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INDUCED GROUND-VIBRATION STUDY AT PUEBLO GRANDE, PHOENIX, ARIZONA

by

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ABSTRACT

This report addresses concerns about potential damage to the archeological structures at Pueblo Grande due to the induced ground shaking from the construction of the Hohokam Freeway, the construction of the expanded Pueblo Grande Museum and Cultural Park, and during future use of the park. The city of Phoenix Parks, Recreation, and Library Department and the Pueblo Grande Museum funded and coordinated the study to develop parameters which will allow construction near the ruins with minimal risk of damage. This report describes the risk to the archaeological structures from the induced ground vibrations.

Our findings show that the vibrations from construction of the Hohokam Freeway, the activities at the adjacent airport, and railroad traffic create low or no risk of damage to the ruins from induced ground vibrations. Ground shaking induced by some of the activities at the existing observation tower, certain construction at the museum which is adjacent to the ruins, and low-flying helicopters can be a vibration risks to the complex. A zone map is included in the report as a guide for present park developments and for future planning purposes. Measures such as backfilling, reconstruction, and use of lighter vehicles can reduce the risk to fragile structures during construction near archeological structures.

INTRODUCTION

The Pueblo Grande complex archaeological site is located in south-central Arizona within the city limits of Phoenix (fig. 1). The site has the only known excavated Hohokam platform mound in public ownership. This mound is nearly rectangular in shape, 3 acres in area, and approximately 4-5 m high. This mound was built and occupied between 840 and 540 yrs B.P. and is a rich source of information from that era. The mound consists of approximately 35 rooms. Several excavation programs have left many of the walls, rooms, and benches structurally unstable and exposed to the elements. The exposed walls in the mound complex range from 1 to 3 m in height.

A second Hohokam building complex (approximately 25 rooms at ground level) is located at the northwest corner of the mound. Seven rooms in the northern area of this complex are intact. The exposed walls are approximately 1-2 m in height. An oval-shaped depression approximately 1 m deep, 15 m long and 5 m wide is located approximately 100 m north of the mound. This structure is thought to have been a "ball court", and it has been reinforced with a concrete coating.

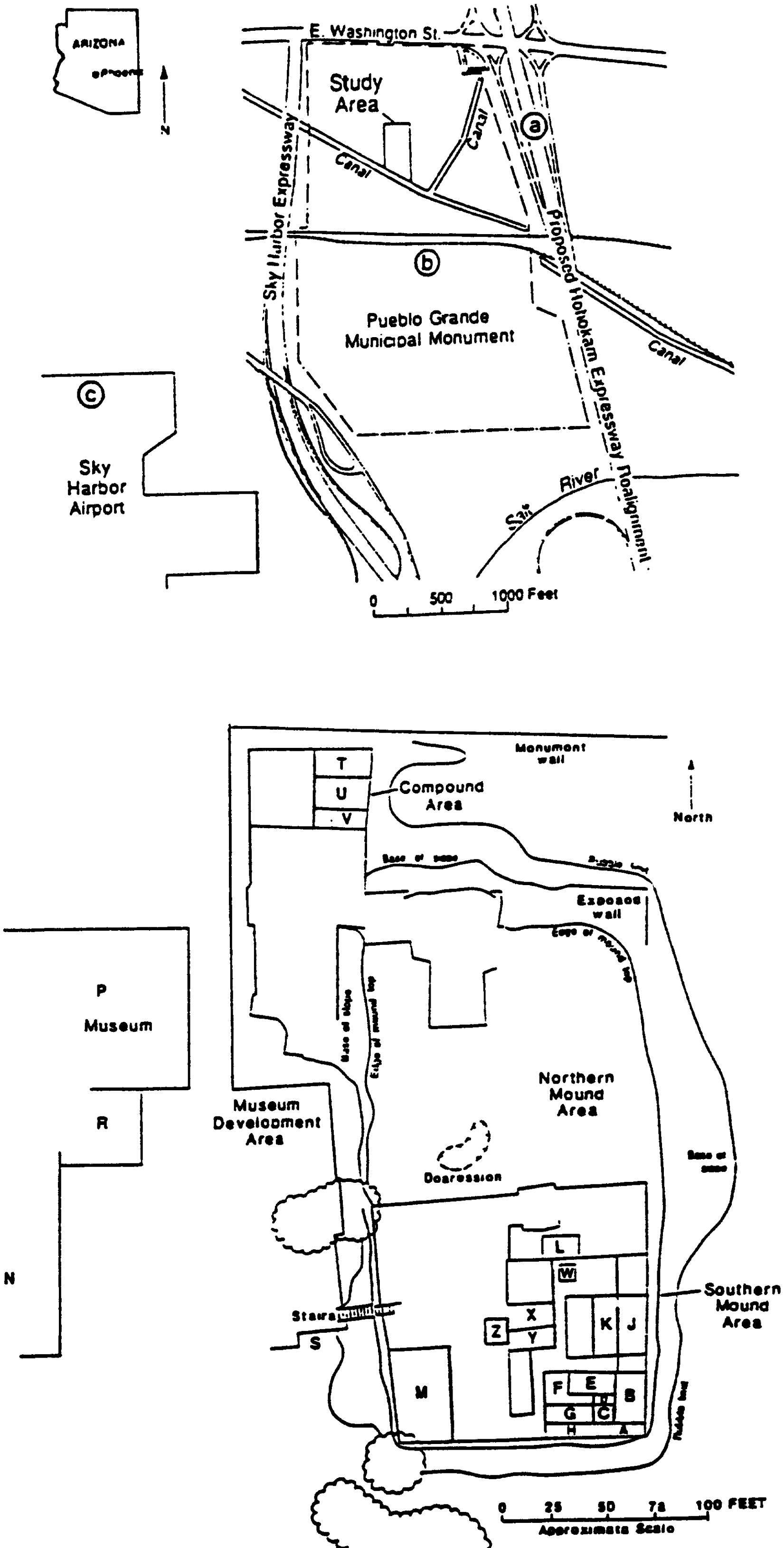


Figure 1. Map showing the location of Pueblo Grande and the mound area within the park. Vibration sources a = Freeway construction, b = railroad, c = airport.

The exposed archeological structures of Pueblo Grande generally consist of single, right-angled, or box-shaped walls with few window or door openings. The walls are constructed of puddled adobe or adobe matrix with layers of stone in a generally rectangular-modular outline with no roofs remaining. The exposed Hohokam structures show severe erosion which can be attributed to one or all of the following: wind, rain, vibrations, vegetation, rodents, insects, and soil/foundation problems. In this report we describe the mechanically-induced vibrations, their sources, and their attenuation. We develop a zoning for construction and personnel activities at the archaeological complex through a logical sequence of source, transmission path, and site study.

ACKNOWLEDGMENTS

We would like to acknowledge the cooperation and outstanding work of the U.S. National Park Service personnel doing reclamation and protection of the Pueblo Grande mound structure. We thank Mr. T. Morgart (NPS) for his cooperation and helpful discussions. E. King took photographs and other documentation that greatly aided our study.

METHODOLOGY

Methods for deriving levels of ground shaking for mapping or zoning urban areas have evolved from geophysical and geologic urban-hazards research projects (Murphy and others, 1975; King and others, 1982, 87, 88, 90; Algermissen and others, 1982, 1990). The general method used in these studies consisted of comparing the parameters of the induced vibrations in the structures to those on the ground near the base of the structure, and, when possible, at the source of the vibrations. Once the energy level and frequencies of concern were determined for the structure under study, these values were compared with the induced vibrations from various sources. After the attenuation-with-distance of the induced energy from the source is determined, these values (attenuation and structural sensitivity) were used to zone the allowable activities near the archeological ruins. The use of site-specific empirical data when available, rather than employing geographical models to detail vibration limits at a specific location, resulted in better zoning resolution and accuracy.

Portable, triaxial, velocity-sensing seismographs (natural period of 0.65 seconds, damped at 60 percent of critical) were used to record the induced ground and structural shaking. The seismometers were leveled, oriented, and calibrated for each event or field test using standardized procedures developed by U.S. Geological Survey (Carver and others,1986). The vibration data were digitized and recorded on magnetic tape at 200 samples per second per channel by the field seismographs. The sample rate allows frequency resolution sufficient to analyze ground vibrations in the 1- to 50-Hz spectral range. The natural frequencies of the walls and roofs were expected to be within this frequency range. Two to three separate systems were used for the wall, site, and attenuation testing (fig. 2A). One to two seismic systems were installed for long-term, unattended monitoring of the vibrations induced during the main freeway construction and preservation work. The systems were manually activated for the field tests and automatically activated during the long-term monitoring. During automatic operation, the seismograph were set to record when a certain vibration threshold was exceeded.

The vibration data were recorded on magnetic cassette tape and analyzed using VAX 750 and a PC-286 computers using spectral analysis software developed by Cranswick and others (1989). The data recorded for the tests and the long-term monitoring generally had an average of 3.0 s of pre-event recording and 30 s of post-event recording. These data were reduced to amplitude-normalized seismograms (fig. 2B) for inspection and analysis. Only the horizontal components of ground motion were analyzed for this report because most shaking damage is due to horizontal ground motion (Hays, 1969).

A 10-s duration window of digital data from the recorded vibrations, beginning with the first impulsive compressional wave arrival and including all of the major wave train, was selected for analysis. The window is tapered with a whole-cosine bell (Hanning window) before being transformed by a standard Fast Fourier Transform (FFT) program (fig. 2C). It was unnecessary to normalize spectral amplitudes by window length as all spectra in this study were derived from data windows with identical duration.

STRUCTURAL TESTING

Although a detailed description of the dynamic behavior of a structure located on or in soil and rock is beyond the scope of this report, it is important to note that the soil-structure combination and its interaction with seismic waves form a very complex dynamic system. The interaction of the source energy with the source geology, distance transmitted, amount of energy dissipated, and the geology underlying the structure produces the characteristics of the ground motion excitation at the structure. The structure will then move in response to the ground motion excitation as a function of its natural frequencies. The vibration amplifications in structures have been found to be strongly dependent on the natural frequencies of the structures, and weakly dependent on wave type, signal-to-source azimuth, and the angle of incidence (Murphy and others, 1971; Joyner and others, 1981; King and others, 1985, 90). It is therefore important to know the ground motion frequencies that have the most influence on this type of structure. The procedure for obtaining the natural frequencies of vibration and the damping coefficient of the walls generally consists of installing portable, horizontal-motion-sensing seismometers on the top and at the midpoint of bearing walls of the structure (fig. 2A). Vibrations were then induced by body movement of a person. The source movement is abruptly stopped allowing the wall to continue vibration at its natural frequency with decreasing amplitude (damping). The roofs of the museum were similarly tested, except that a vertical motion-sensing seismometer was placed in the midpoint of the roof and shaking was induced by a person doing knee-bends or by a weight drop. This technique has been described in detail by Hudson and others (1964) and King (1969, 1985).

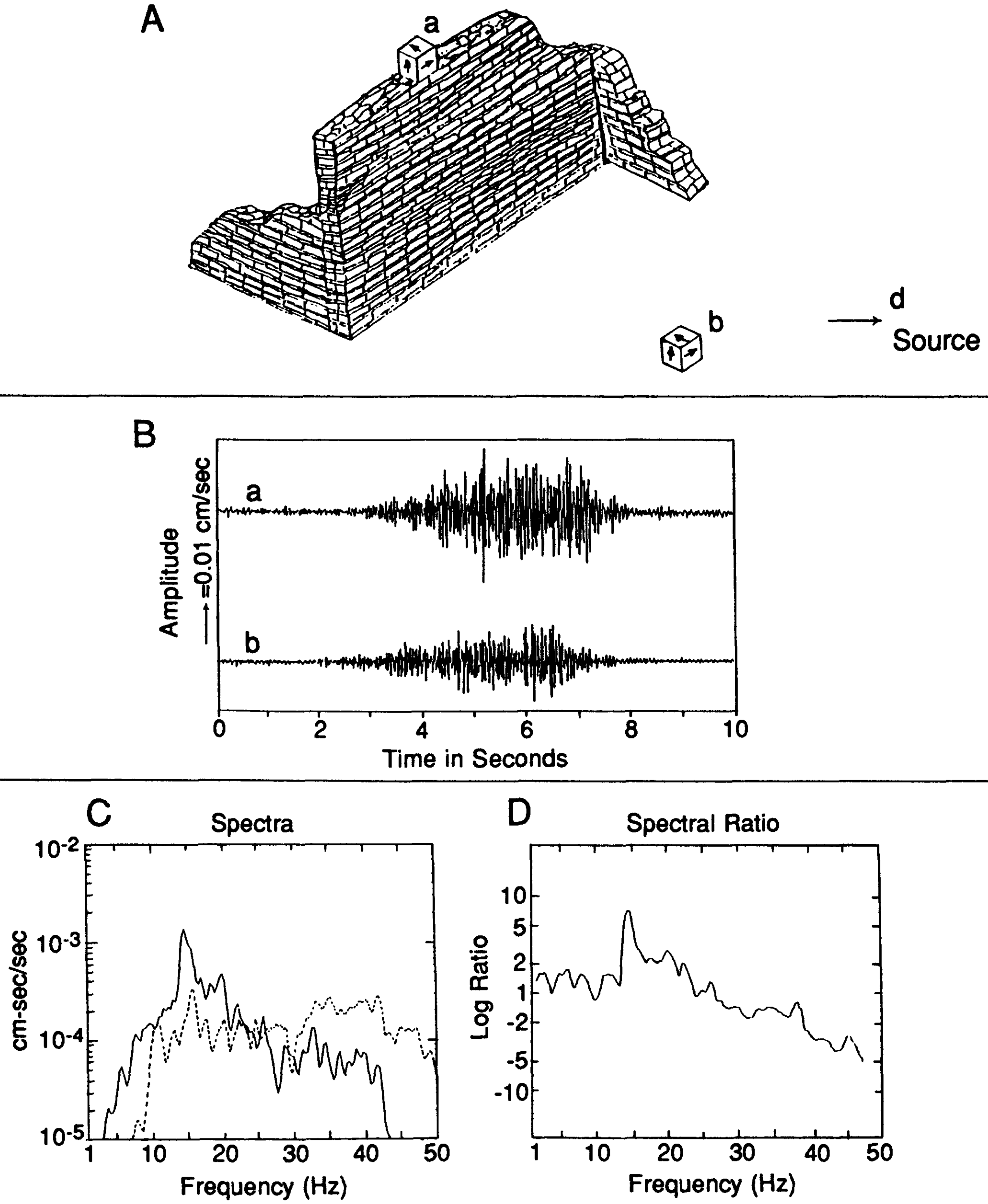


Figure 2. Illustration showing data collection and analysis process. A = wall showing: a = seismometer on top of wall, b= seismometer at free-field. B = seismograms from wall test. a = seismogram from top of wall. b = seismogram from free-field. C = spectra derived from seismograms, — = top of wall, --- = free field. D = spectral ratios derived from C showing peak amplification at natural frequency of wall.

The peak frequency and harmonics of that frequency determined from the spectrum derived from the wall test data were considered to be the frequencies to which the walls were most sensitive. The data were analyzed to obtain the approximate percentage of critical damping using the following formula:

$$b = \frac{1}{2\pi} \left(-\ln \frac{Xn - 1}{Xn}\right)$$

where b is the percent critical damping and Xn is the velocity amplitude for the nth cycle of motion.

Thirty-six walls of the archeological structure, three museum walls, and the museum roofs were tested for their natural frequencies and damping characteristics. A numbering system was used to identify the structures or walls tested. The letter signifies the location of the structure as shown in figure 1B, the number indicates the cardinal location of the wall; that is, A1 indicates structure A and the north wall and, B2 indicates structure B, the east wall. Several minutes of ambient vibration background noise and two to five man-induced vibration events were recorded for each structural test. The vibration data were analyzed to obtain the natural frequency and the percentage of critical damping of each structure (table 1). A plot of the natural frequencies of the walls versus the wall's heights is shown in figure 3. The natural frequency of the walls tested are dependent on the height of the wall. Regression analysis of the data by an exponential curve fit gives the relationship of h=40.7e-0.13f. The equation is very similar to the one derived from the testing of Anasazi walls in Chaco Canyon (King and Algermissen, 1985).

