DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Seismic and Vibration Hazard Investigations of Chaco Culture National Historical Park

by

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Open-File Report 85-529

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

[1]U.S. Geological Survey
Denver, Colorado

1985

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ABSTRACT

The potential for damage to structures in Chaco Culture National Historical Park resulting from earthquakes, landslides, industrial blasting, road building and vehicular traffic has been investigated. The Historical Park, located in northwestern New Mexico, contains over 2,000 known archeological sites. The structures of interest, many of them multistory and a few containing over 200 rooms, date from the 11th and 12th centuries. Most of the remaining walls are 1.5 to 3.0 m in height, but a number exceed 5.0 m. A 2.0 mm/sec particle velocity is recommended as the upper limit for induced motions in the structures resulting from industrial blasting, road building and vehicular traffic. Minimum distances of these activities from the structures are recommended based on field recordings and analysis of the induced vibrations from these sources. Minimum distances of 1.2 km from blasting, 0.5 km from railroad traffic, 45 m from road building and 25 m from vehicular traffic are recommended based on normal blasting practices in the area, conventional rail traffic, usage of road building equipment and normal vehicular traffic patterns.

Recommendations are also made for controlling vibrations from one road in the Historical Park considered to be too close to historical structures. Levels of expected ground motion from earthquakes, even for relatively short time periods of interest such as 50 yrs, indicate that possible future earthquake damage to the structures should be considered. The implication is that at least some of the past deterioration of the structures in the Historical Park may have been caused by earthquake ground motion.

INTRODUCTION

Chaco Culture National Historical Park is located in northwestern New Mexico about 73 km southeast of Farmington, New Mexico and 93 km northeast of Gallup, New Mexico (fig. 1). The park contains 21,500 acres and over 2,000 known archeological sites. The most complex and best preserved archeological sites are large stone pueblo and kiva complexes located in the upper confines of Chaco Canyon. The larger structures in the canyon of archeological interest were constructed by the Anasazi Indians in the 11th and 12th century when the population reached about 11,000. The canyon was abandoned by the Indians in the late 12th century. The area surrounding the canyon is now occupied by the Navajo Indians (Pierson, 1956).

This report analyzes the risk to the larger structures resulting from possible ground shaking associated with earthquakes, blasting, road building and vehicular traffic.

Chaco Canyon is an incised valley cut into the Colorado Plateau. The valley is presently drained by an intermittent stream and no springs or perennial water sources now exist in the valley (Li and Associates, Inc., 1982). The most striking topographic feature of the canyon is the asymmetry

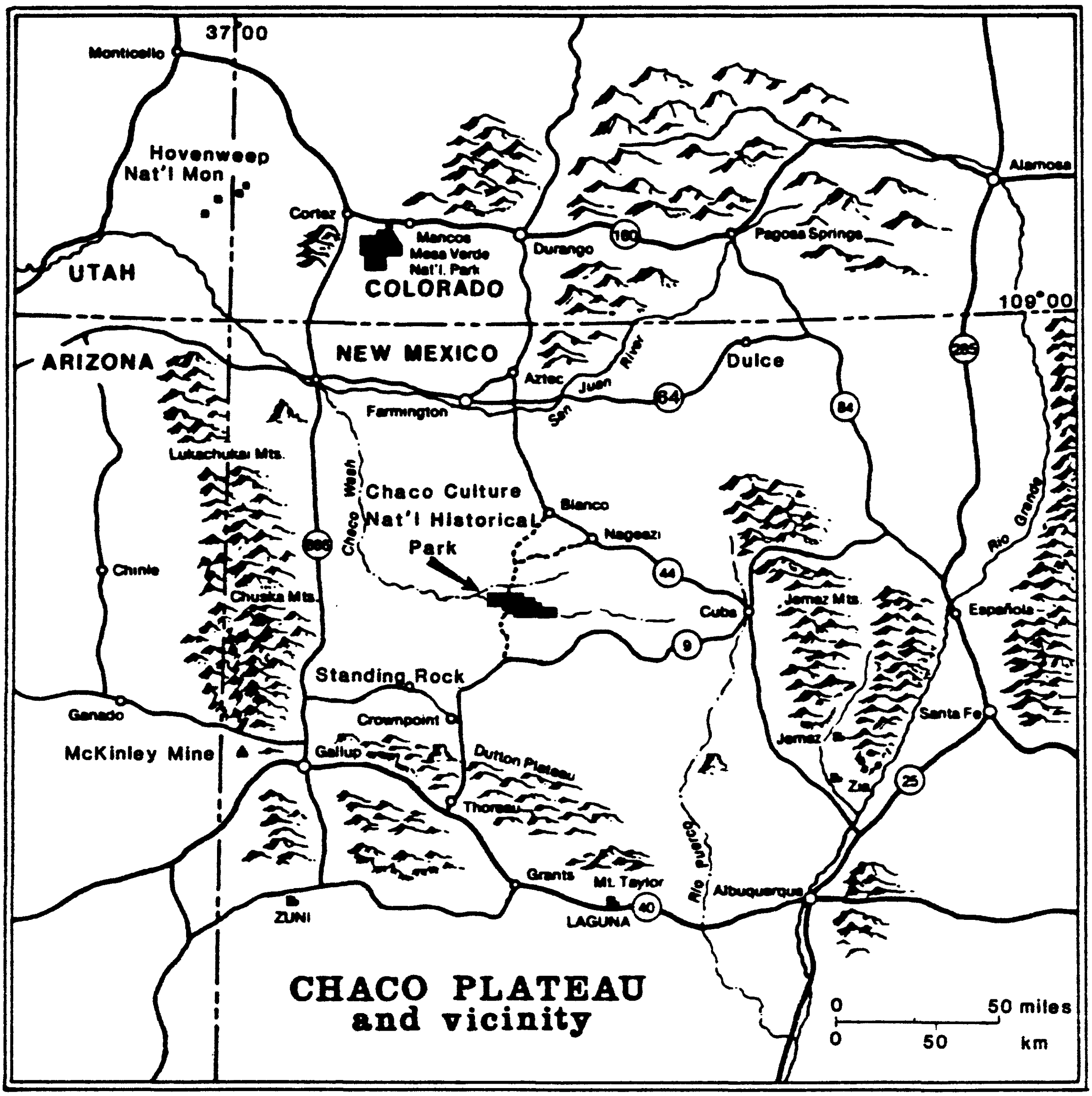

Figure 1.--Location map of the Chaco Canyon area.

