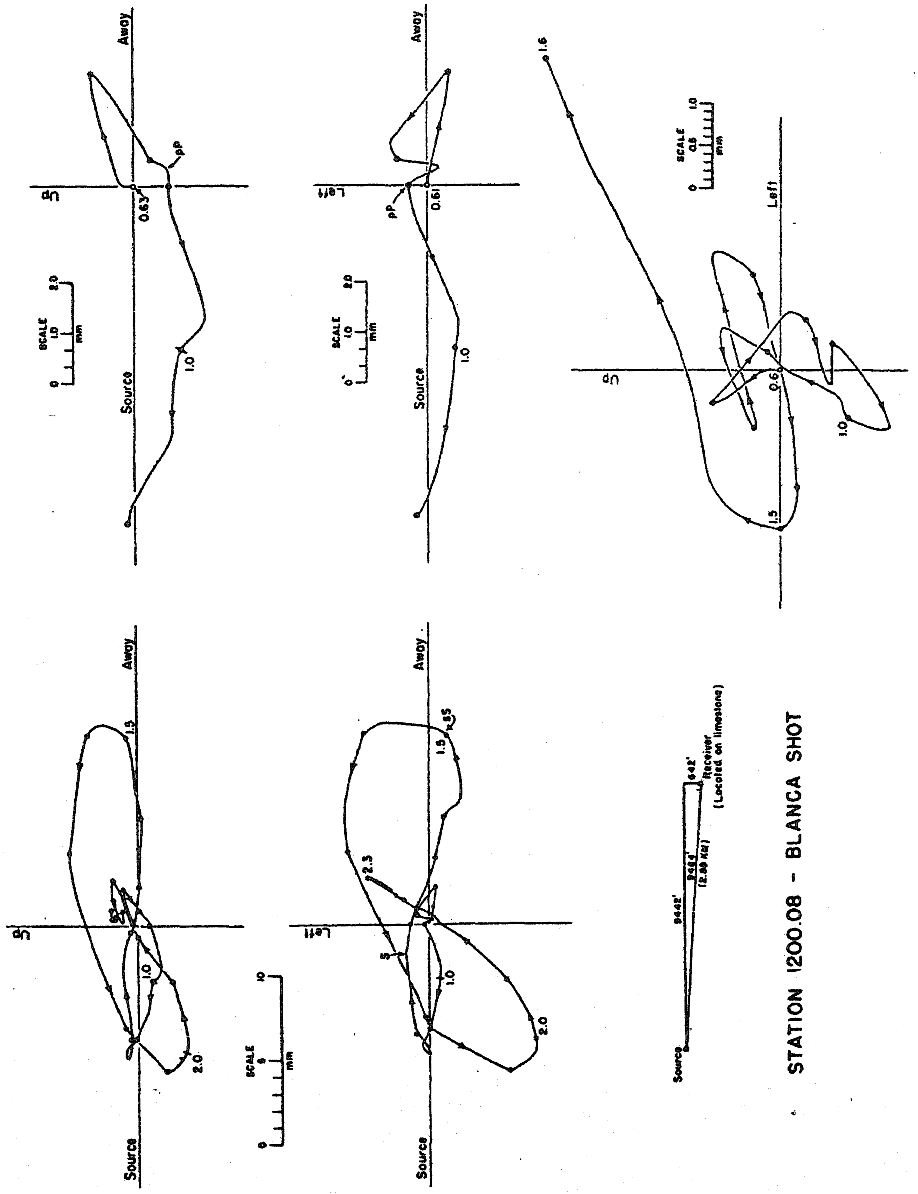


Figure 10--Trajectory of particle motion - Blanca Shot. Station 1200.05



STATION 1200.08 - BLANCA SHOT

Figure 11--Trajectory of particle motion - Blanca Shot. Station 1200.08

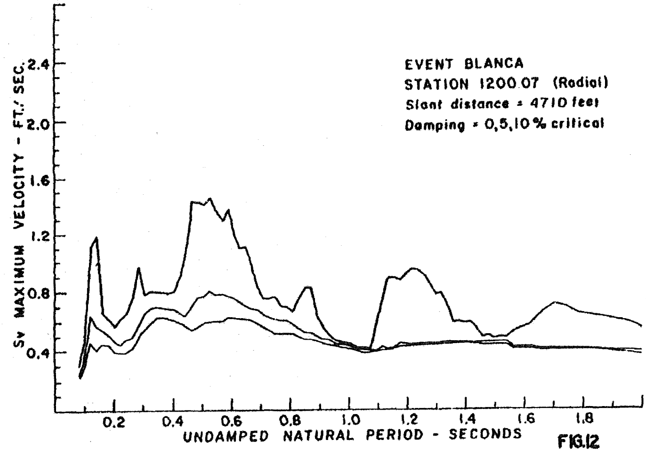


FIG.12

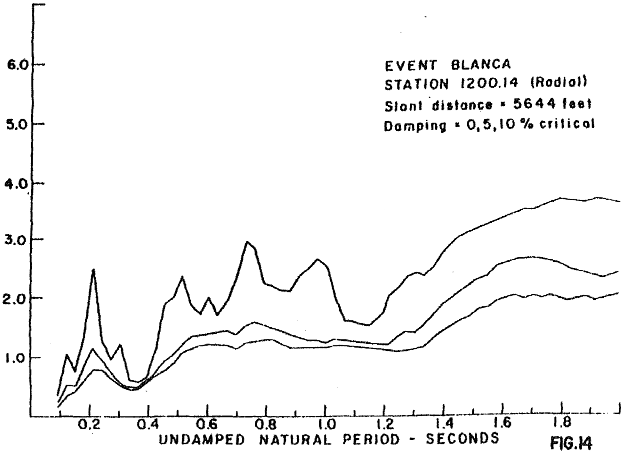