Walls A3, M3, T4, U1, U4, and V1 (fig. 1) were tested before the National Park Service backfilled or rehabilitated the walls. The effective height of walls A3 and M3 were shortened by an increase in floor level inside the rooms with a meter or less with packed dirt fill and by backfill to near the top of the walls on the outside. The seismogram from a test during the pre-backfill and post-backfill time is shown in figure 4. This figure shows that backfill on the wall changes the natural frequency of the wall from approximately 15 Hz (pre backfill) to approximately 40 Hz (post-backfill). Also, the backfill caused a significant decrease in the amplitude of wall shaking. A quantitive number can not be assigned to the decrease in sensitivity as sufficient control could not be maintained on the vibration source (a vehicle drive-by at approximately 15 m distance).

Walls T4, U1, U4, and V1 (fig. 1) were rehabilitated by adding adobe mortar in areas where the original mortar had been removed by erosion primarily near the walls' foundations. The pre and post-repair testing of walls T4, U1, U4, and V1 did not indicate a shift in natural frequency as with walls A and M, (the effective heights were not significantly changed), but the damping coefficient was increased (fig. 5A).

Table 1 Structure Wall Testing

WALL	HEIGHT	NATURAL FREQ. (Hz)	% DAMPING
A1	8-10'	17.1	3
A3	5'	18.9	6
A3'#	5-3'	25.1#	2
B2	8'	11.6	4
B3	7-14'	17.1-8.5	4
C1	6'	17.2	2
D1	5'	11.9	4
E3	4'	19.5	
E4	2'	25	
F4		17.2	
J1	9'	8.2	2
J2	9'	11.6	2
J2'	4'	16.4	
K1	9'	10.3	3
K2	9'	11.1	6
L1	2.5'	19.5	2
M3	7'	14.7	2
M3#	5-	22-38	3-5
M4	7'	13.0	3
T1	2.5'	24.0	4
T4	4'	19.0	1.5-4*
U1	6'	18.0	1- -3*
U4	3.5'	18.6	1+ -3*
V1	5.5'	18.8	1- -4*
V2	5'	10.9	
V3	3.7'	15.6	7
X1	4'	16.2	
Y1	7'	12.6	4
Y2	2.5'	18.8	2
Y3	4-5'	17.1	
Y4	3'	18.0	

MUSEUM		NATURAL FREQ. modes		% DAMPING
WALL	HEIGHT	1ST	2-3RD	
N2	19'	7.2	22.6	3
P3	19'	6.0	23.5	3
R3		13.4	19.5	3
ROOF	DIMENSIONS			
N9	41x61'	5.2		3
P9	37x48'	5.0		2
R9	18x17'	8.2		2

All tests except the roof tests are from the horizontal-short-axis of walls. #=figures show natural frequency and damping before and after backfill. *= figures show damping before and after wall repair. Percentage damping could not be calculated for all walls.

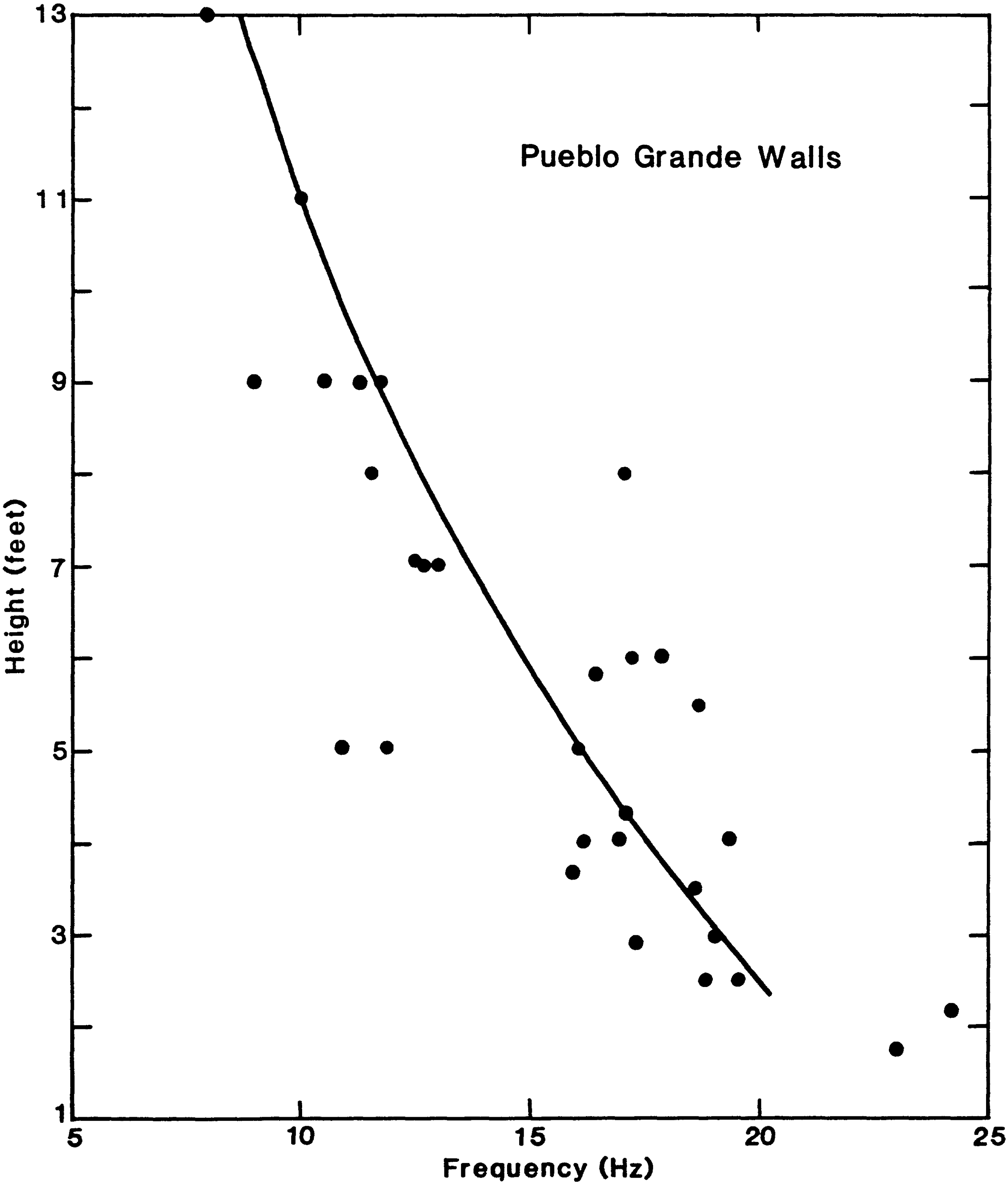


Figure 3. Plot of the natural frequencies of the walls against their heights
Curve is a least-square fit.

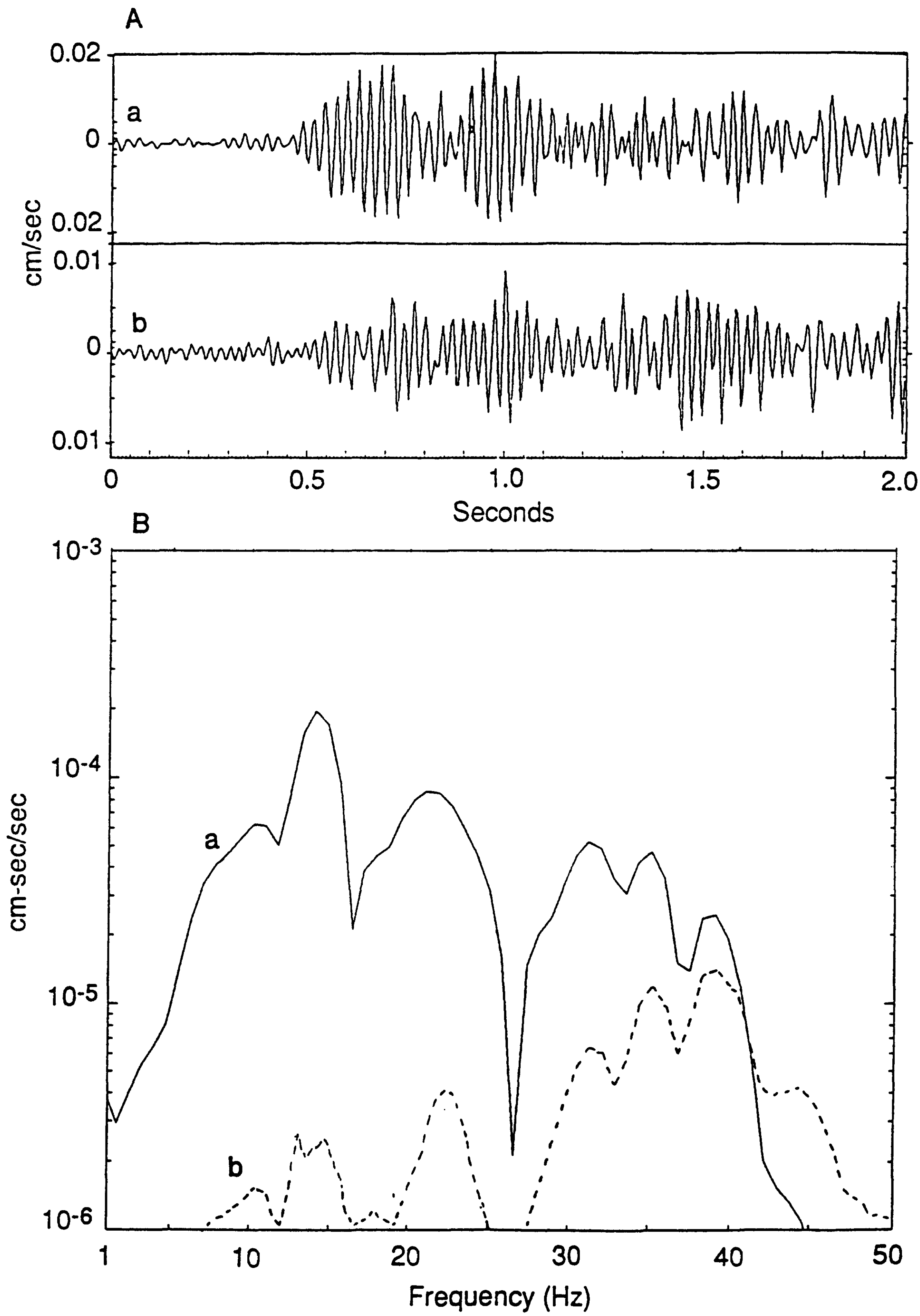


Figure 4. Example of a shift in natural frequency due to shortening of the wall by backfilling at wall M3. A = seismogram and derived spectra from top of wall before backfilling. B = seismogram and spectra from top of wall after backfilling. Induced vibration source is a vehicle drive-by.

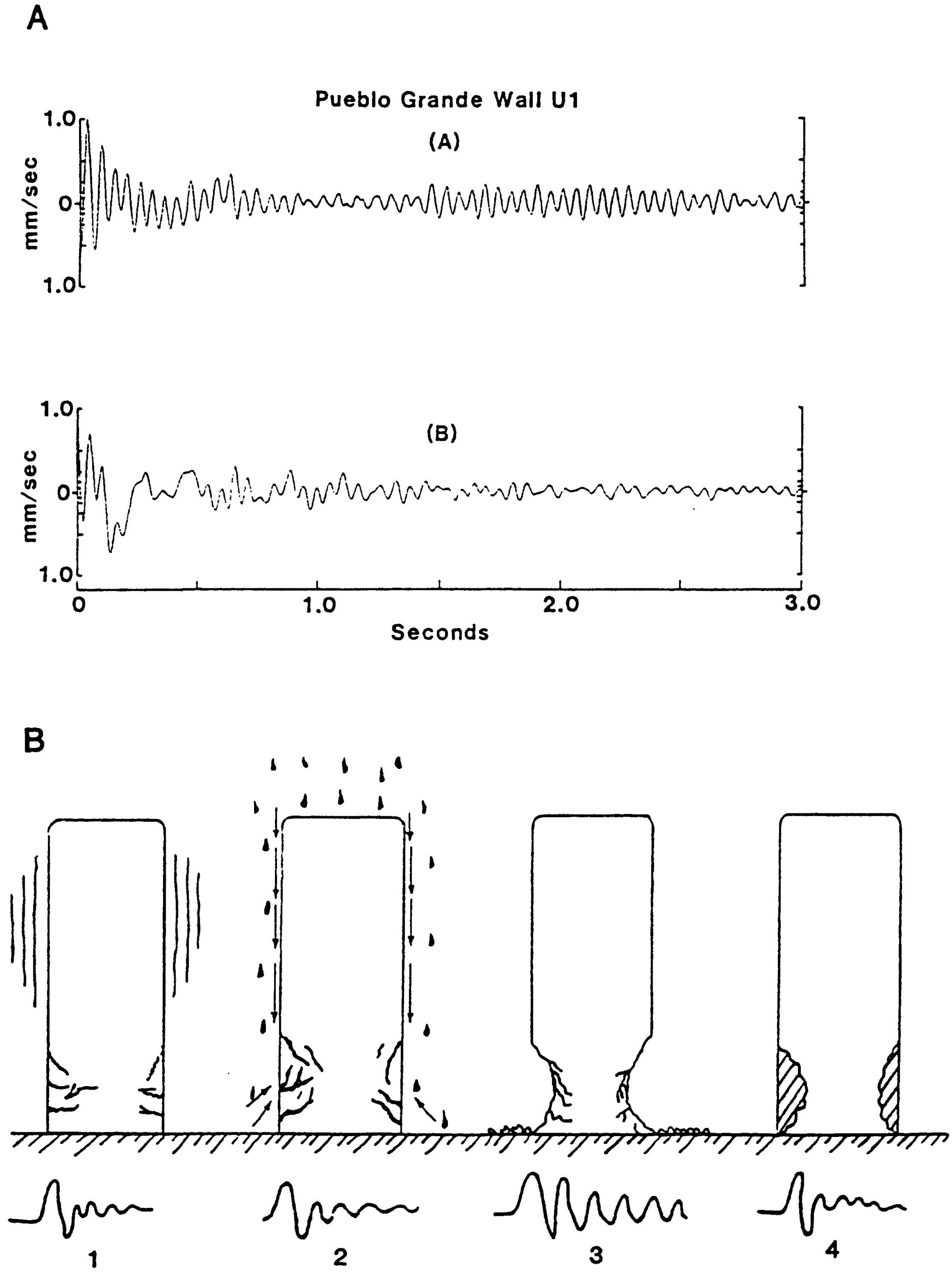


Figure 5. Example of damping shift at wall U1 during repairs. AA = seismogram before repairs showing minimum damping (note "ringing" of wall). AB = seismogram after repairs showing increased damping. B = indicates a possible scenario showing evolution of wall damage. B1=rocking motion from induced vibrations causing cracking at foundation and probable seismogram showing damping. B2 = water invades wall through vibration caused micro-cracks which reduces damping. B3 = sluffing at base of wall and further reduction in damping. B4 = wall repaired, seismogram indicated the returned to normal of damping.

VIBRATION ATTENUATION STUDY

Most ground shaking sources induce a stress wave that decays into an elastic wave which propagates outward. The important source variables are the amount and duration of energy induced and the efficiency of coupling of the energy to the ground. The natural anisotropy and inhomogeneity of the earth modify the induced wavelets which change shape and become dispersed with time and distance. The energy in the waves is reduced with distance by geometric spreading, absorption and scattering. These factors will decrease the amount of energy as the distance from the source increases and will be considered in-total in this report as the "attenuation". The spectral composition of the induced vibrations is initially quite broad-band at the source, but is modified by the filtering actions of the transmission path. In general, the transmission path acts as a low-pass filter.