of the canyon walls. The northern walls consist of Cliff House sandstone of the Mesa Verde Group of the upper Cretaceous period and are very steep to vertical ranging from 30 to 50 m high. The southern walls are much more gentle in relief and are breached by many branch canyons. The north side of the canyon with the steep walls is more exposed to the sun, has more evaporation and less plant growth, and is the location of the larger archeological sites (fig. 2). Shales underlying the sandstone cliffs produce a sandy bentonitic type of soil which can absorb large quantities of water during spring runoff and are thought to have some potential for liquefaction if subjected to ground shaking from earthquakes or blasting (E. Winkler, Professor, Department of Earth Sciences, University of Notre Dame, written commun., 1979).

NATURE OF THE STRUCTURES

Most of the visible archeological ruins in the areas of concern are carefully planned multistory structures which contain several hundred rooms. Generally the buildings were constructed using wide rubble-cored walls with exterior and interior veneers of well-shaped stones. The massiveness of the walls and the detailed workmanship are distinctive of the Chaco area and leave walls standing up to four stories high. The wall thickness, some up to 1.2 m at the lowest section, is dependent upon the height of the wall. The core and veneer masonry walls are used for the smaller as well as the larger structures. Over 27,870 sq m of wall fabric are exposed in the canyon. Most walls are 1.5 to 3 m high but many are over 4.5 m in height. Chetro Ketl, Pueblo Bonito, and Pueblo del Arroyo have walls four stories high. The major weaknesses of the structures are the use of horizontal logs for roof, door and window openings rather than keystone construction to distribute the forces away from the bridges, and the lack of structural ties between wall intersections.

POSSIBLE SOURCES OF GROUND SHAKING

Sources of ground shaking that are potentially damaging to the structures in Chaco Canyon are: earthquakes, landslides, industrial blasting, road building and vehicular traffic. In addition, high winds and sonic booms could be possible sources of damage.

Earthquakes

The historical distribution of seismicity is shown in figure 3. The nearest, well-defined seismic zone to Chaco Canyon is approximately 80 km southwest of the canyon. An earthquake with M_L magnitude 4.3 occurred about 50 km southwest of the canyon on January 23, 1966 (Sanford and others, 1981). This is the largest shock known to have occurred near Chaco Canyon in the period 1962 to the present. Larger earthquakes, however, could have occurred near the canyon prior to 1962, since earthquake magnitudes are poorly determined in this area. Using acceleration and velocity attenuation curves developed by Campbell (1984) as a first approximation, an earthquake of 4.3 M_L magnitude at a distance of about 50 km from the canyon would be expected to develop a maximum acceleration of about 0.01 g and a maximum velocity of about 0.5 cm/sec. Higher accelerations and velocities are possible because of local site response characteristics.

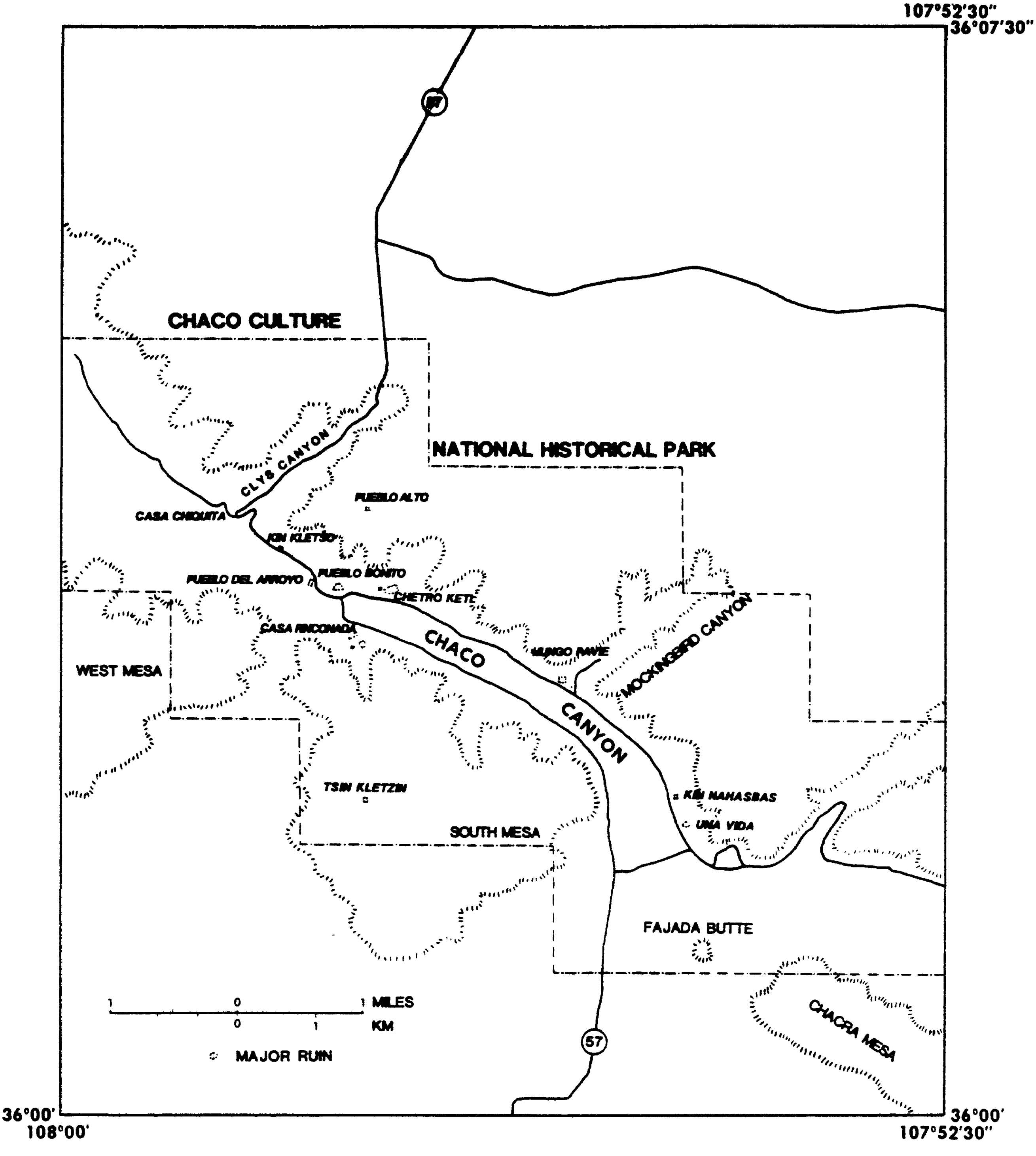

Figure 2.--Location map of Chaco Canyon.