FIG.14

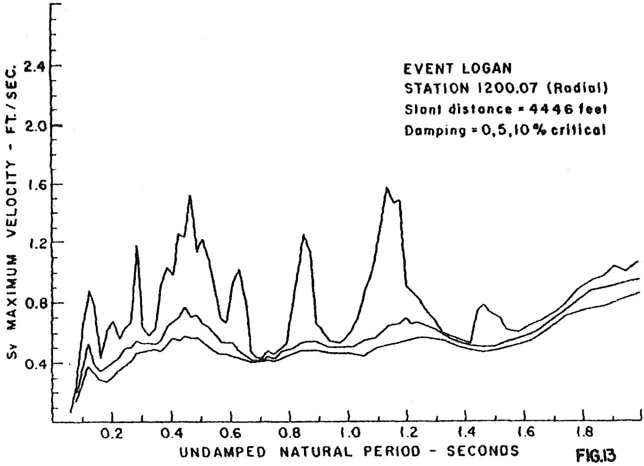


FIG.13

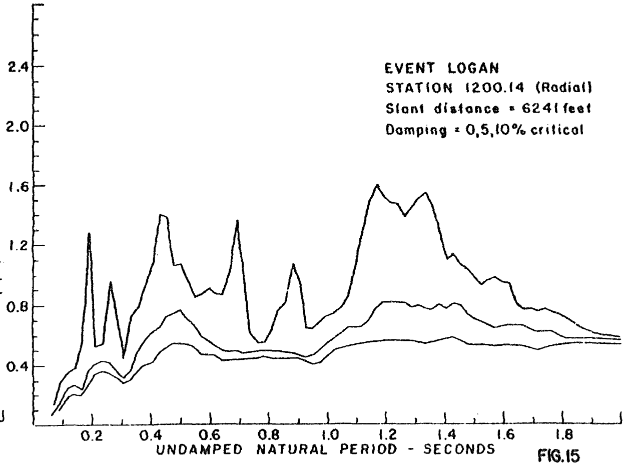


FIG.15

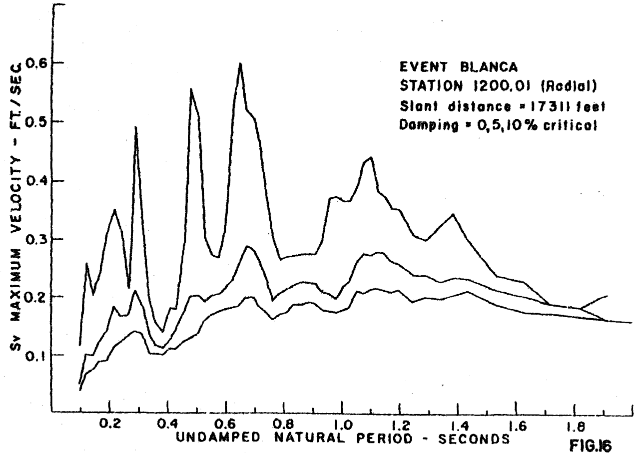


FIG.16

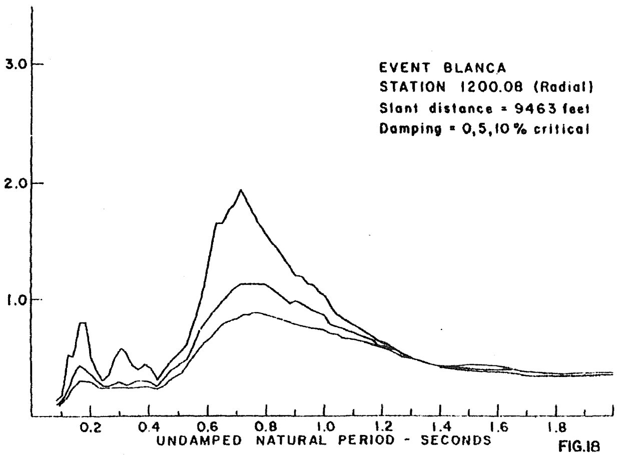


FIG.18

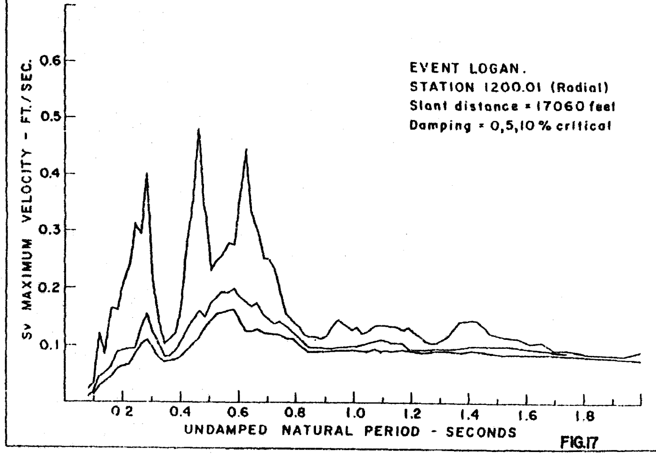


FIG.17

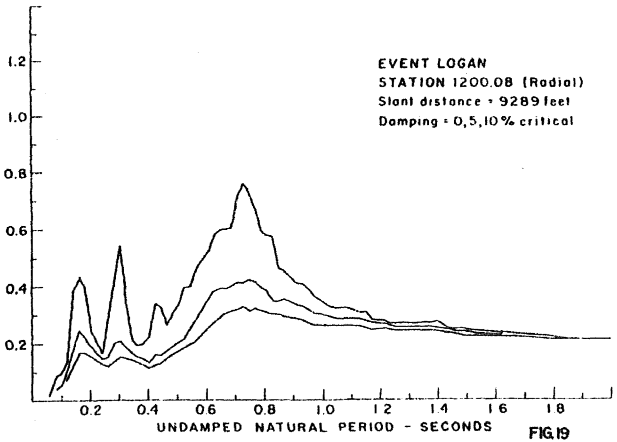


FIG.19