The location of the known vibration sources in the vicinity of the park are shown on figure 1. The sources are the highway construction at the Hohokam Freeway which is approximately 600 m from the mound (fig. 1a), the railroad which is approximately 130 m from the mound (fig. 1b), the vibration induced by jet aircraft take-offs and landings at Sky Harbor Airport which is approximately 790 m from the mound (fig. 1c), and the Museum-Park preservation, maintenance, and public traffic which varies from a few meters to 30 m from the mound.

The general method used to establish the attenuation and frequencies of the induced energy from the vibration sources-of-concern was to record the ground shaking at different ranges on a straight line between the source and pertinent walls of the archeological ruin or the mound. Figure 6 shows the seismograms and spectra derived from recording vibrations using a linear array from the railroad track to the mound during the passing of a train. Attenuation tests were made using a pick-up truck, a small all-terrain-vehicle ("Bob Cat"), and passing railroad trains as vibration sources. The tests with the truck and Bob-Cat consisted of changing the distances of the induced vibrations rather than moving the seismometers. The range or distance scaling function (attenuation with distance) was derived by linear least-squares regression of the peak-particle velocity data versus the distance plotted on a log-log scale (fig. 7). The data fit a power-law function equation of $Y = aR^b$ where Y = peak particle velocity, a = constant, R = distance, ^{b} = attenuation exponent (slope). The distance-derived attenuation exponent (b) from the recorded peak-particle-velocities induced by the pick-up motion in the frequency bandwidth of 10-30 Hz. is -1.64. The attenuation exponent (b) for the motions induced by the train is -1.63. The induced motion from the "Bob-Cat" is at a slightly lower frequency (8-20 Hz) and has an attenuation exponent (b) of -1.45.

Several tests including inducing vibrations from a pick-up truck running over a 4 cm block to simulate a hole or rough spot on the road and the abrupt deceleration (stopping) of the vehicles were recorded and analyzed (table 2). The analyses show that traffic on a rough road within 15 m of the mound can induce approximately twice the motion that would be induced by traffic on a smooth road. The analyses show that abrupt stopping of a vehicle within 15 m of the mound will introduce approximately 25 percent more vibration amplitude

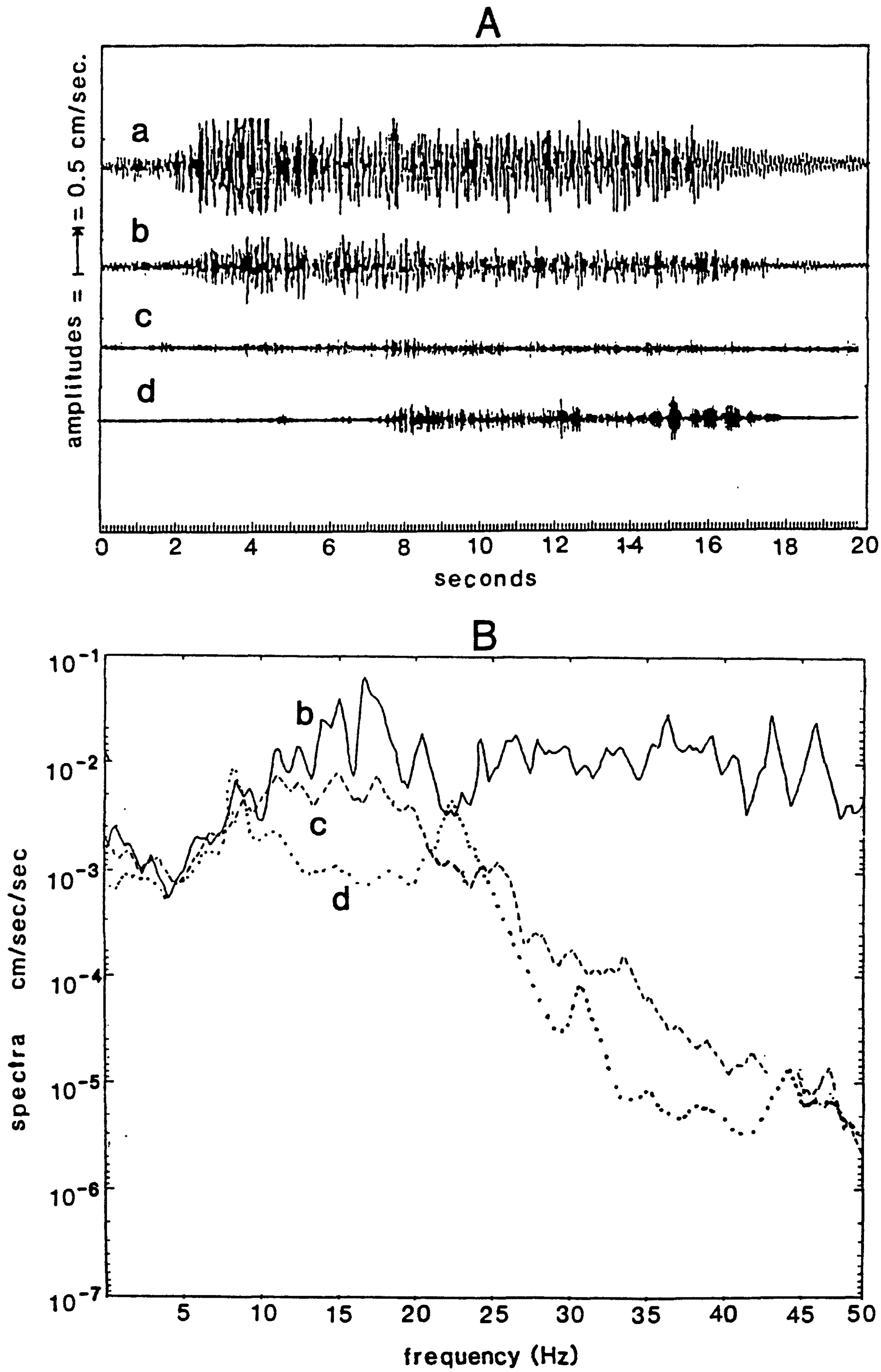


Figure 6. Attenuation with distance of induced motions from railroad train. Aa=seismogram from 5 m from train. Ab = 30.2 m from train, Ac=134 m from train, Ad = top of wall J1. B=spectra derived from the seismograms respectively. (No spectra from 5 m as data was too great to be recorded on-scale.

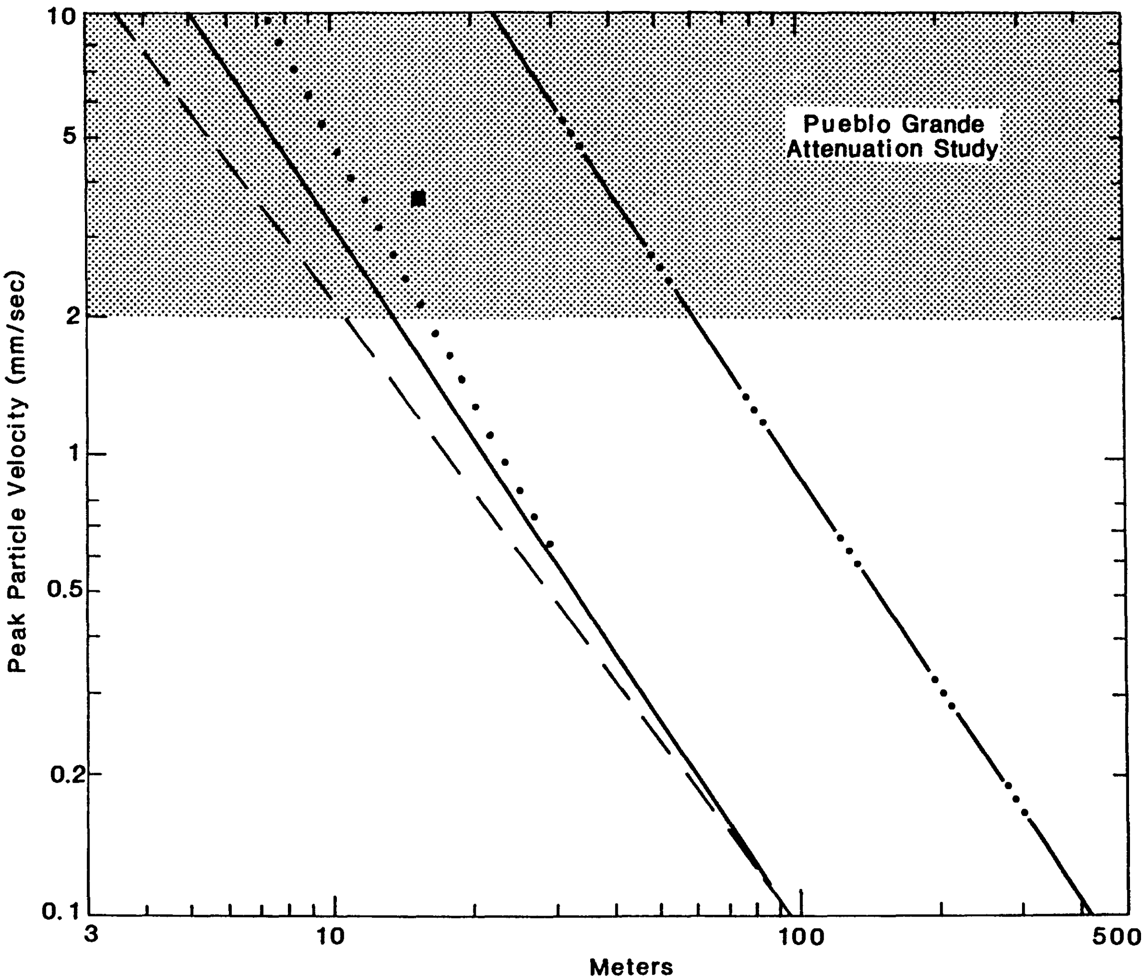


Figure 7. Attenuation study. Least squares plot of peak velocities. — — =Bobcat ——=pick-up truck. ....=truck decelerating. ■ =truck running over 3cm bump. —···—=railroad train

Table 2 Attenuation Tests

Distance m (ft)	Channel	Particle Velocity mm/sec Top Wall U1	Free Field
A. Induced motion from 1/2T pick-up moving at constant velocity (slow pass)			
9.1m-(30')	1	0.65 @ 24 Hz	0.69 @ 24 Hz
	2	7.92 @ 18 Hz	3.82 @ 27 Hz
	3	1.90 @ 25 Hz	1.41 @ 27 Hz
15.2m-(50')	1	0.42 @ 24 Hz	0.44 @ 25 Hz
	2	4.42 @ 18 Hz	1.63 @ 27 Hz
	3	0.56 @ 22 Hz	1.11 @ 26 Hz
30.5m-(100')	1	0.40 @ 20 Hz	0.28 @ 21 Hz
	2	0.98 @ 18 Hz	0.54 @ 26 Hz
	3	0.10 @ 18 Hz	0.21 @ 25 Hz
B. Induced motion from Pick-up <20mph brought to a dead stop.			
9.1m-(30')	1	0.90 @ 29 Hz	0.84 @ 30 Hz
	2	6.82 @ 19 Hz	5.92 @ 30 Hz
	3	1.91 @ 25 Hz	1.51 @ 30 Hz
15.2m-(50')	1	0.88 @ 28 Hz	0.50 @ 30 Hz
	2	5.52 @ 18 Hz	2.00 @ 28 Hz
	3	1.20 @ 26 Hz	0.71 @ 28 Hz
30.5m-(100')	1	0.18 @ 24 Hz	0.20 @ 25 Hz
	2	0.54 @ 18 Hz	0.54 @ 26 Hz
	3	0.20 @ 20 Hz	0.19 @ 22 Hz
C. Pick-up driving at constant velocity over 8" bump under one wheel.			
15.2m-(50')	1	0.72 @ 25 Hz	0.77 @ 30 Hz
	2	4.24 @ 19 Hz	3.77 @ 30 Hz
	3	2.02 @ 25 Hz	1.70 @ 32 Hz
D. Induce motion from a "Bob Cat" moving at a constant velocity.			
9.1m-(30')	2		2.77 @ 15 Hz
15.2m-(50')	2		1.45 @ 12 Hz
30.5m-(100')	2		0.05 @ 12 Hz
E. Induced motion from a "Bob Cat" stopping and dropping scoop.			
9.1m-(30')	2		5.01 @ 35 Hz
15.2m-(50')	2		5.10 @ 30 Hz
30.5m-(100')	2		1.58 @ 24 Hz
F. Induced motion from a railroad train.			
30.2m-(99')	2		6.02 @ 22 Hz
134.1m-(440')	2		0.61 @ 12 Hz

1=vertical component, 2=horizontal component oriented to short axis of wall, 3=horizontal component oriented to long axis of wall.

Table 3 Construction and Induced Vibrations

Wall	Test	Chan.	1st Max. Freq. Hz.	2nd Max. Freq. Hz.	3rd Max. Freq. Hz.	Max. Amplitude mm/sec
A1	T	2	17.6	16.2	35.2	1.592
	T	3	19.8	34.8	26.2	0.424
	T	2	17.0	14.6	21.5	1.992
	C	3	34.2	31.2	19.6	0.824
	FC	2	35.5			0.032
J2	T	2	11.4	16.8	22.8	1.281
	T	3	12.6	45.6	39.8	0.122
	FC	2	11.5	32.2		0.028
L2	T	2	18.5			0.592
M4	T	2	12.1	16.7	33.1	1.264
	T	3	13.0	17.2	33.2	0.681
	C	2	13.5	27.2	35.8	1.8****
	FC	2	13.1	28.2	34.1	0.022
		3	17.1	18.1		0.013
	FX	2	13.0			1.5****
U1	T	2	18.0	37.2		0.043
	T	2	18.2	42.0		1.027

2=horiz. short axis of wall; 3=horiz. long axis of wall. T=railroad train. C=local construction. FC=freeway construction. FX= explosion at freeway. ***=scaled for top of wall from free-field motion.

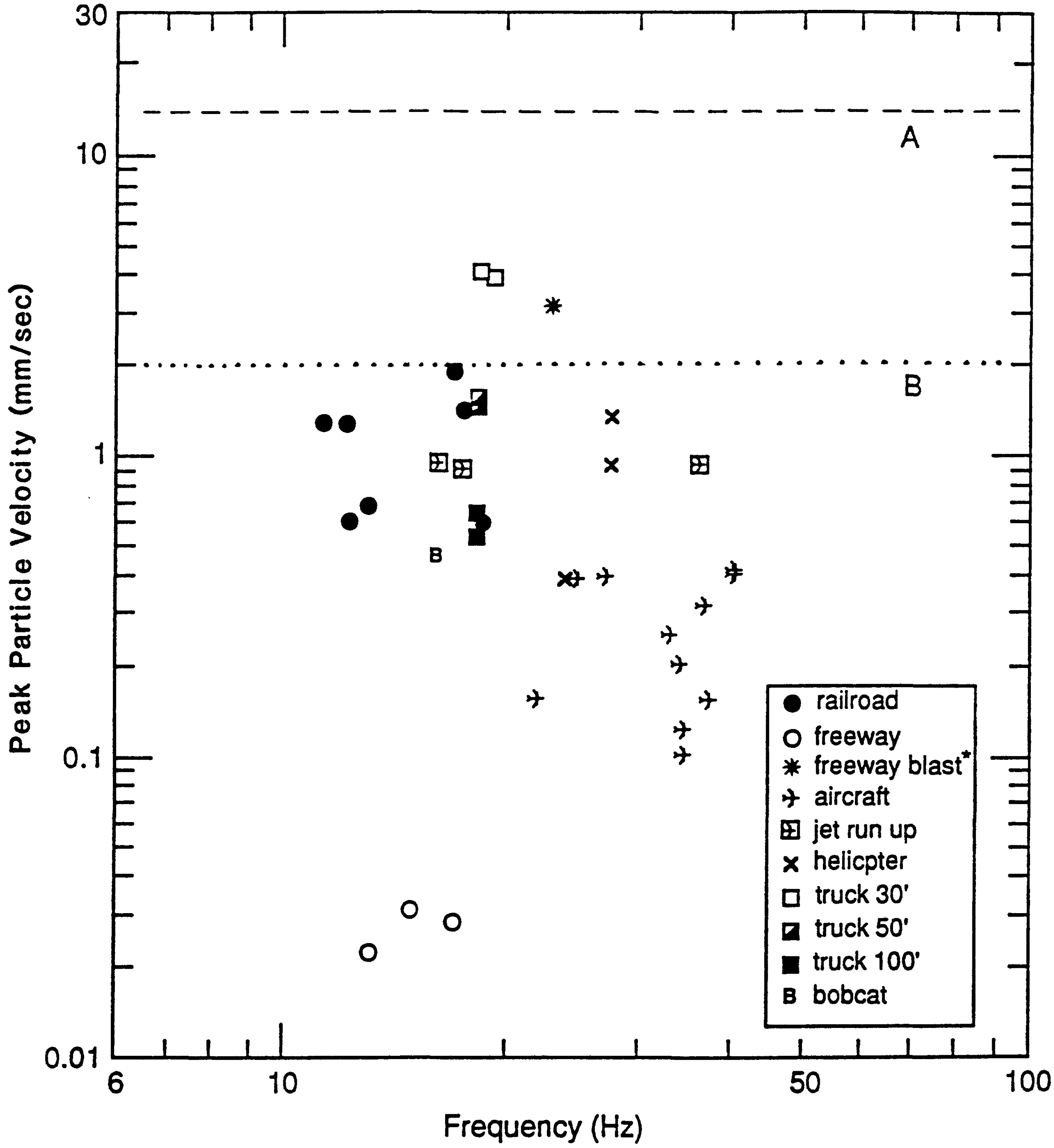


Figure 8. Peak induced vibration motions documented during test period. A = vibration level where damage may occur in normal frame buildings. B = recommended maximum vibration limit for sensitive archeological structures.