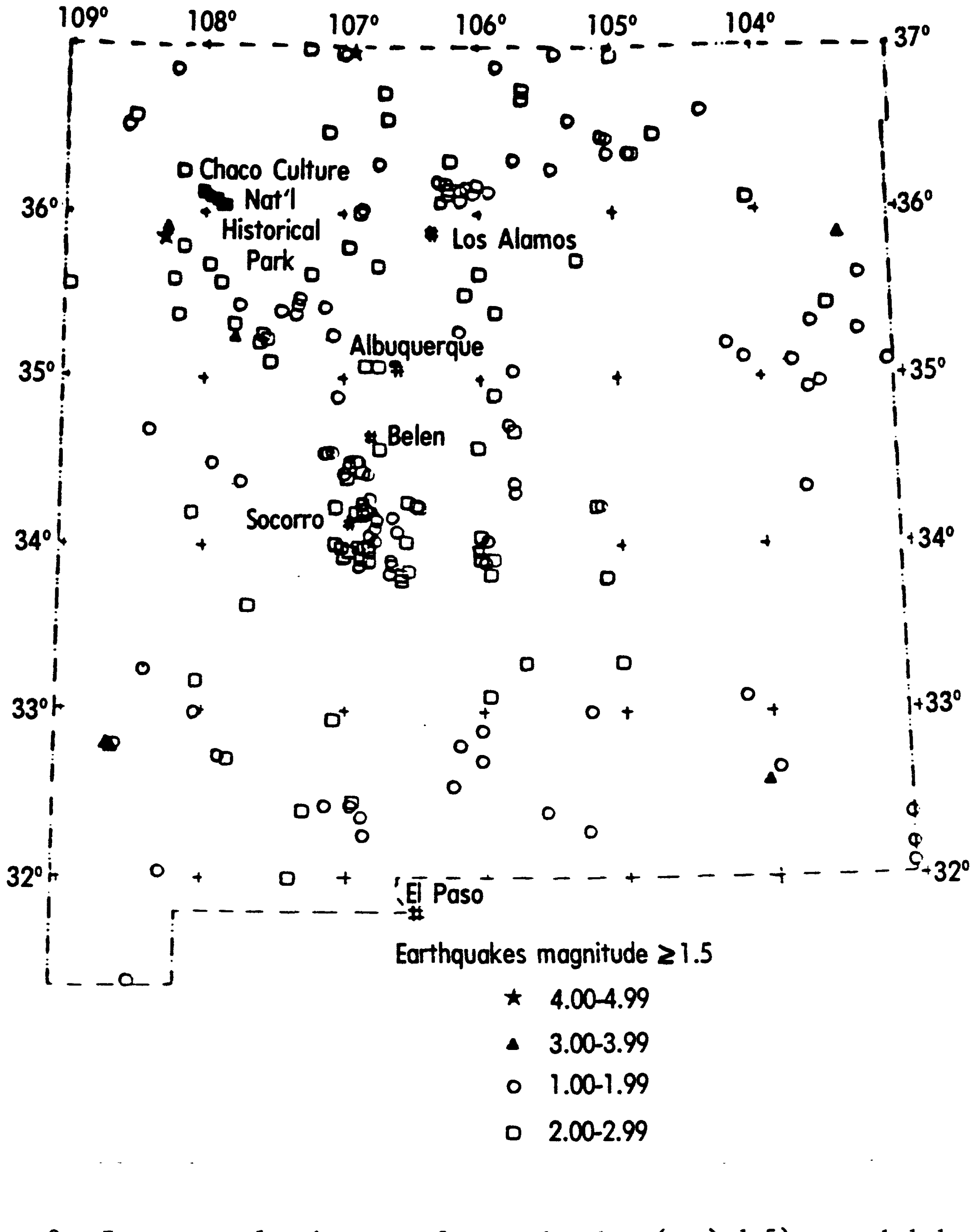

Figure 3.—Instrumental epicenters for earthquakes ($M_L \geq 1.5$) recorded during period of 1962-1977. (Modified from New Mexico Bureau of Mines and Mineral Resources Circular 171, Sanford and others, 1981.)

Algermissen and others (1982) have studied the regional seismic hazard throughout the United States on a probabilistic basis. Figures 4 through 7 show the expected acceleration and velocity in rock in 50 and 250 yrs with a 10-percent probability of exceedance for the Chaco Canyon area. The estimated accelerations and velocities are summarized in table 1. The levels of expected ground motion shown in table 1 are sufficient to cause damage to the structures in Chaco Canyon even for a relatively short exposure period of 50 yrs.

This suggests: (1) that earthquake damage to the structures may occur in the future and; (2) that the structures in Chaco Canyon were probably damaged by earthquakes on a number of occasions since their construction.

TABLE 1.--Expected accelerations and velocities at Chaco Canyon in 50 and 250 yrs with a 90-percent chance of not being exceeded (taken from Algermissen and others, 1982)

Time	Acceleration (g)	Velocity (cm/sec)
50	.07	3.5
250	.12	7.0

Industrial Blasting, Railroads, Road Building and Vehicular Traffic

Man-induced vibrations may be a potential hazard to Chaco Canyon structures and can be categorized as either cultural (public and vehicular traffic) or industrial (blasting, railroads, road building, and traffic).