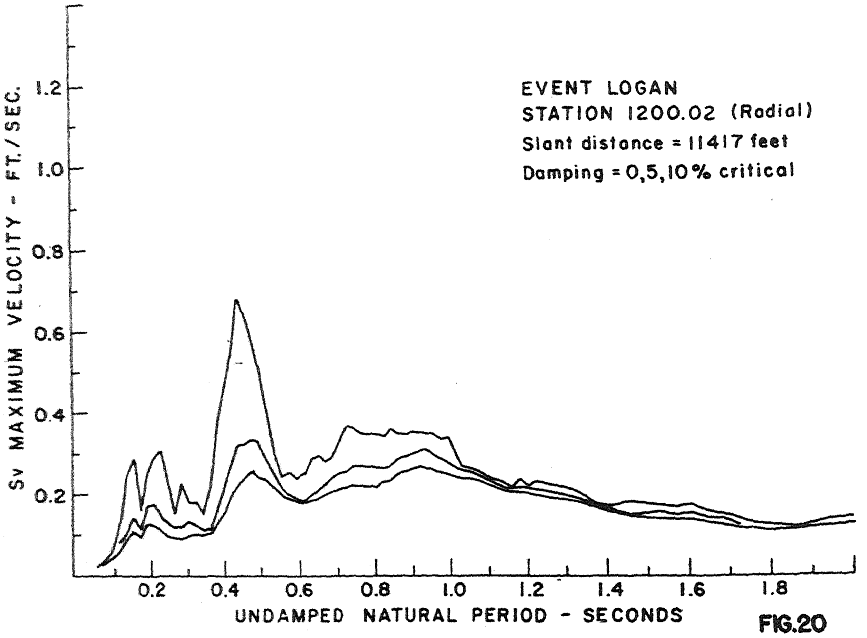

EVENT LOGAN
STATION 1200.02 (Radial)
Slant distance = 11417 feet
Damping = 0,5,10 % critical
Sv MAXIMUM VELOCITY - FT./SEC.
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
UNDAMPED NATURAL PERIOD - SECONDS

FIG.20

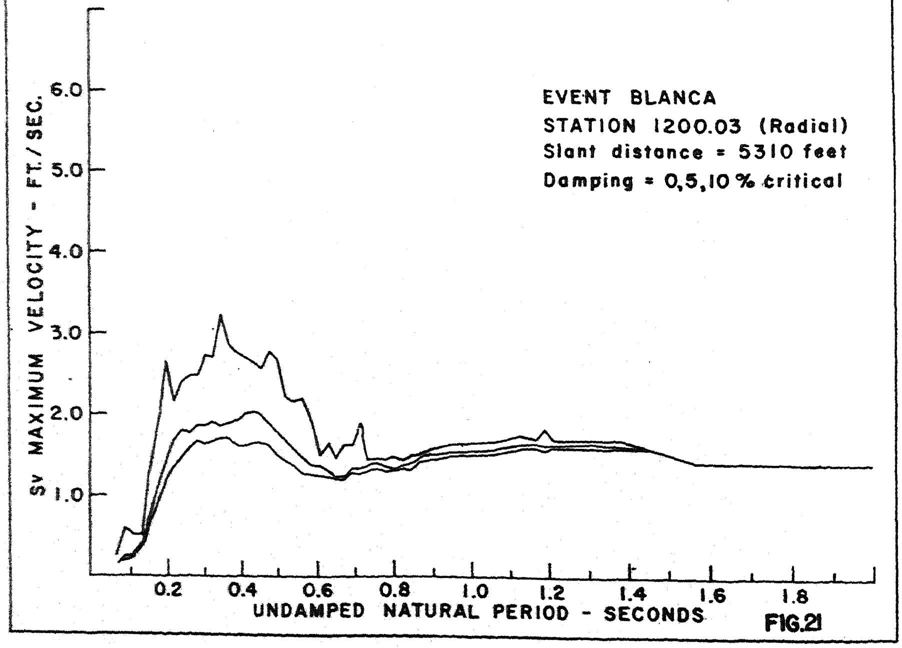

EVENT BLANCA