Table 4 Induced Vibrations-Local

Wall	Test	Chan.	1st Max. Freq. Hz.	2nd Max. Freq. Hz.	3rd Max. Freq. Hz.	1st Max. Amplitude mm/sec	1st Amplification Peak Part.
A1	V	2	35.5	39.5	17.8	1.370	3
	V	3	40.4	34.8	19.8	0.333	
	v	2	17.1			0.703	2.5
	B	2	35.5	17.5		0.851	2.2
	C	2	35.8	17.6		0.108	
	P	2	17.1	36.0		0.201	3.2
	p	2	36.1			0.060**	
A3	V	2	18.4	25.2		1.822	3.8
	V	3	21.3	19.5		1.224	1.7
	V	2	25.1			1.999	1.4
	v	2	18.3	23.0	17.8	0.848	
	B	2	19.0	38.3		0.982	2.2
	C	2	18.5	36.7		0.102	
	P	2	18.4	16.8		0.252	2.2
	p	2	32.1			0.094**	
B2	V	2	42.7	22.6	11.6	1.731	3.8
	V	3	22.5	11.8	42.2	1.002	1.5
	v	2	24.3	11.6		0.518	
	B	2	22.8	11.5		0.911	3.4
	P	2	22.9			0.332	1.9
	p	2	11.6			0.08**	
E4	v	2	25.2	27.0		0.103	
	v	3	25.0	27.4	32.8	0.307	
	P	2	25.8			0.511	2.2
	p	2	32.4			0.10**	
J2	V	2	35.2	11.4	19.0	1.023	4.4
	V	2	11.4	35.2		0.441	3.8
	P	2	11.8	17.1		0.643	2.6
	p	2	36.0			0.07**	
	T	2	11.2			1.002	
M4	V	2	13.2	15.2	33.6	2.430	4.2
	V	3	37.2	39.4	16.4	0.704	1.9
	v	2	13.4	27.2		0.795	
	B	2	13.5	29.2		0.916	3.9
	W	2	28.1	13.1		2.431	4.2
	P	2	29.2	13.6		0.102	3.2
	p	2	38.5			0.08**	
U1	V	2	18.6	37.2		5.40	3.1
	V	3	25.2			1.12	1.8
	v	2	18.9			0.38	
	B	2	18.8	37.8		1.77	4.8
	P	2	36.9	18.5		0.976	3.8
	p	2	38.2			0.09**	

V=vehicle <15m, v=vehicle >15m, P=personnel <9m, p=personnel >9m, C=conveyer, B=bobcat, W=earth tamper, T=personnel on observation tower, 2=horizontal short axis of wall; 3=horizizontal long axis of wall. All vehicles within 30m of wall. **=amplitude =or< ambient background.

than is introduced by a vehicle passing by at constant velocity. The motions induced by abrupt stopping, however, do not seem to be significantly different at 30 m distance than the vibrations induced by pass-by traffic (fig. 7).

SHORT-TERM MONITORING TESTS

Structure and wall vibrations that were induced by motions from aircraft, train, vehicle, construction work and museum personnel and visitors were also recorded and analyzed. During these tests a seismic system recorded the vibrations on the top of a selected wall and usually a second system would record the ground vibration at a free-field location (fig. 2A). The seismometer for the second system was located approximately one-wall-height away from the walls to record the ground vibrations free from the influence of the wall's vibrations. The data from these tests were analyzed to determine the maximum amplitudes and frequencies of the wall shaking caused by the induced sources, and to derive the vibration transfer function from the ground site to a site located on the top midpoint of the wall. The peak amplitudes recorded from all of the activities during the short term monitoring are shown graphically on figure 8. A 2mm/s peak-particle velocity level is shown for reference.

A summation of the data recorded from motions induced by railroad and construction activities is shown on table 3. The analysis of the data indicate that the railroad traffic induces shaking amplitudes into the walls approximately 50 times larger than the shaking induced by the construction activity on the freeway with the exception of the construction blasting. The vibrations at the mound induced by the blast were approximately 10% higher than the motions caused by the passing of a large train (fig. 8).

The data also show that local construction can induce relatively high amplitude vibrations in the walls. Table 4 indicates that vehicle traffic (public and Park service) that is within 15 m of the walls induce the largest motions documented on the walls during this testing period.

The test with the earth-tamper was at a distance of 20 m from the walls and was used only for the vibration tests. The analysis shows that the tamper induces large motions within the first or second mode of many of the walls. Many of the secondary peaks derived by the spectral analysis shown in tables 3, 4, 5 and figures 5, 6, 7, and 8 are harmonics of the natural frequency of the wall, secondary torsional motions, or interference-type motions from adjacent walls/roof. The conveyer which was used to backfill the structures induced less motion than a person walking close to the walls and approximately 20 times less motion than an earth compactor operating 20 m from the wall.

The data show that normal activities such as walking and running and light construction activities such as using hand-powered rollers to compact earth fill within 9 m of the wall do not induce significant motions to the structures. However, shaking induced by the observation tower which are activated by personnel on the tower's observation deck can induce considerable motions at or near the 2 mm/s suggested vibration limits.

The vibrations induced by aircraft during the testing period were generally of low amplitude. The maximum vibration amplitudes induced by the aircraft were generally a second mode (table 5). The highest motions were induced by a helicopter which hovered overhead and was within approximately 100 m of the mound. The second largest amplitude was induced by a low flying two-engine aircraft (no estimate on altitude).

The transfer function (TF) or spectral ratio of the ground site to the top-wall site indicates the frequencies to which the walls are most sensitive and the amount of amplification the walls will contribute to the amplitudes of those frequencies. The velocity vibration peak-particle amplitudes of the top-wall motions generally indicate a single-cycle, maximum amplification factor above the ground motion of approximately 3 (Table 4). The spectral ratio factors are better than the peak-particle amplification factors for indication of the potential damaging source as they include the total energy for a specific duration at a specific frequency band rather than a single cycle peak value. The transfer function is calculated using $TFf=STf/SBf$, where f= frequency in cycles/second, ST= spectra at top of wall, SB=spectra at base of wall.

Figure 4 and 9 show the velocity particle motion and spectral differences between the induced motions on the ground or free-field near a wall and the motions of the wall. The walls in general are not sensitive to frequencies lower than 5 Hz or greater than 30 Hz., they amplify the motions at or near the natural frequencies and modes of the walls, and the induced vibrations decay at a lesser rate than the induced vibration at the ground site. Figure 6B shows the frequency content of the induced motions from a railroad train at 30 m , 134 m, and on the top of wall J1. The higher frequencies of the induced motion are filtered by the transmission medium. The wall then enhances the vibrations which are similar to the natural frequency modes of the wall and further filter the other frequencies.

The vibration data from several of the more typical walls were analyzed by this method to show the average amplification that may be expected. The vibrations of Walls A, B, J and M were analyzed by this method to indicate those frequencies that the walls are most sensitive and the factors of frequency enhancement (wall amplification). Figure 10 indicates a wall shaking magnification factor of 1.5 to 5 in the natural frequencies of the walls. Also shown is the effect of backfilling against wall A3. The backfilling has decreased the sensitivity of the wall to vibrations in its natural frequency band by a factor greater than 5.

LONG-TERM MONITORING TESTS

The vibration recording system was installed in a semi-permanent location to monitor the daily park and freeway construction activities. The seismic system was programmed to continuously operate with solid-state memory data-storage in wrap-around mode which would turn the recorder on only when the ground vibrations exceeded a velocity peak particle amplitude of 0.2 mm/s. The triggered vibrations were recorded in digital mode on magnetic tape for approximately 1.5 s pre-event and 8 s post-event. The system would continue recording if the vibrations continued over the trigger amplitude setting (0.2 mm/s).

Table 5. Aircraft Induced Vibrations

Wall	Test	Chan.	1st Max. Freq. Hz.	2nd Max. Freq. Hz.	3rd Max. Freq. Hz.	Max.Amplitude mm/sec
A1	a.##	2	35.0	18.2	17.9	0.053
		3	34.0	6.8	17.6	
	b.#	2	33.5	17.2	47.2	0.253
		3	33.2	34.8	37.0	0.033
A5	a.##	2	34.8	44.0		0.089
		3	44.3	39.2		0.061
	b.#	2	34.4	39.4	17.6	0.204
		3	37.5	39.6	33.6	0.154
B2	a.#	2	34.5			0.102
	b.#	2	21.9	34.0	25.2	0.159
C1	a.#	2	17.1			0.811
J2	a.##	2	21.6	36.2	11.6	0.062
		3	46.2	39.0		0.074
	b.#	2	36.3	39.8	11.4	0.933
		3	36.9	43.3		0.314
	c.#	2	16.3	17.8	15.6	0.940
		3	40.2	45.4	33.3	0.404
	d.##	2	41.2	35.7	17.0	0.075
		3	35.4	27.0	44.8	0.080
K2	a.#	2	19.8	34.0	8.0	0.122
		3	35.9	33.3	17.8	0.018
M4	a.*	2	24.2	32.7	13.0	0.393
		3	33.2	13.0	17.3	0.041
	b.**	2	27.5	13.1	41.2	1.331
		3	39.7	41.2	13.9	0.610
	c.#	2	27.2	32.6	13.2	0.393
		3	36.2	38.4	13.0	0.130
	d.***	2	27.6	13.4	47.8	0.932
		3	34.8	36.2	40.0	0.123
	e.##	2	13.9	39.0	25.7	0.030
		3	33.8	40.6	31.4	0.020

a,b=seperate tests; 2=horiz. short axis of wall; 3= horiz. long axis of wall; *=helicopter overhead flyby; **= helicopter overhead hovering; ***= two engine prop overhead; #= large jet aircraft takeoff; ##=large jet fly-by.

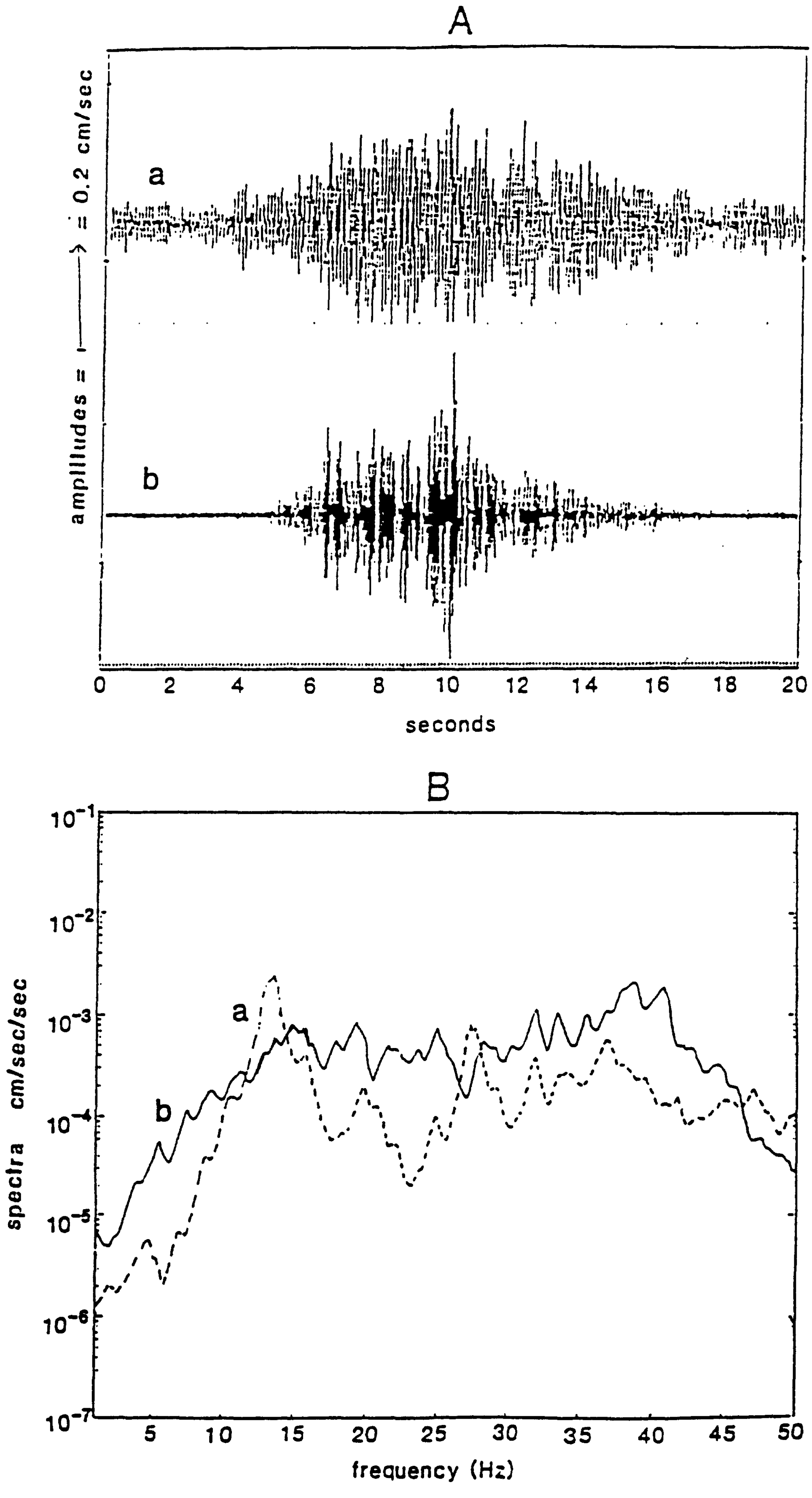


Figure 9. A = seismograms from top and base of wall. B = derived spectra from seismograms. a=top of wall. b=base of wall. Induced motion from vehicle pass-by.