No mining or drilling operations are active within 32 km of Chaco Canyon at the time of this report. The nearest potential mining site to Chaco Canyon is approximately 13 km north of the Pueblo Bonito ruins (fig. 8). The surface formation at this potential mining site is a sandstone cap of the upper Cliff House formation which is a member of the Mesaverde group of sedimentary rocks. The Mesaverde group contains some rich deposits of coal which may or may not be present in the area of the potential mining site. It is reasonable to assume that any blasting/mining operations at this lease would be the nearest industrial development to the canyon.

Construction of a rail line is under consideration north of the canyon area. This line would pass within 24 km of the canyon and would be used to transport coal from the coal fields at Bisti, New Mexico, to Grants, New Mexico. The area available for mineral leasing northeast of the canyon may contain economical deposits of coal and eventual coal production. Associated with the coal production would be mining vibrations (blasting, mining, transportation, etc.) and potentially a railroad spur from the Bisti line.

Road building is a possible damaging source of induced ground motions to the structures in the canyon. The National Park Service is paving the one road through the canyon because of increased pressure for public access. Road building equipment induces vibrations into the ground (trucks, thumpers,

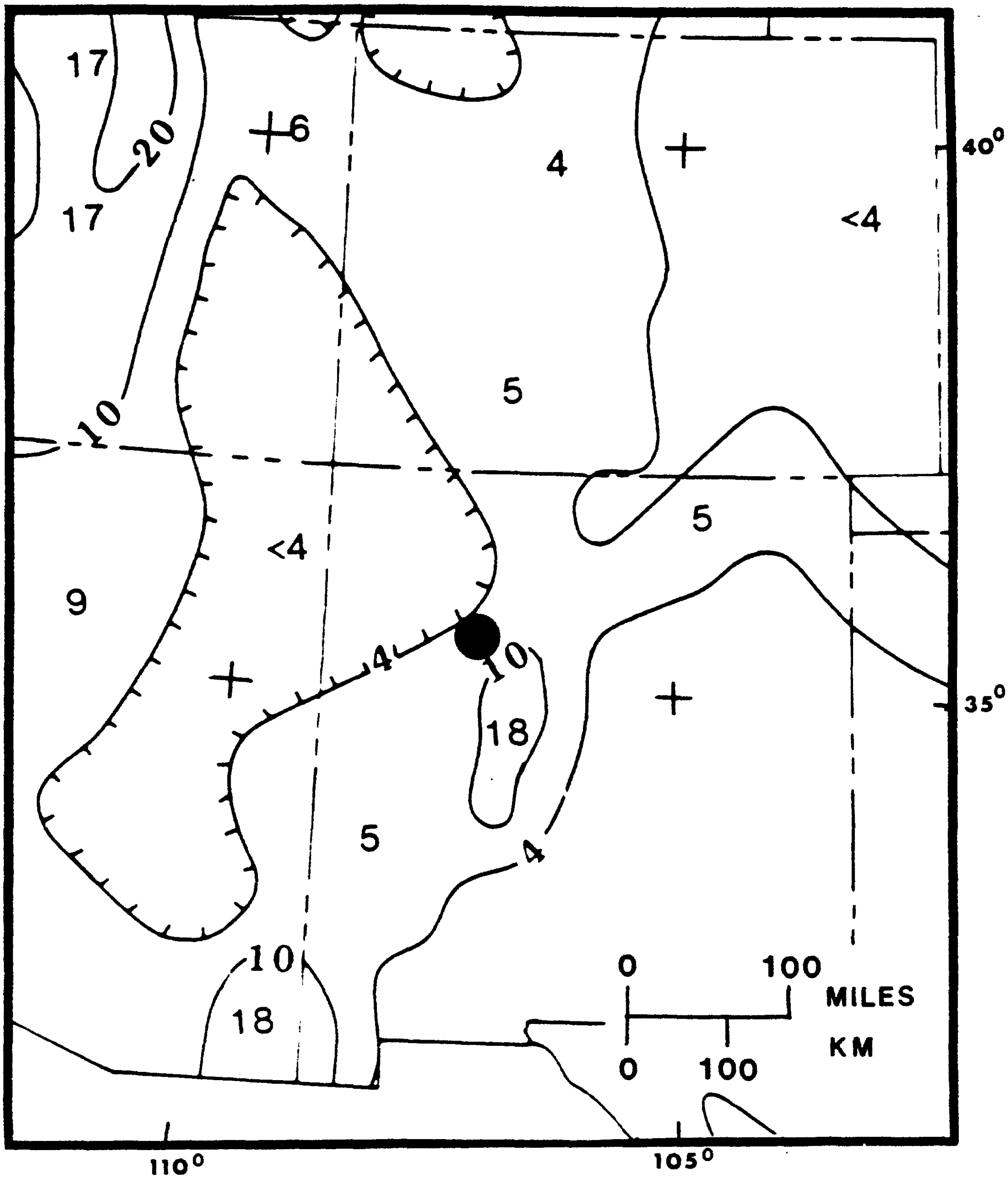

Figure 4.--Expected acceleration (percent of g) in rock with a 90-percent chance of not being exceeded in 50 yrs (after Algermissen and others, 1982). Chaco Canyon is shown by a solid circle.