STATION 1200.03 (Radial)
Slant distance = 5310 feet
Damping = 0,5,10 % critical
Sv MAXIMUM VELOCITY - FT./SEC.
6.0
5.0
4.0
3.0
2.0
1.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
UNDAMPED NATURAL PERIOD - SECONDS

FIG.21

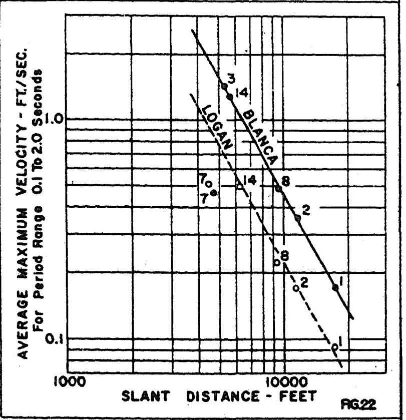
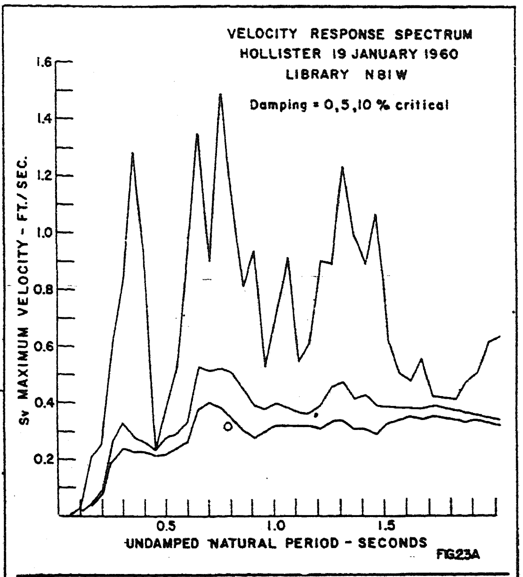