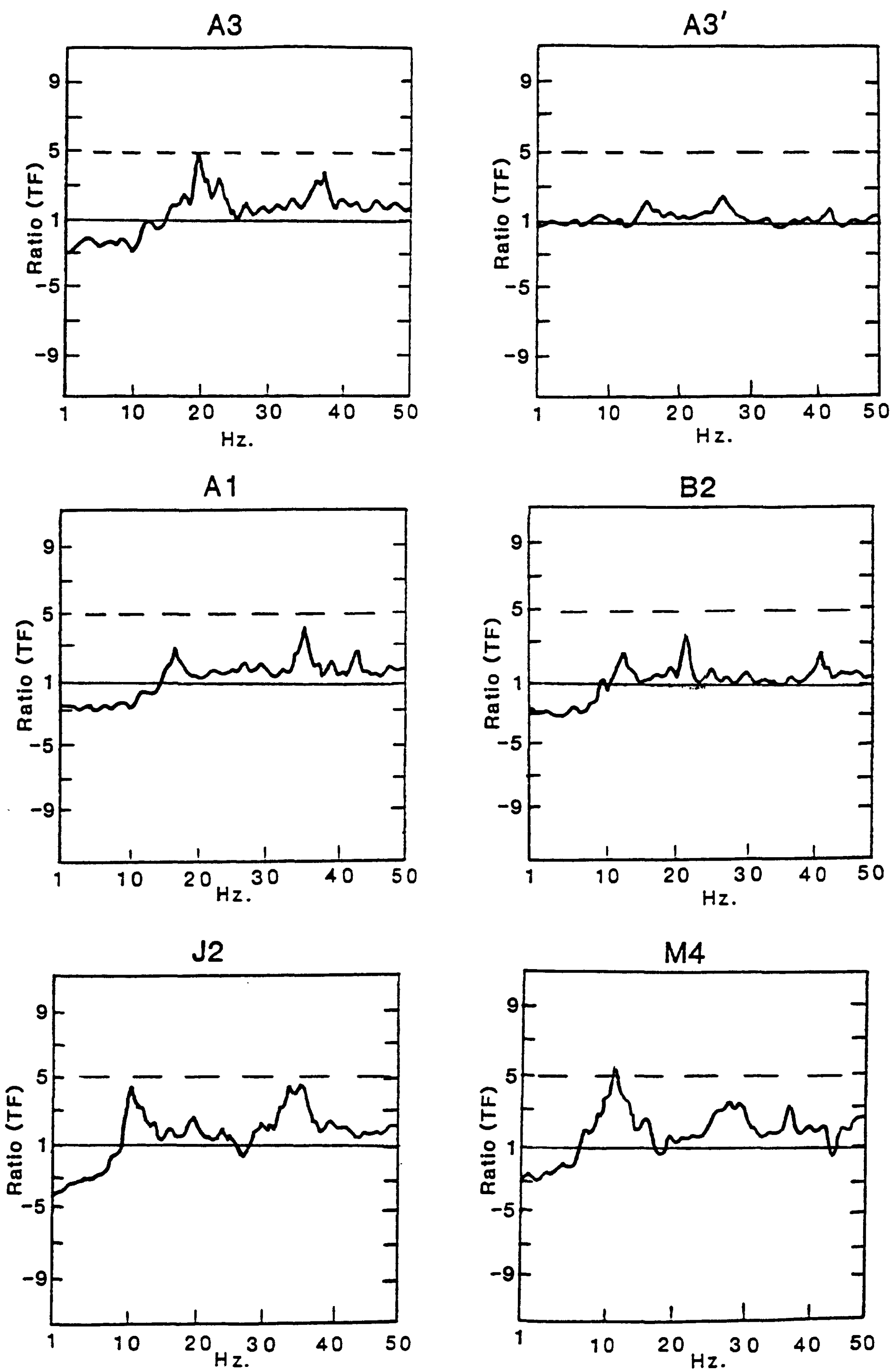


Figure 10. Spectral ratios. Derived from divided the spectrum form the top of a wall by the free-field spectrum. Ratios indicate the frequencies and amount of amplification induced by the walls. Letters denote name of walls as show in figure 1. A3 = before backfilling. A3'=after backfilling. Other tests before backfilling. Induced vibrations from local traffic.

Some of the typical seismograms are shown in the appendix of this report. The largest known event recorded from the freeway construction is from a construction blast (shown in appendix F3). The largest motions documented during the time of recording were from the local museum construction (appendix B2-19). Some of the seismograms shown in the appendix can be easily identified as: railroad train A4,15,16,and 18; trucks near the walls A 12, 13, and 14; Aircraft take-off A5, B1, and C8; and probable blasts C18, and F3.

DISCUSSIONS AND RECOMMENDATIONS

The natural frequencies of the walls range from approximately 8 to 25 Hz and the percent of critical damping for the walls range from 1.2% to 5% of critical. These frequencies and damping values are generally comparable to those found in the one-two story archeological structures (King and Algermissen, 1985, King and others, 1986). However, it is important to note that the wall vibrations due to the locally induced sources show that the walls tend to respond more selectively to the higher modes in the 11 to 35 Hz range. It is also important to note that the natural frequencies for the museum roof are near the frequency of the vertical motions induced by a hovering helicopter and that the roof will amplify those frequencies by a factor of approximately 10. The seismometers were not located on the museum roof during the helicopter pass; however, the assumed vibration frequency induced by the helicopter is made from past experience on similar structures at White Sands and Mesa Verde National Parks, (King and Algermissen, 1988, King and others).

The attenuation factors are normal for a general "hard" ground site; that is, the attenuation exponents are not anomalously low which would cause more vibration energy to be induced to the mound from surrounding construction work than expected. The relatively high attenuation of the mid-frequencies (10-40 Hz) and the distances to the freeway, airport, and railroad are fortuitous for the preservation of the ruins at the mound as the most damaging induced motions are attenuated to a level below 2 mm/s particle velocity before the motions reach the walls. If any of these sources were 100 m closer, the vibration problems could be critical to the ruins.

The maximum vibration levels that were documented during this study are well within the safe zone as designated for mine blasts near frame and brick homes (Siskind and others, 1980). However, the acceptable vibration level should be considerably less for irreplaceable historic structures, especially those of adobe and flat-roof construction. The general vibration standard is set for structures that can be repaired without risk of loss of historical significance. Because of the irreplaceability of the structures, the historic contents, and the absence of knowledge of the cumulative effect of low to medium level of vibrations (1-20 mm/s at 1-40 Hz) on adobe construction, a conservative level of induced vibrations should be established. A maximum particle velocity vibration level of 2 mm/s was established at Hovenweep, Chaco Canyon and Mesa Verde National Parks (King and Algermissen, 1985, 88). This level affords a safe upper level of induced motion without overly restricting normal cultural and industrial activities. A highway was constructed in Chaco Canyon within 60 m of an archeological ruin without compromise to the structure or internal artifacts.

Assuming that 2mm/s is an acceptable upper vibration level for induced vibration at the Pueblo Grande Ruins, figure 8 shows that freeway construction and museum/park construction can be conducted with little or no risk to the mound ruins if certain precautions are taken. Only blasting during the freeway construction and vehicles traveling within 10 m of the walls are above the 2 mm/s level. The general railroad traffic is near but just below that level.

Figure 11 is a map of the suggested vibration zoning in the 5-40 Hz frequency bandwidth for the Pueblo Grande Ruins. The map is based on the analysis of the induced vibrations, the attenuation of vibratory energy, and the natural periods of the walls. The park is divided into four zones:

Zone 1: This is the area within a 13.3 m (44 feet) perimeter from the most critical walls. Public activities (walking etc.) can occur in this zone (except on the walls), but vehicle traffic, construction, continuous vibrating equipment, hammer drills and similar equipment must be limited. Irregular or random small motions for maintenance of importance would be acceptable. If any heavy work must be accomplished in this zone, backfilling or adding support plates to the walls within 23 m of the work must be considered. Hovering helicopters should not be within 30 m of this zone.

Zone 2: The second zone is the area from 13.3 m (44 feet) to 23 m (76 feet) from the critical walls. This area should not have continuous traffic unless the following conditions are met: the road must be very smooth (no bumps greater than 1 cm) and the vehicles should move with a constant velocity (no stopping and starting). A soft tired ATV type vehicle, personnel traffic and activity, and if necessary a smooth-paved pass-by road is acceptable. No compressors, back-hoes, earth compactors and similar equipment should be used in this area.

Zone 3: Zone 3 is a buffer zone. It extends from 23 m (76 feet) to approximately 45 m (150 feet) from the critical walls. Heavy earthmoving equipment and heavy paving equipment should be restricted. General construction can be accomplished without risk to the mound ruins; as an example, a heavy earth-compactor roller can be used if it does not use the vibrator.

Zone 4: Zone 4 is the area beyond 45 m to approximately 900 m (3,000 feet). The Park personnel should be sure they have knowledge of any blasting or pile driving in this area and evaluate each vibration source on a case by case basis.

The zoning is a guide based on present conditions. The present conditions will change with time and should be re-evaluated periodically to assure the stability of the ruins. The zoning can also be changed by selective backfilling and repointing selected walls if certain construction is deemed necessary.

It is apparent from this project that careful planning has allowed the rehabilitation of delicate archeological ruins and the development of adjacent areas to the ruins without compromise or loss of valuable archeological information. The National Park Service and

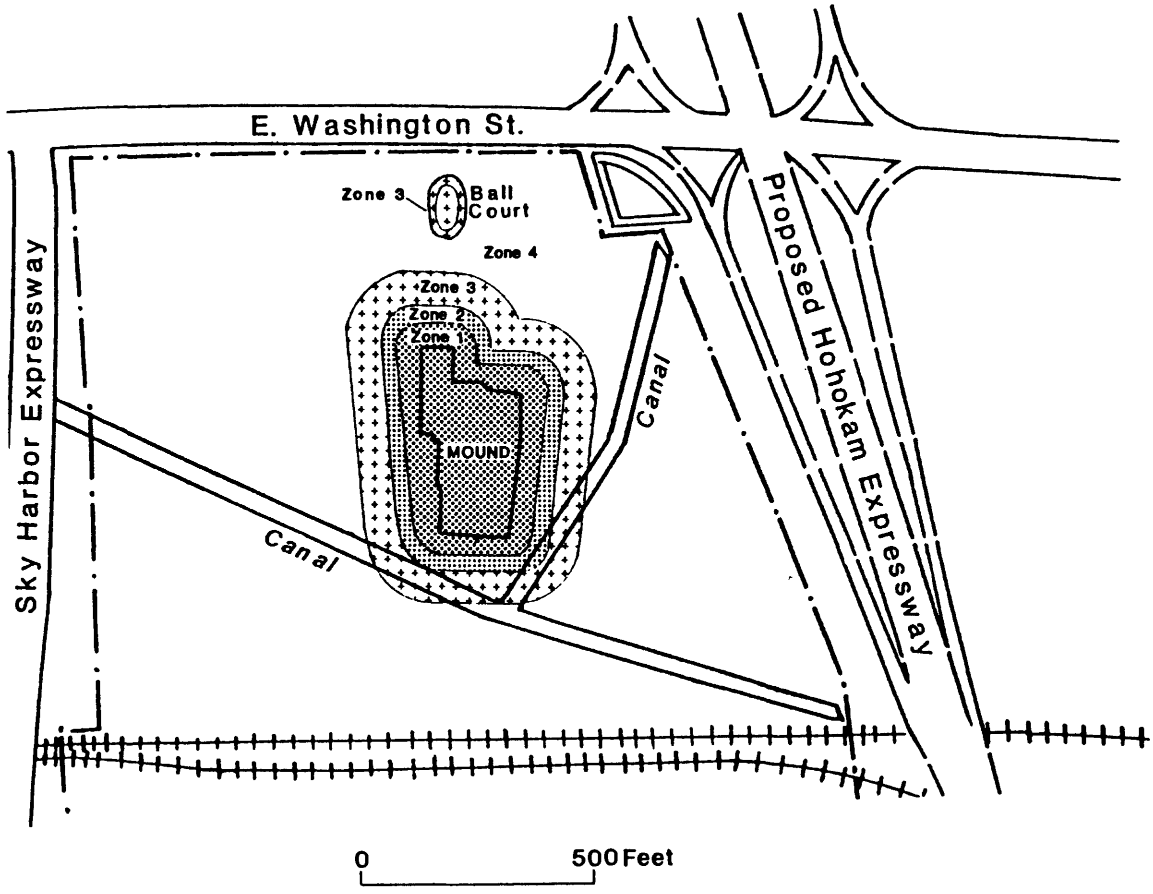


Figure 11. Recommended vibration zoning for Pueblo Grande.

the Museum personnel used selective procedures such as: backfilling walls that were susceptible to the induced motions, using conveyors rather than dump trucks to move soil to the walls for backfilling, not using earthtampers to pack the backfill soil, using a "Bob-Cat" for general construction support rather than a regular truck near the wall, pointing the walls with adobe which has been matched to the original masonry, and in general being alert to vibration sources which could cause damage to the structures.

The walls do not in general vibrate like a straw in the wind. Rather they are stiff and tend to rock like a rigid block. When the walls are forced to vibrate above a certain level by induced motions, it is possible that rocking motions of the walls will cause low-level, near-foundation cracking (fig. 5B). Once the adobe near the foundation is cracked, the mud sheen which prevented the invasion of water is compromised. Once the water invades the interior of the adobe, the damage from both vibration, chemical, and water erosion is accelerated. It is probable that the walls have always exhibited a certain amount of erosion even during Hohokam time. However, it has been shown that the walls are sensitive to frequencies which are easily induced by vehicle traffic and modern activities. It is doubtful if a corollary to these vibration sources existed during Hohokam time. In conclusion we make the following recommendations:

A. The zoning map is a model to be followed until the parameters for the walls change.
B. If the museum is going to have a flat roof and a masonry veneer on the outside as it has now, all helicopters flying above the museum should be restricted to an altitude of 30 m or greater.
C. Be alert to any plans or activities by the railroads in construction of a new switching yard or additional facilities within 100 m of the mound.
D. The observation towers' natural frequencies should not be allowed to match those of the walls.
E. Use a soft wheeled ATV for maintenance near the mound.
F. Allow no public roads or parking lots within approximately 30 m (100 ft) of the walls (many RV's now use generators which might produce vibrations).
G. Do not exhume the walls until there is no risk of freeway construction blasting or pile driving.
E. Extreme care must be taken if any sidewalk or pavement is to be removed within 30 m of the walls.

REFERENCES

Algermissen, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L, and Bender, B.L. (1982), Probabilistic estimates of maximum acceleration and velocity in rock in the contiguous United States: U.S. Geological Survey Open-File Report 82-1033, 99 p.

Algermissen, S.T., Perkins, D.M., Thenhaus, P.C., Hanson, S.L, and Bender, B.L., (1990), Probabilistic earthquake acceleration and velocity maps for the United States and Puerto Rico: U.S. Geological Survey Miscellaneous Field Studies Maps, MF-2120, 2 sheets.

Carver, D.L., D.R. Cunningham, and K.W. King (1986). Calibration and acceptance testing of the DR-200 digital seismograph: U.S. Geological Survey Open-File Report 86-340, 28 p.

Cranswick, E., K.W. King, R. Banfill, (1989). A program to perform time and frequency domain analysis of vector timeseries' recorded by portable autonomous digital seismographs: U.S. Geological Survey Open-File Report 89-172, 62 p.

Hays, W.W, and Algermissen, S.T., 1982, Problems in the construction of a map to zone the earthquake ground shaking hazard: *in* International earthquake microzonation Conference, 3d, Seattle, Wash. 1982, Proceeding: 1307-1318 p.

Hudson, D.E., Keighley, W.O., and Nielsen, N.N., 1964, A new method for measurement of the natural periods of buildings: Bulletin of the Seismological Society of America, v. 54, no. 1, 233-243 p.

Joyner, W.B., R.E. Warrick, and T.E. Fumal (1981). The effects of quaternary alluvium on strong ground motion in the Coyote Lake, California, earthquake of 1979: Bulletin of the Seismological Society of America 71, 1333-1349 p.

King, K.W., 1969, Ground motion and structural response instrumentation: Chapter 8, Technical Discussion of off-site safety programs for underground nuclear detonations Atomic Energy Commission report, NVO-40, Rev. 2, 83-97 p.

King, K.W., W.W. Hays, P.J. McDermott (1982). Wasatch front urban area seismic response data report, U.S. Geological Survey Open-File Report 83-452, 67 p.