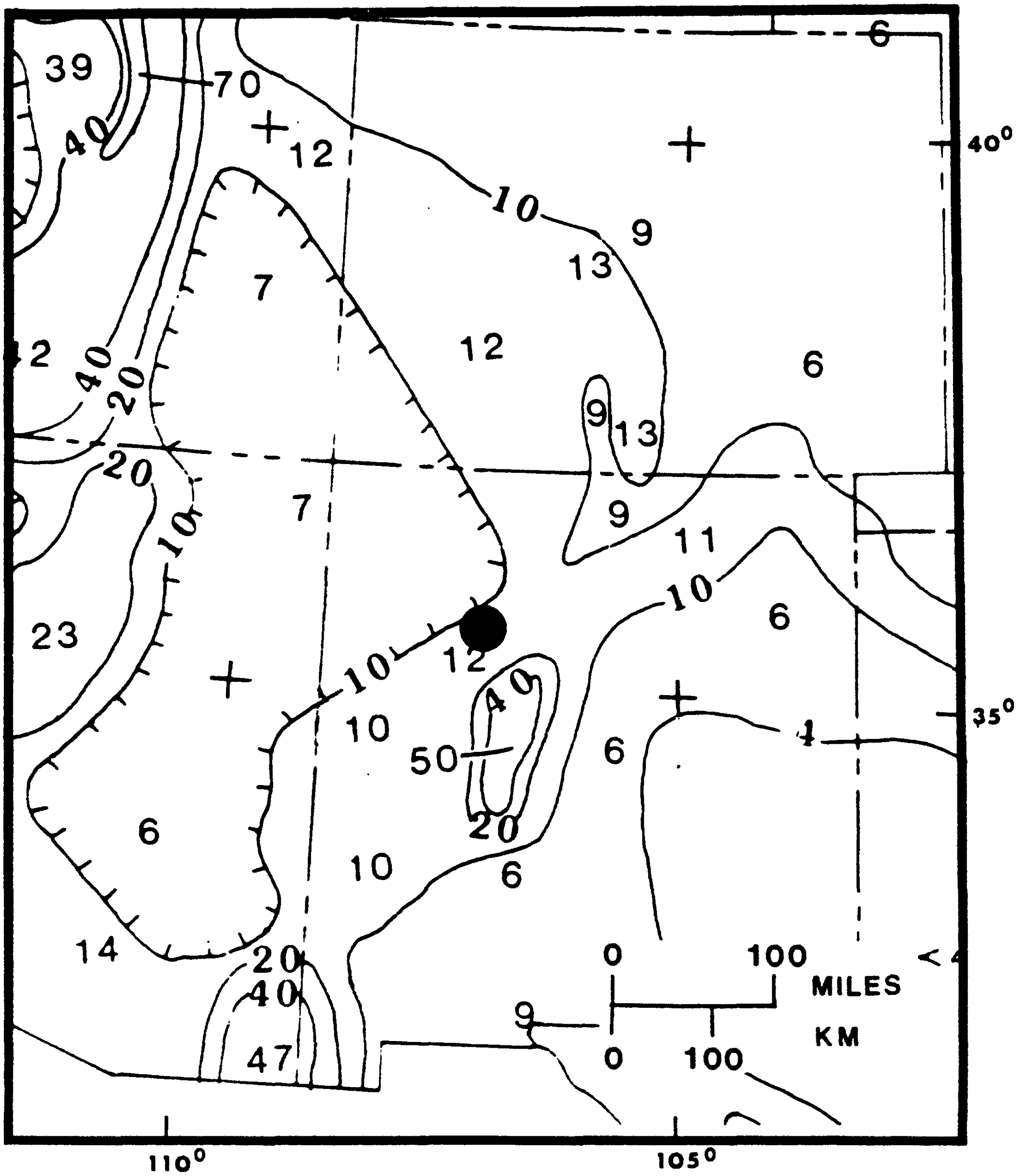

Figure 5.--Expected acceleration in rock with a 90-percent chance of not being exceeded in 250 yrs (after Algermissen and others, 1982).