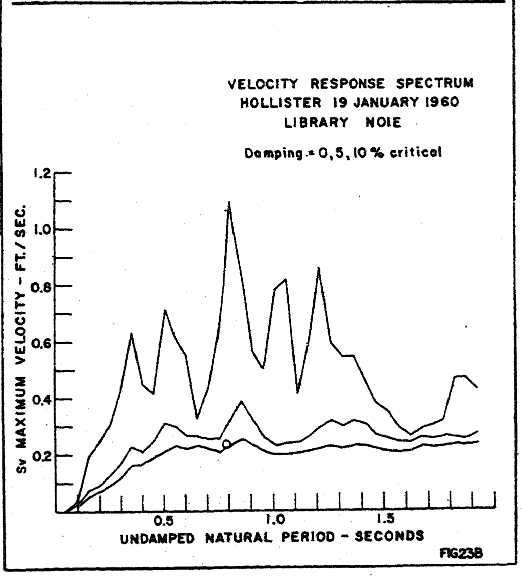
FIG22



VELOCITY RESPONSE SPECTRUM
HOLLISTER 19 JANUARY 1960
LIBRARY N81W

Damping = 0,5,10 % critical

FIG23A



VELOCITY RESPONSE SPECTRUM
HOLLISTER 19 JANUARY 1960
LIBRARY N01E

Damping = 0,5,10 % critical

FIG23B

TABLE I. Data on underground nuclear detonations.

Event	Date	Time (UT)	N. Latitude	W. Longitude	Elevation (ft)	Yield (kt)
Rainier	19 Sept 1957	1659:59.454	37 11 44.800	116 12 11.35	6615	1.7±0.1
Tamalpais	8 Oct 1958	2200:00.131	37 11 43.10	116 12 01.64	6616	0.070±.010
Logan	16 Oct 1958	0600:00.140	37 11 03.03	116 12 04.04	6141	$5.0^{+0.2}_{-0.4}$
Evans	29 Oct 1958	0000:00.15	37 11 41.46	116 12 17.03	6620	0.055±.030
Blanca	30 Oct 1958	1500:00.15	37 11 09.36	116 12 07.28	6138	19.0±1.5

TABLE 2. Comparison of seismic energy calculated by use of tentative formula with seismic energy calculated by seismologists.

	V (1) (ft/sec)	D (2) (ft)	E From Formula(3) (logarithm - ergs)	E From Seismologists(4) (logarithm - ergs)
Logan Nuclear Detonation	0.210	10,000	18.1	18.0 - 18.1 (Carder)
Hollister, California, Earthquake of 19 January 1960				
	0.285	25,800	18.9	18.8 (Tocher)
Hebgen Lake, Montana, Earthquake of 17 August 1959				
Bozeman, Mont.	0.254	305,000	20.8	21.9 (Richter)
Port Hueneme, California, Earthquake of 18 March 1957				
Port Hueneme	0.80	26,000	19.4	18.3 (Richter)
San Francisco, California, Earthquake of 22 March 1957				
Golden Gate Park	0.284	32,200	19.1	
State Building	0.310	44,300	19.4	19.2 (Tocher)
Alexander Building	0.140	50.700	19.2	
Oakland City Hall	0.104	86,600	19.4	

(1) For Logan, "V" was obtained from radial component spectrum; for the earthquakes, "V" was obtained from the largest horizontal direction spectrum.

(2) For Logan, "D" is slant distance to detonation; for earthquakes, "D" is horizontal distance to epicenter.

(3) Formula: $E = \frac{10^{12} V D^{1.78}}{2.4}$

(4) For earthquakes, seismic energy was calculated from magnitude rating of seismologist using Gutenberg-Richter formula:

$$\text{Log } E = 9.4 + 2.14\,M - 0.054\,M^2$$

DISCUSSION

C. F. Richter, Visiting Professor at the University of Tokyo, Japan:

I believe the magnitude value used for the Montana earthquake of August 1959 was taken from the Pasadena preliminary bulletin. If so, it represents a preliminary estimate based on recordings at the Pasadena station only, and subject to revision.

W. K. Cloud:

Preliminary estimate of magnitude was used. To my knowledge no other magnitude rating by the seismological laboratory has been published to date.