King, K.W., and Algermissen, S.T., 1985, Seismic and vibration hazard investigation of Chaco Culture National Historical Park: U.S. Geological Survey Open-file report 85-529, 58 p.

King, K.W., Williams, R.A., and Carver, D.L., 1987, A relative ground response study in east Salt Lake City and areas of Springville-Spanish Fork, Utah, *in* Hays, W.W., and Gori, P., eds., Assessment of regional earthquake hazards and risk in Utah: U.S. Geological Survey Open-File Report 87-585.

King, K.W., and Algermissen, 1987, A vibration study of the archeological ruins, Hovenweep National Monument, Utah-Colorado: U.S. Geological Survey Open-File Report 87-181, 18 p.

King, K.W., Algermissen, S.T., 1988, Seismic and vibration hazards to archaeologic and historic structures: International Symposium on Seismic Isolation/Historic Preservation, May 11-14, Salt Lake City, Utah.

King, K.W., Carver, D.L., and Worley, D.M., 1988, Vibration investigation of the White Sands National Monument, New Mexico: U.S. Geological Survey Open-File Report 88-544, 20 p.

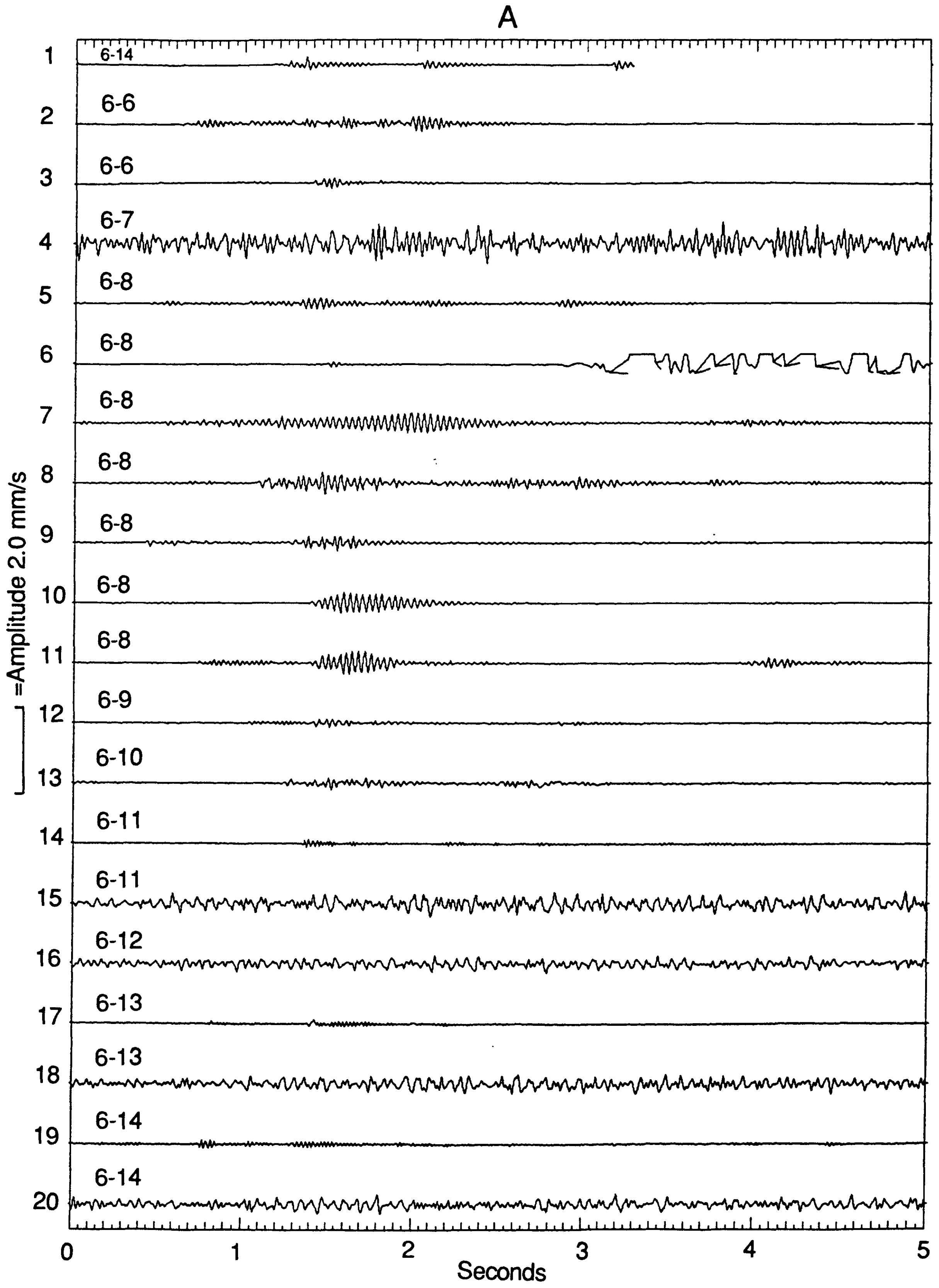
King, K.W., Tarr, A.C., Carver, D.L., Williams, R.A. and Worley, D.M., 1990, Seismic ground-response studies in Olympia, Washington and Vicinity: Bulletin of the Seismological Society of America, v 80, no. 5, 1057-1078 p.

Murphy, J. R. and R. A. Hewlett (1975). Analysis of seismic response in the city of Las Vegas, Nevada--A preliminary microzonation: Bulletin of the Seismological Society of America 65, 1575-1597 p.

Siskind, D.E., Stagg, M.S., Kopp, J.W., and Dowding, C.H., 1980, Structure response and damage produced by ground vibrations from surface mine blasting: U.S. Bureau of Mines Report of Investigations RI 8507, 74 p.