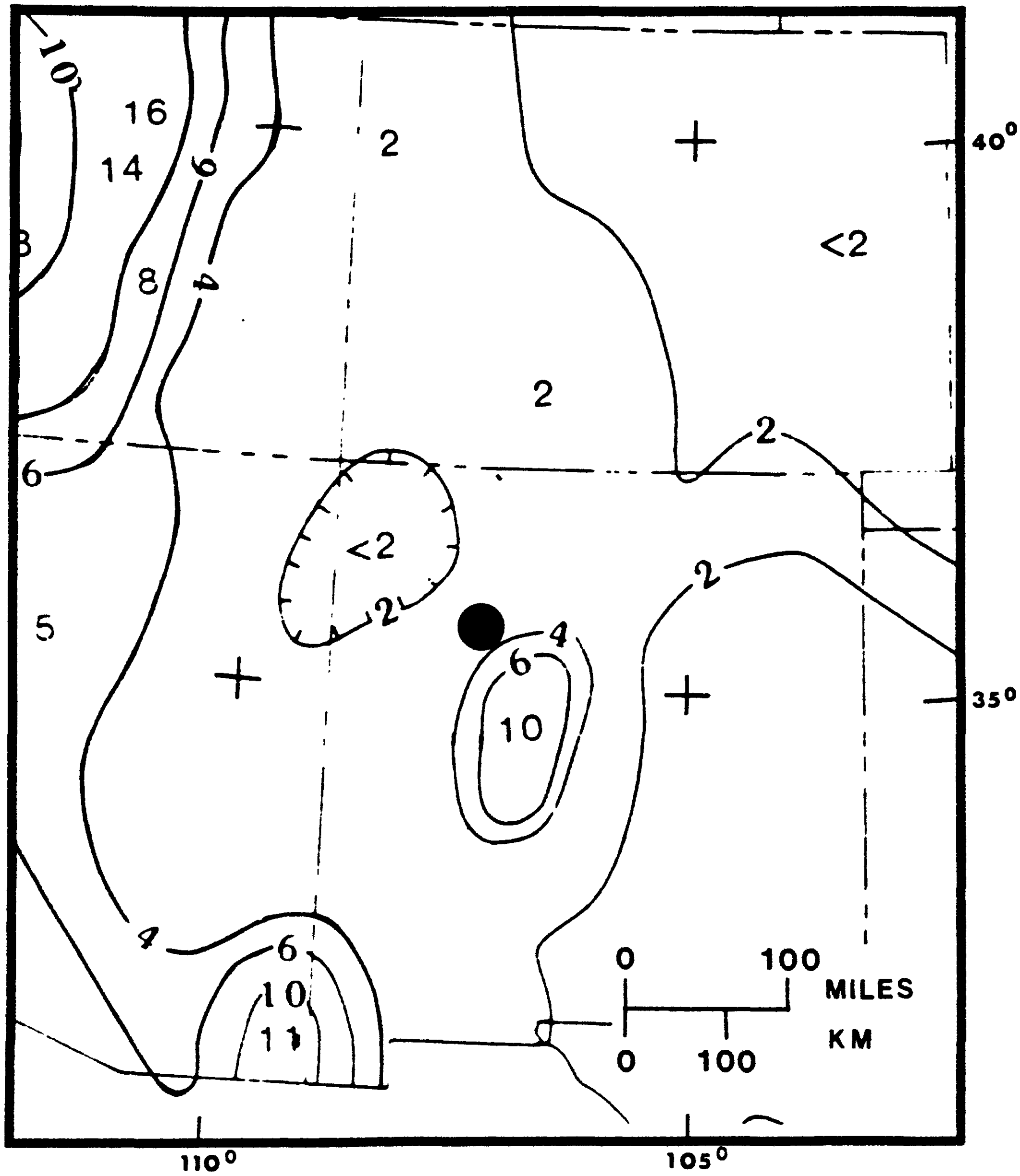

Figure 6.-- Expected velocity (cm/sec) in rock with a 90-percent chance of not being exceeded in 50 yrs (after Algermissen and others, 1982). Chaco Canyon is shown by a solid circle.

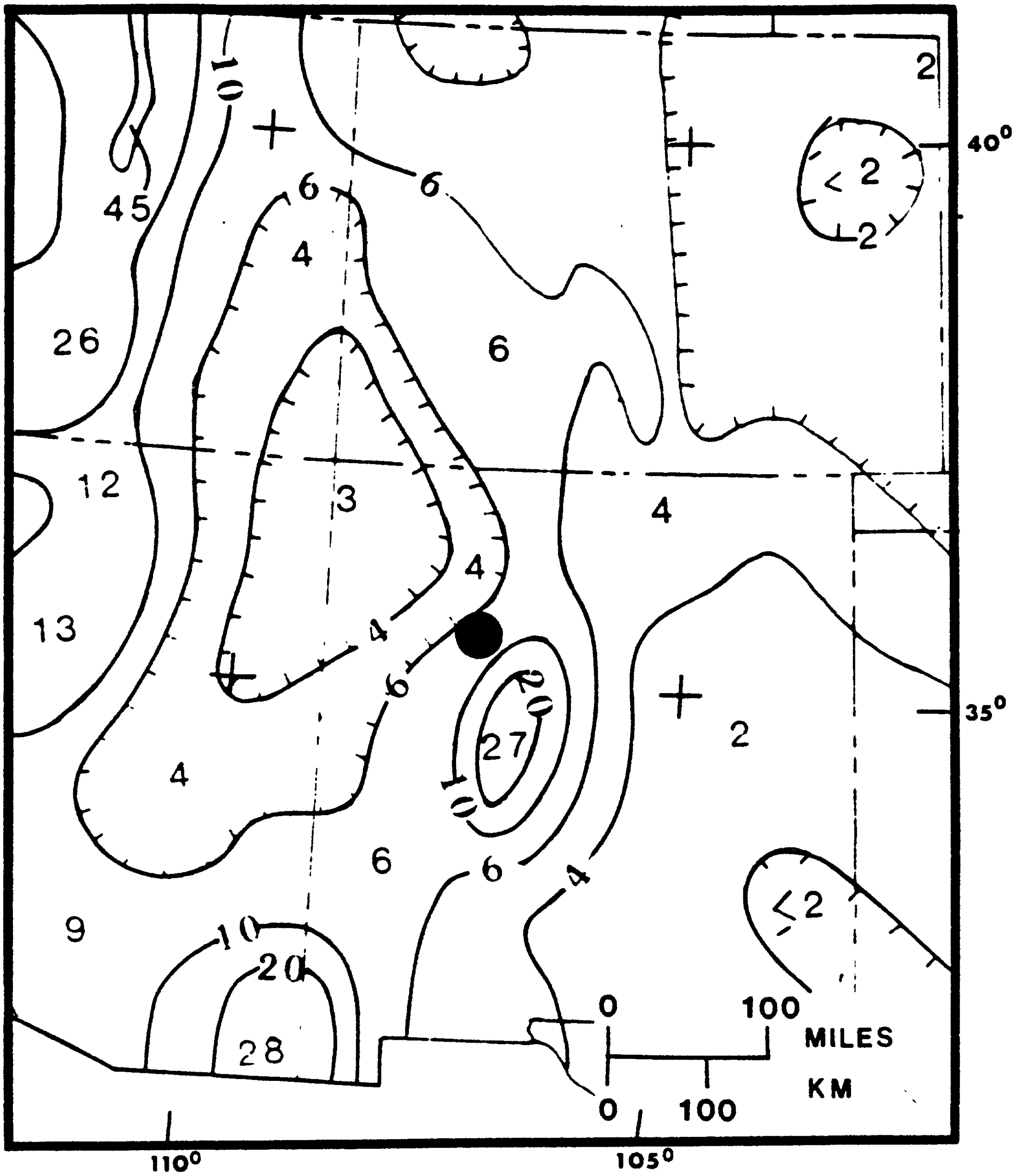

Figure 7.--Expected velocity (cm/sec) in rock with a 90-percent chance of not being exceeded in 250 yrs (after Algermissen and others, 1982). Chaco Canyon is shown by a solid circle.