APPENDIX

(Long term monitoring seismograms)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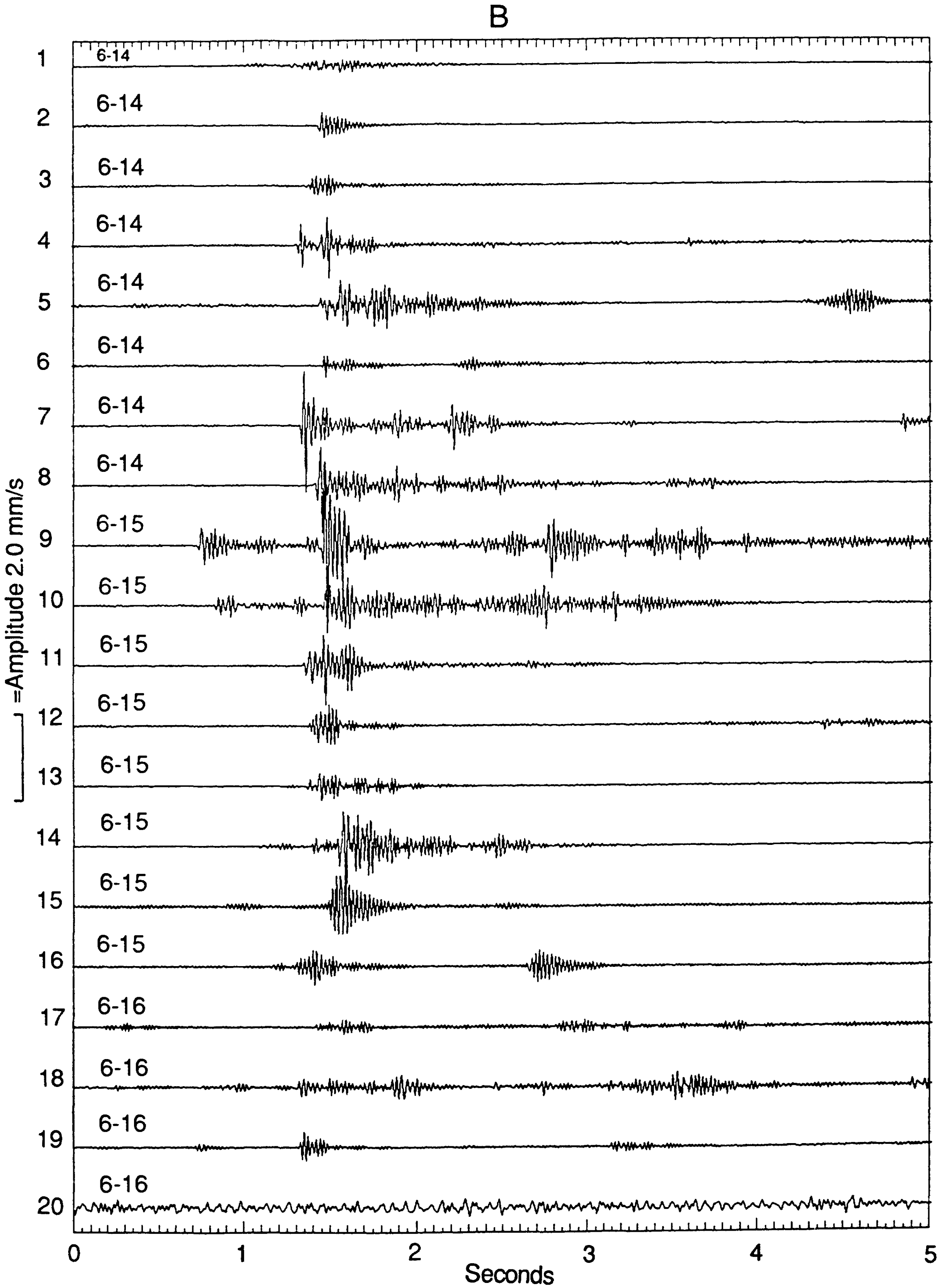
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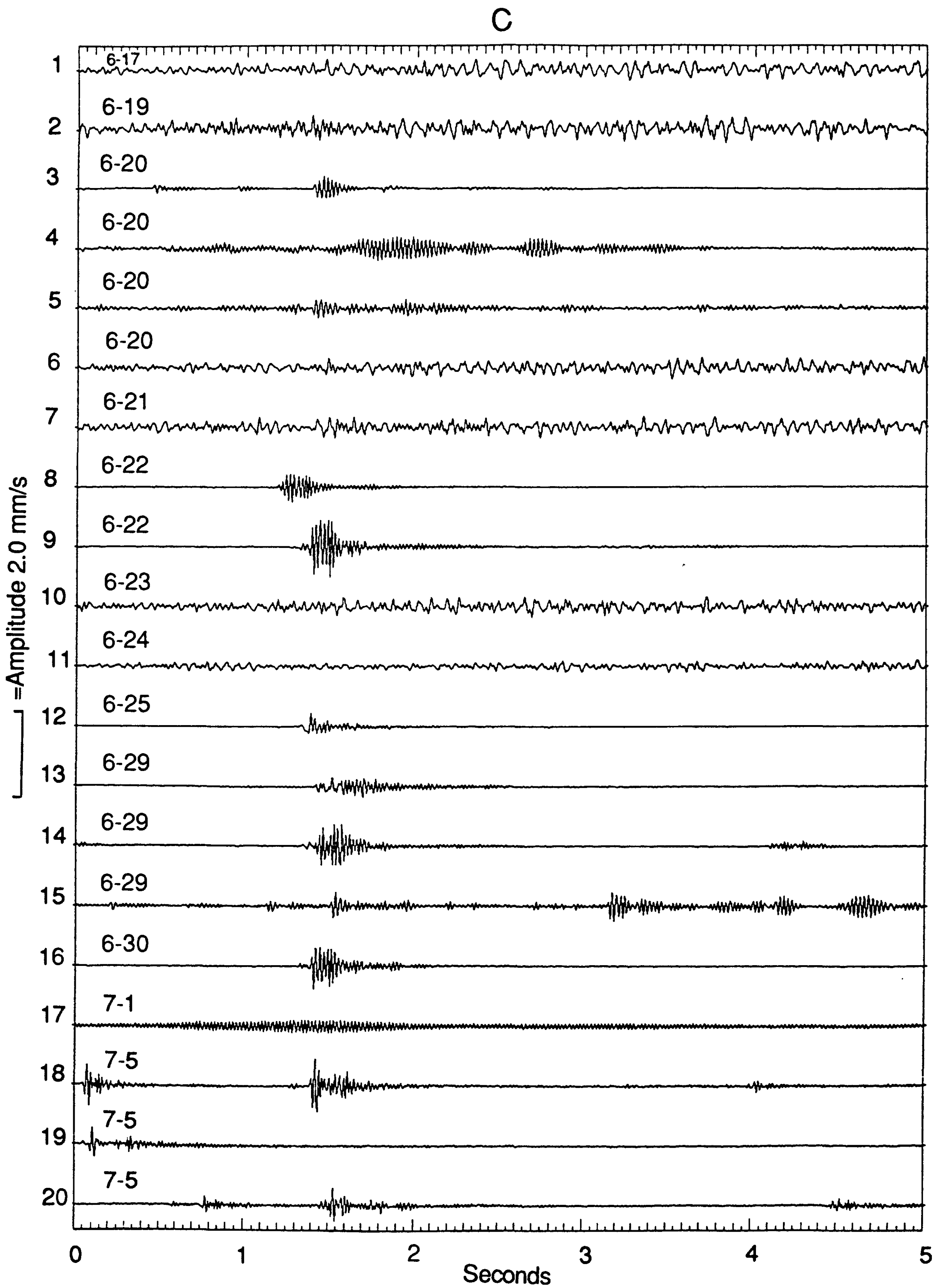
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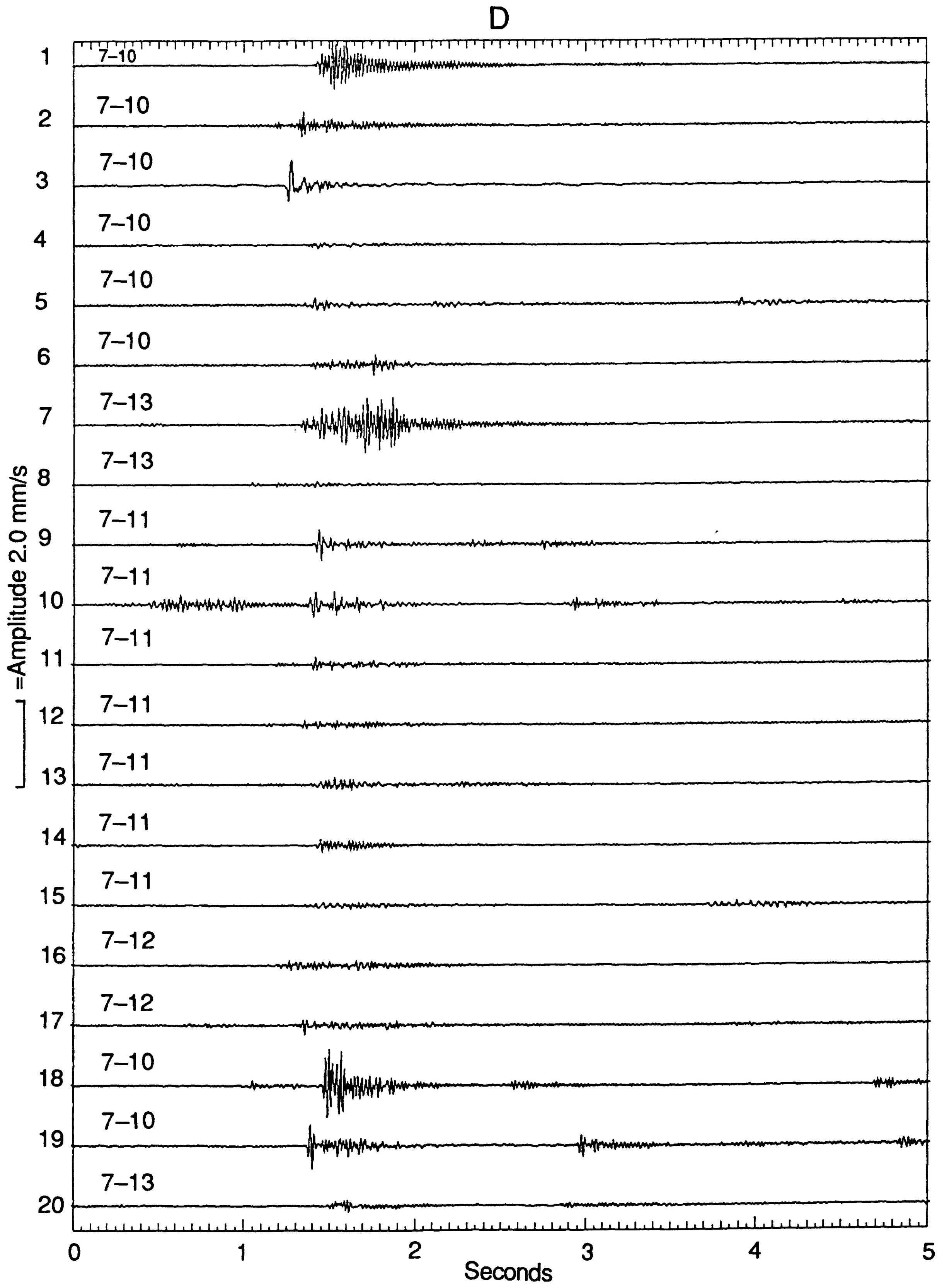
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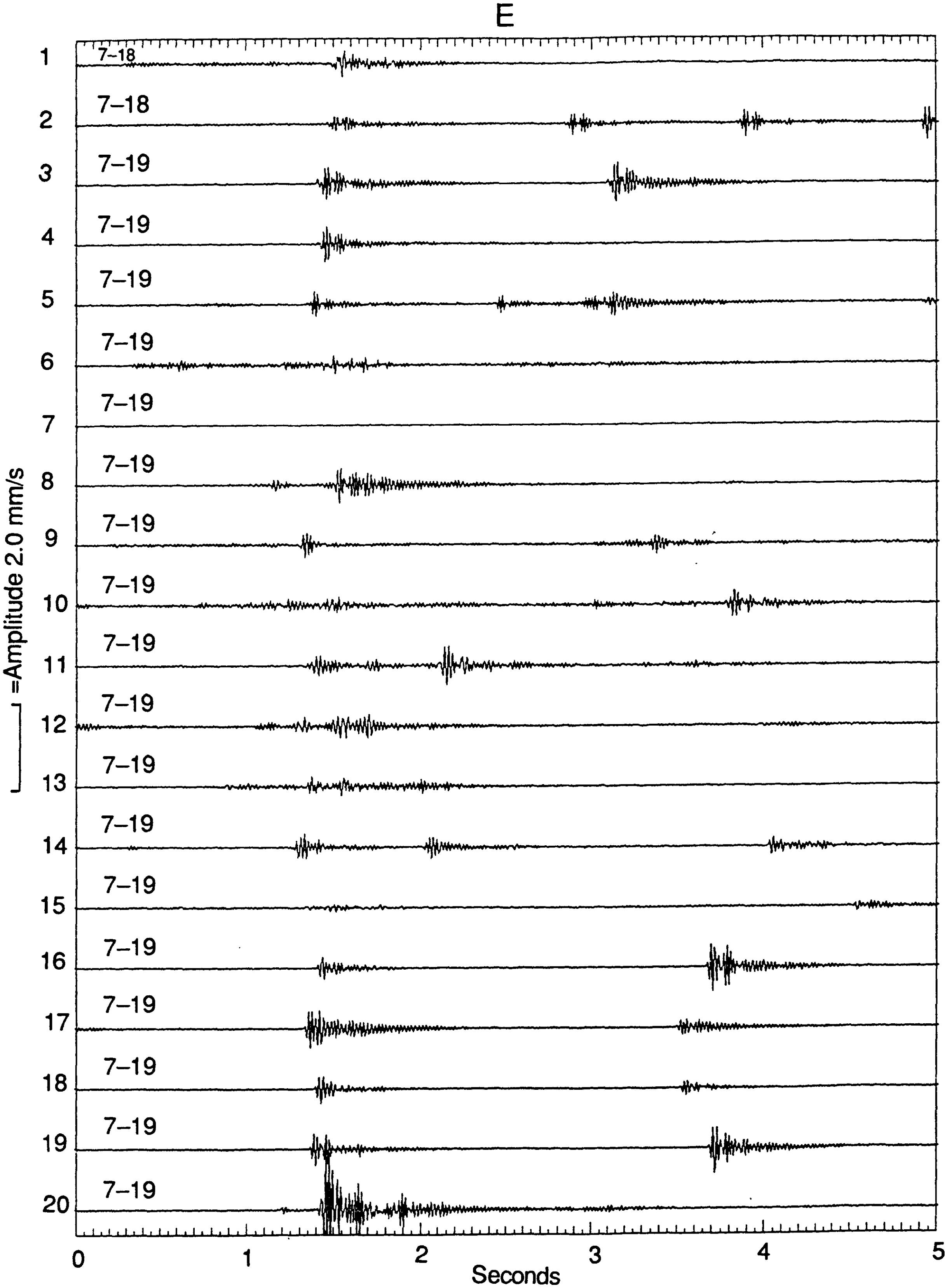
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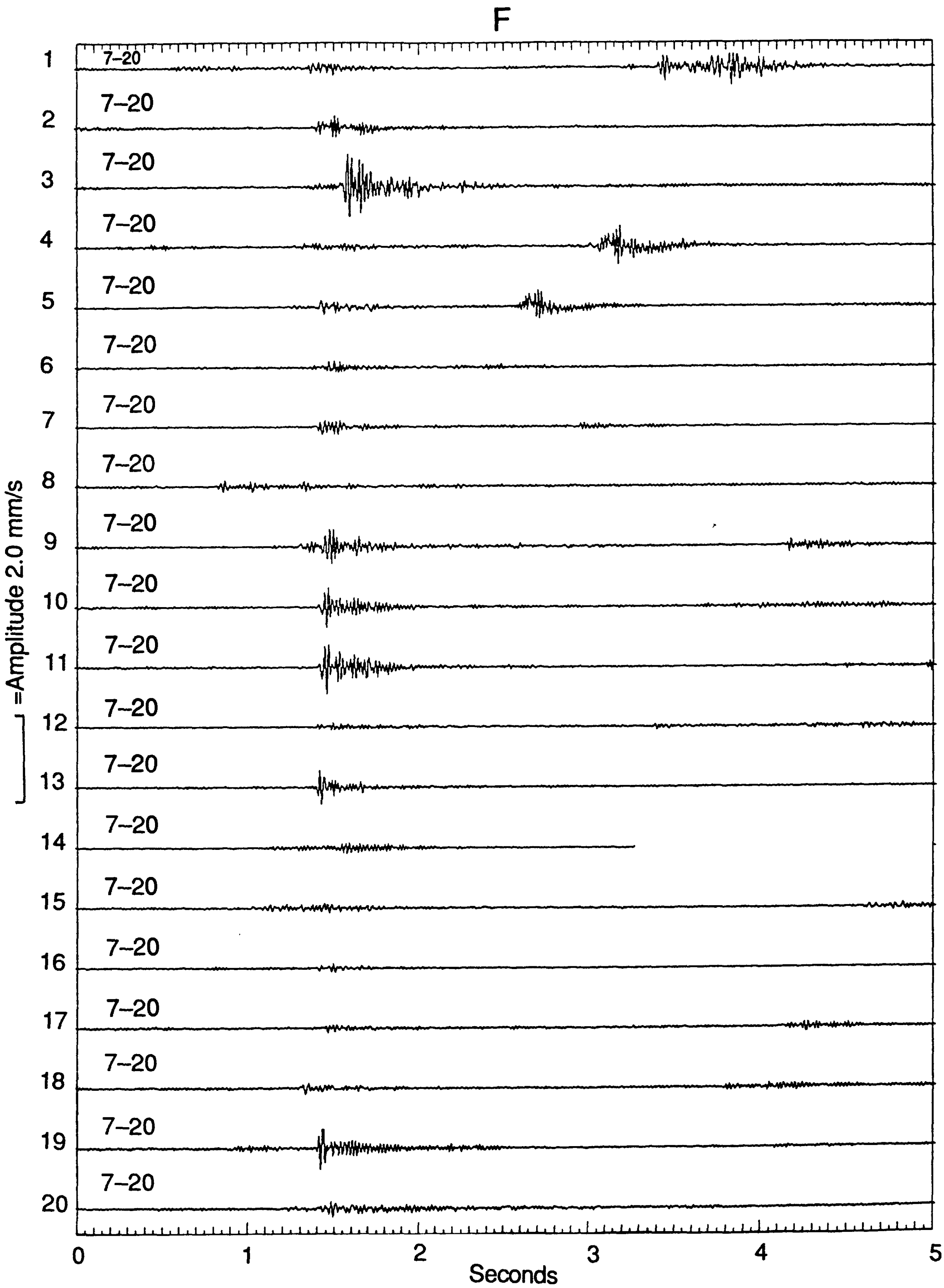
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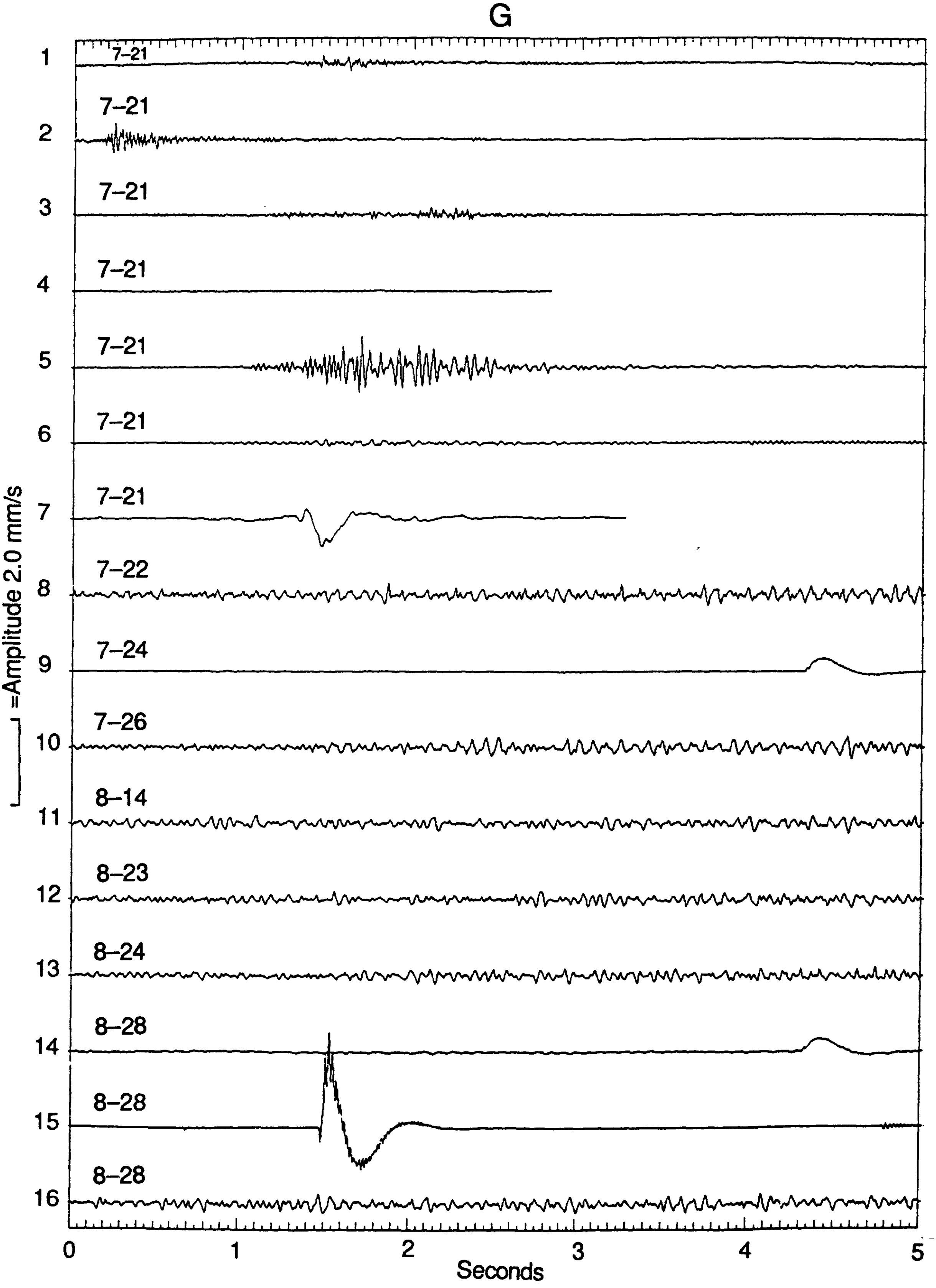