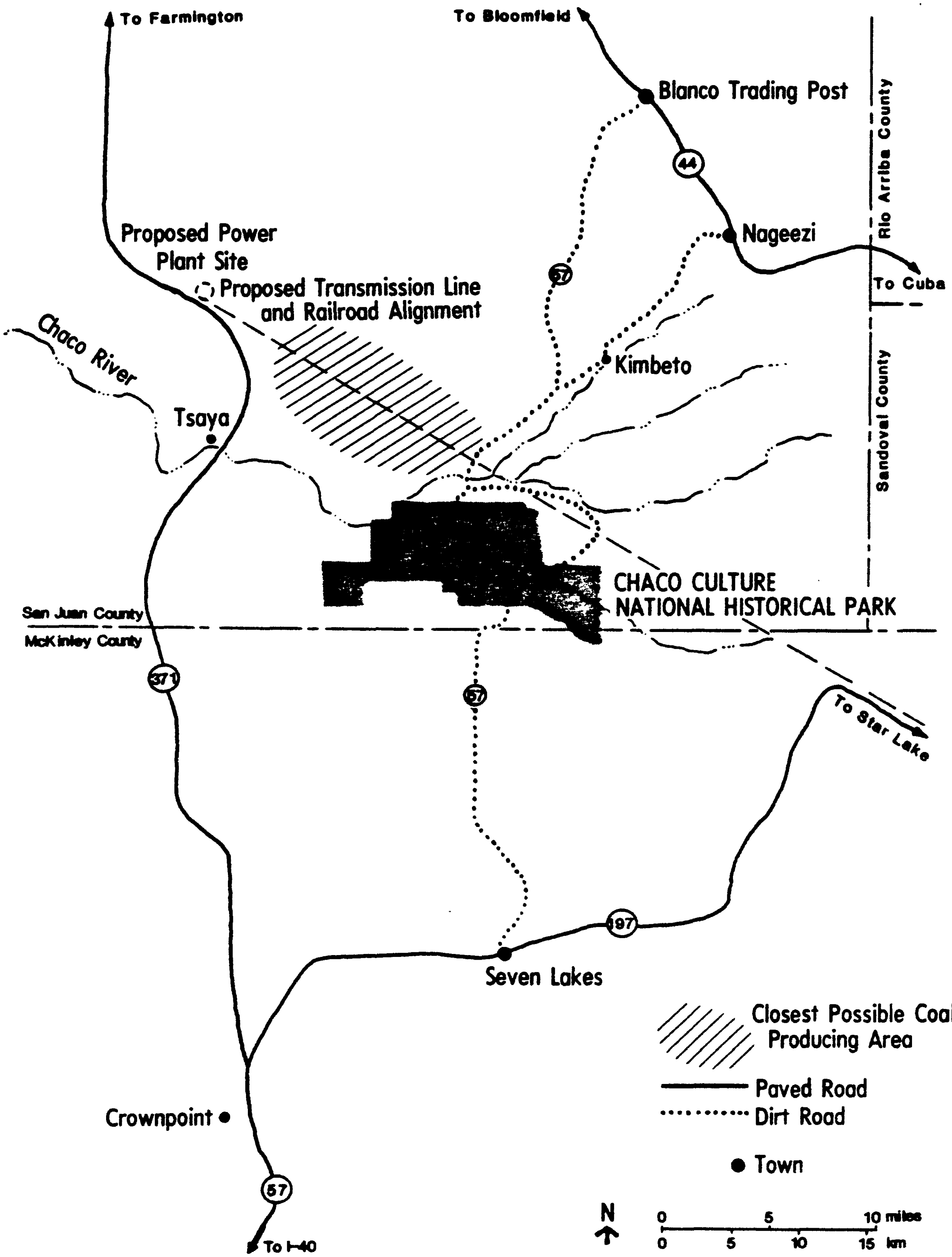

Figure 8.--Location of potential coal mining development with respect to Chaco Canyon.

graders, and pavers) which can be a potential vibration hazard to the archeological structures. Traffic on the access roads also induces vibrations in the structures. These activities increase the ambient vibrations in the structures and may contribute to an immediate and (or) cumulative fatigue damage to the structures.

Winds

The winds of Chaco Canyon are an element of potential hazard to the archeological structures. The average wind velocity in the spring is approximately 16 km/hr with velocities exceeding 40 km/hr over 1 percent of the time. It is not unusual to have a 1- to 2-day windstorm with velocities in the 60-80 km/hr range (Chaco Canyon General Master Plan, 1983). The winds, through varying pressure and vortex shedding, impose a considerable force on, and initiate the vibrations and swaying of the exposed walls. The bracing of the walls by large timbers and steel rods generally increases the natural frequencies of the structures. These higher natural frequencies may then approach the predominant frequencies of the winds in the canyon. Modern rebuilding methods using concrete will result in different structural engineering characteristics than those of the ancient adobe-stone methods. The newer construction methods may introduce a more rigid structure which could be more susceptible to the vibrations induced by wind.

Sonic Booms

The frequency content of the induced vibrations from sonic booms are above 10 Hz and can be a hazard factor to the fragile wall plasters of the ruins (Espinosa and Mickey, 1968). Chaco Canyon is not located in a specific aircraft over-fly area; therefore, the potential for damaging sonic booms is very low. The few sonic booms that do occur are probably associated with singular military aircraft.

ACCEPTABLE LEVELS OF GROUND SHAKING

Evaluations of the ground shaking hazard and risk at Chaco Canyon requires a review of the existing data on levels of ground motion associated with damage to simple structures.

An induced ground-motion particle velocity of 50.8 mm/sec has been recommended by Nicholls and others (1971) as the safe upper limit for industrial blasting. This standard, which is used by many states, recognizes that some minor cosmetic damage such as plaster cracking will occur at ground-motion particle velocities below this standard (fig. 9). Citizen pressures and lawsuits involving alleged residential damage at or below the standard level have caused the Bureau of Mines to further investigate the damage criteria. A more recent study by Siskind and others (1980) suggests that: (1) the single best ground-motion descriptor for damage is particle velocity; (2) the natural frequencies of structures are a particularly important parameter in damage criteria; and, (3) a conservative, safe level of ground motion for dwellings is in the range of 2.0 to 3.8 mm/sec.

The allowable maximum induced ground-motion level at a residential site in Czechoslovakia from a commercial explosion is 10 mm/sec (Dvorak, 1962). The maximum allowable level set by the British Secretary of State is 10 mm/sec at frequencies greater than 12 Hz and 12 mm/sec for frequencies below 12 Hz