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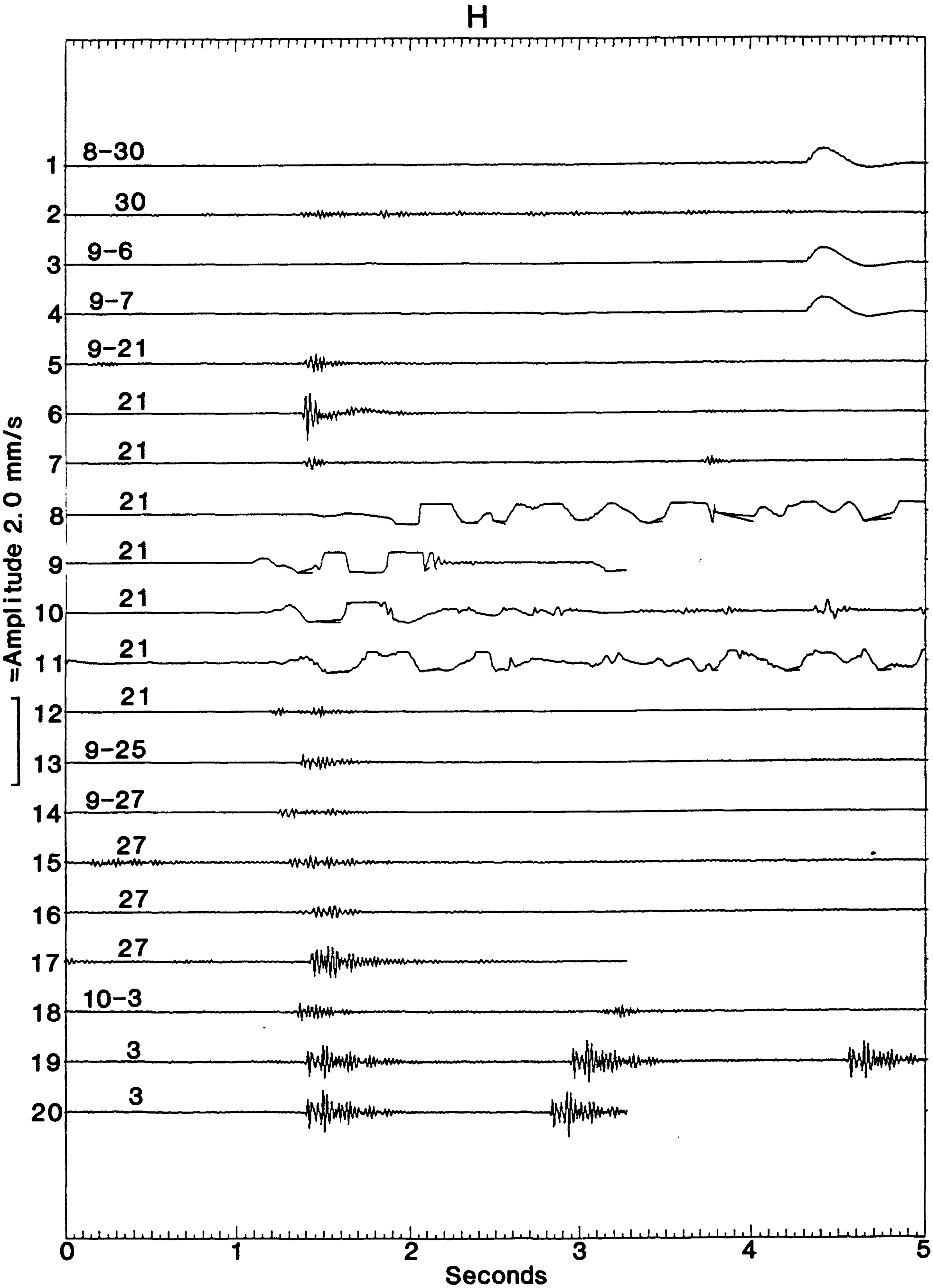
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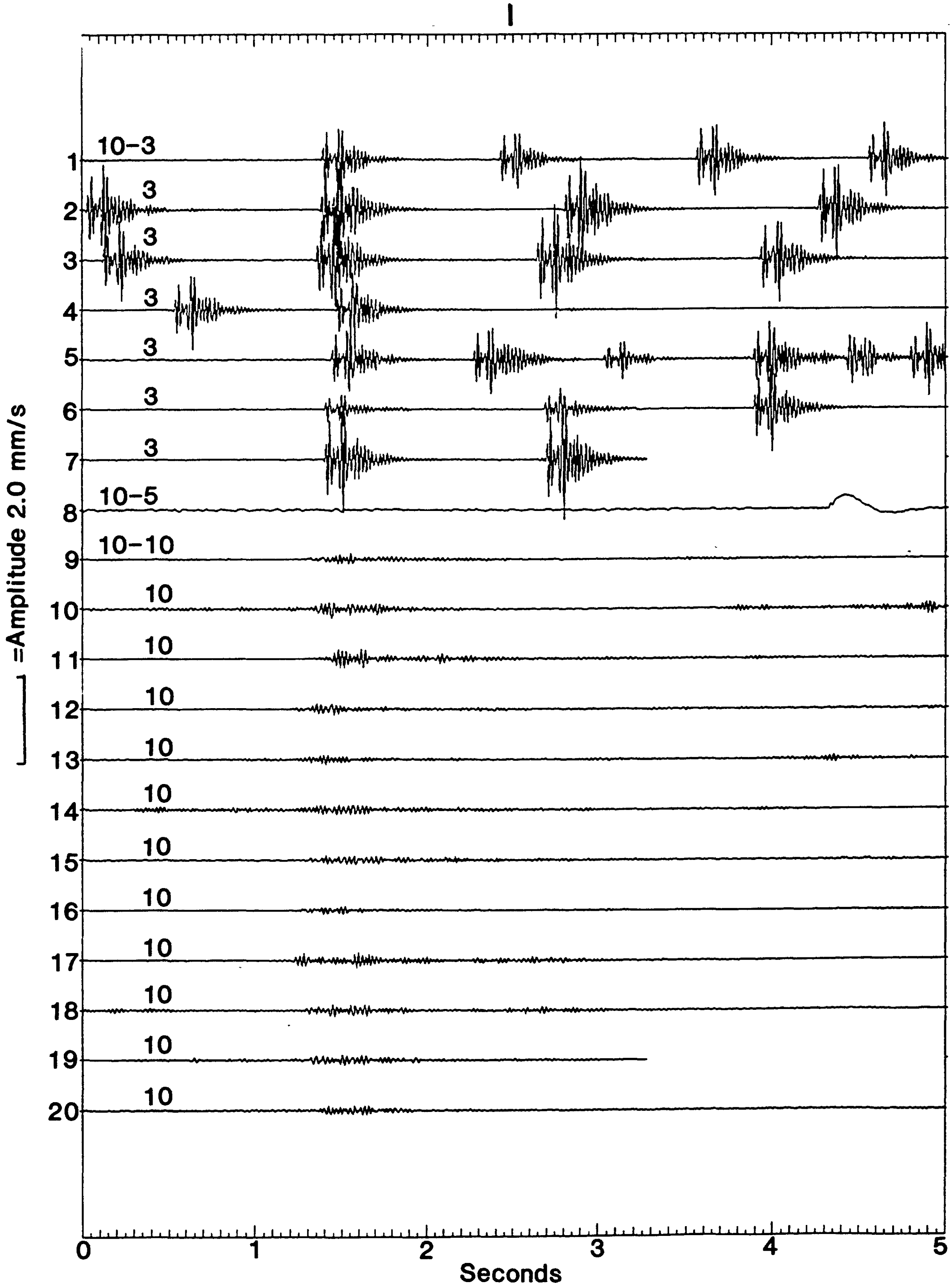
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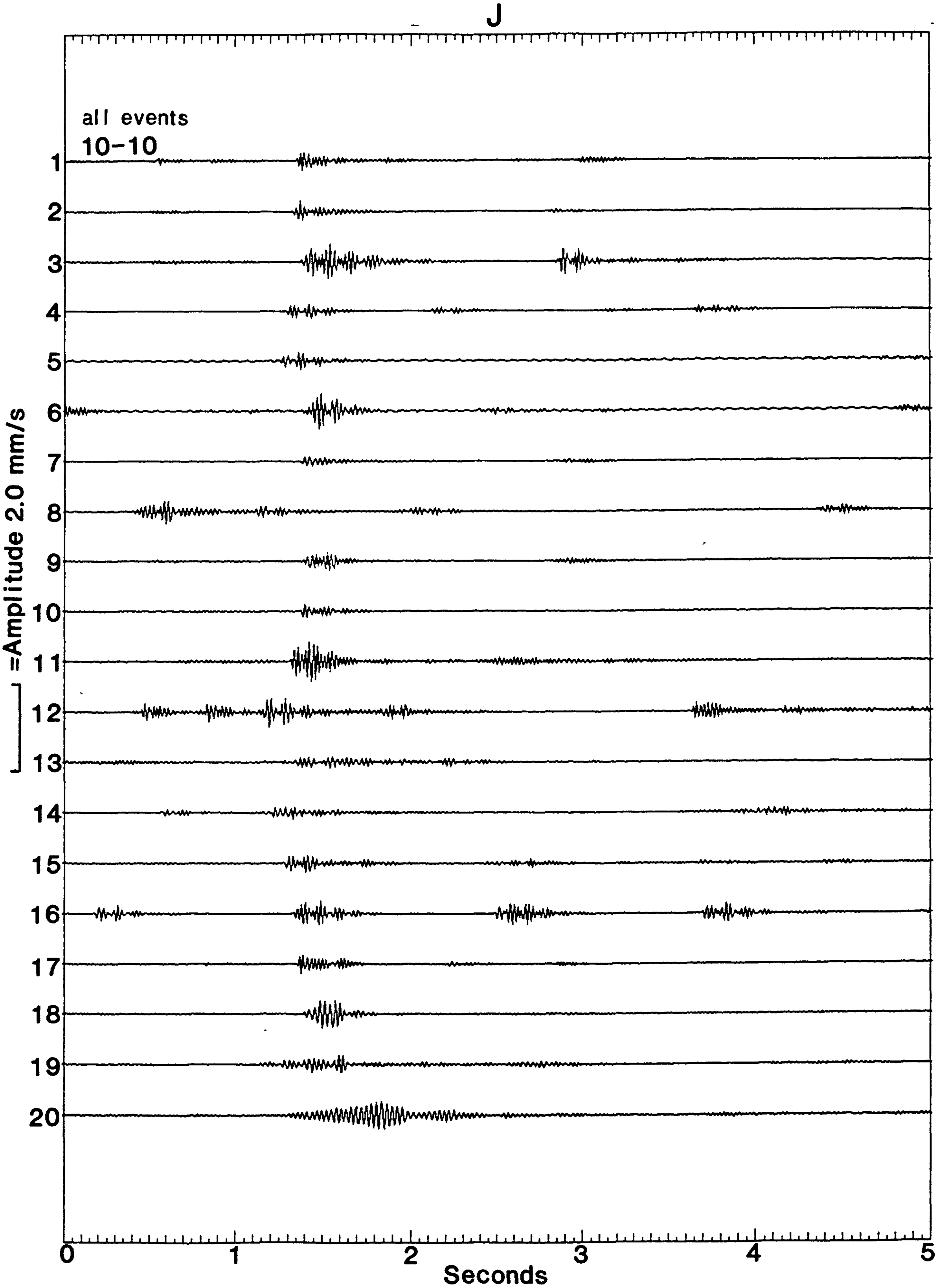
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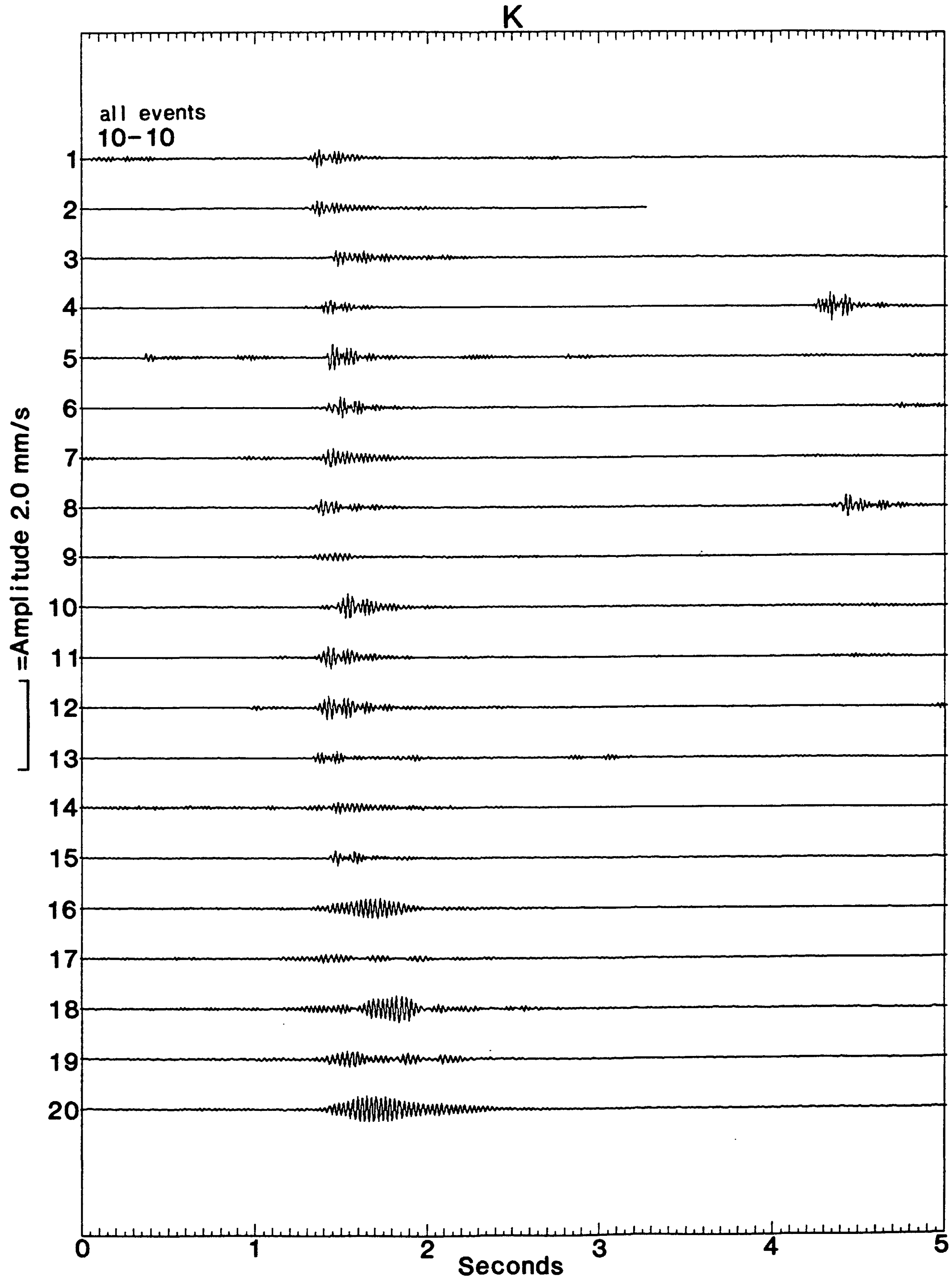
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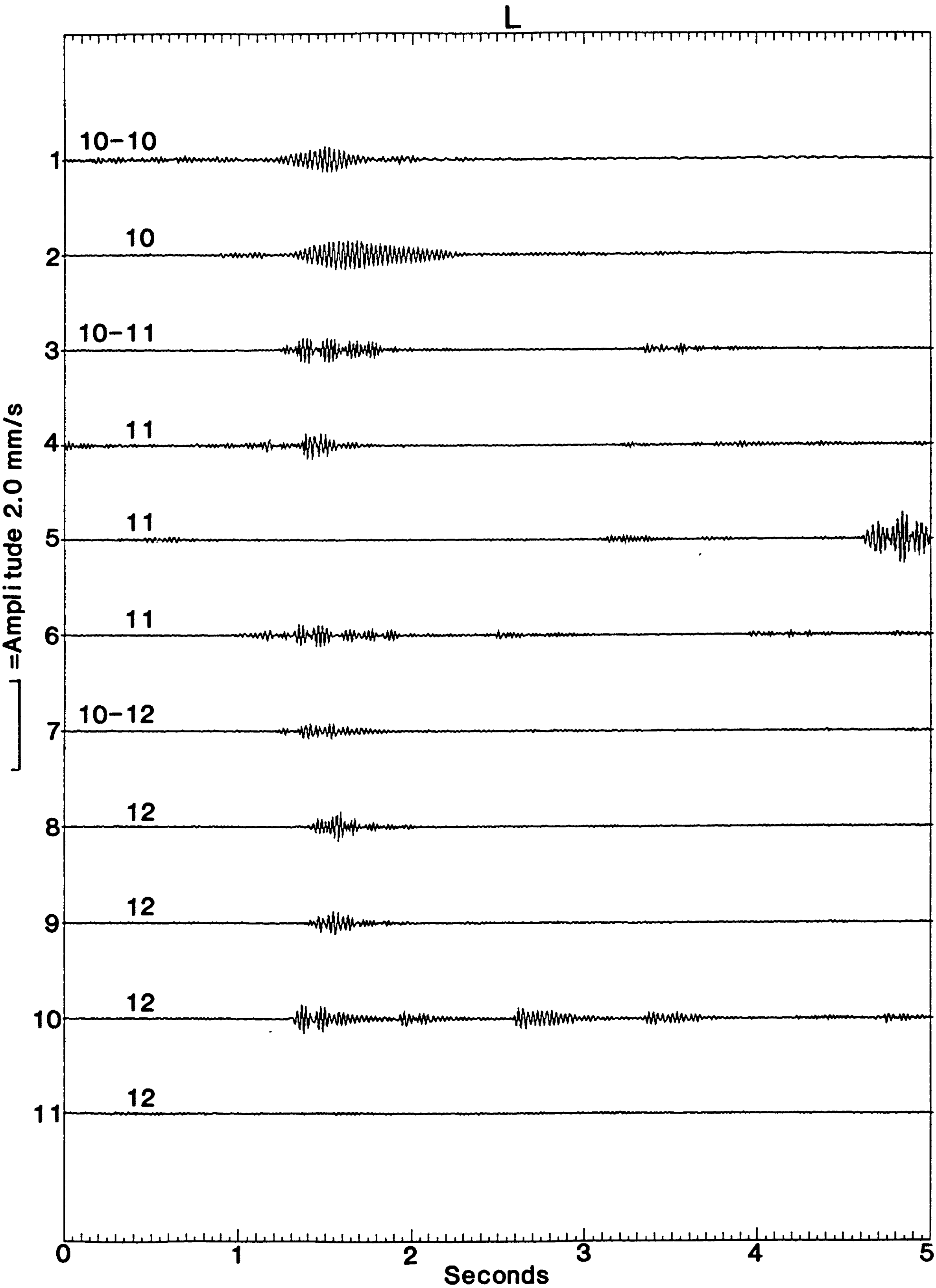
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=Amplitude 2.0 mm/s
0
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Seconds