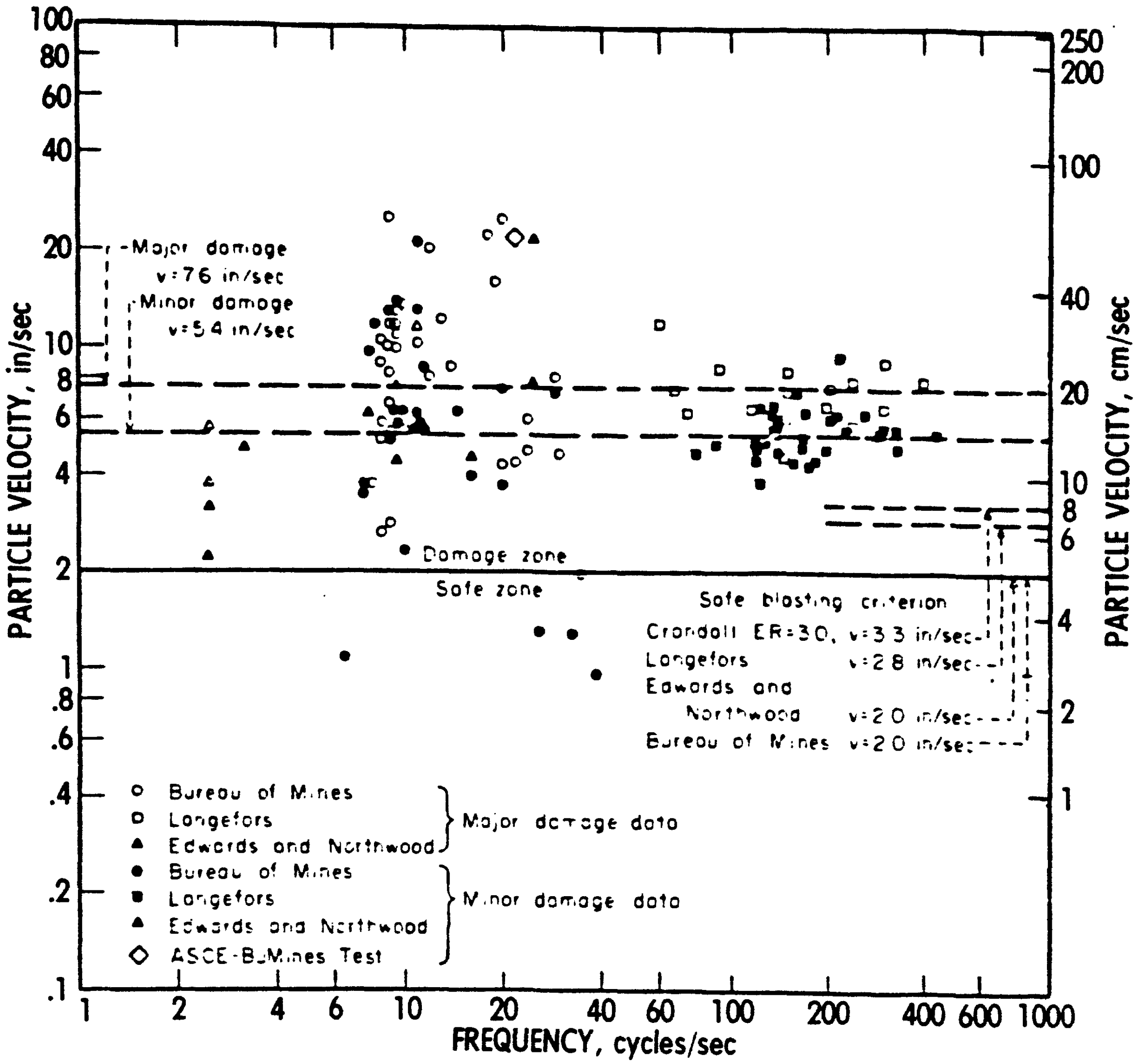

Figure 9.—Safe vibration levels for residential structure (modified from Nicholls and others, 1971).

(Skipp, 1977). A maximum allowable ground-motion level of 12 mm/sec at 10 Hz and 6 mm/sec at 5 Hz has been used in Australia (Tynan, 1973). The German vibration standards (DIN 4150) state that a vibration of more than 4 mm/sec, will not be allowed at average building sites (Skipp, 1977).

A generally accepted view in Germany, Great Britain, and Sweden is that historic buildings and ancient sites should not be subjected to even minor vibration damage resulting from commercially or industrially induced ground motions. Government set levels of maximum ground motion for historic buildings and sites in Germany, Great Britain and Sweden are 2 mm/sec, 2.5 mm/sec and 2 mm/sec, respectively.

In Great Britain and Sweden several vibration studies of motions induced from roadways have been made. The British studies indicate that a stone base versus a soil base for a highway will attenuate the induced motions by a factor of 1.75 (Whiffin and Leonard, 1971). Ground motion investigations made in Sweden on the effects of ramps or bumps on a road indicate that a 100 mm bump will induce from 2.5 to more than 10 times more ground motion, out to 50 m from the road, than will a smooth road (fig. 10). Similar tests on a paved road and an unpaved road indicate that a paved road and base will absorb most of the induced frequencies above 20 Hz and, in general, passes induced frequencies in the 10 to 14 Hz range. The same tests show that the ramps do not introduce new frequencies; therefore, the difference in the induced motion from traffic on a rough road versus a smooth road is generally in amplitude and not in frequency. The same series of tests (fig. 11) indicate that varying the traffic speed from 30 to 50 km/hr does not significantly change the induced motions out to 50 m from the roadway. The study of induced ground motions from traffic by the Swedish and British investigations show that paving roads, installing a proper rock base, and providing a smooth road can reduce the induced ground motions to adjacent sites. The velocity of the traffic appears to have little effect on the induced motion. These studies also indicate that traffic on a paved road induces ground motions in the 10 to 15 Hz range (Whiffin and Leonard, 1971).

Limit of Allowable Induced Ground Motion

The National Park Service wishes to establish a reasonable allowable maximum induced-vibration level from industrial and traffic sources that will cause no appreciable or progressive damage to the historic structures in the canyon. Based on the existing studies reviewed, we recommended that a 2.0 mm/sec particle velocity be the upper limit for induced motions in the structures. We suspect that larger ground motions are possible from natural hazards such as earthquakes and windstorms, but this does not affect the allowable industrial or cultural induced maximum level.

We assumed a 2.0 mm/sec particle-velocity value in the frequency range of 1 to 20 Hz as the maximum allowable motion on the Chaco Canyon archeological sites to determine the range or zone around the structures where certain types of equipment or activities should not be allowed. This study proposes minimum distances from the structures in the canyon for highway traffic, highway building equipment, railroads, and strip-mine detonations.

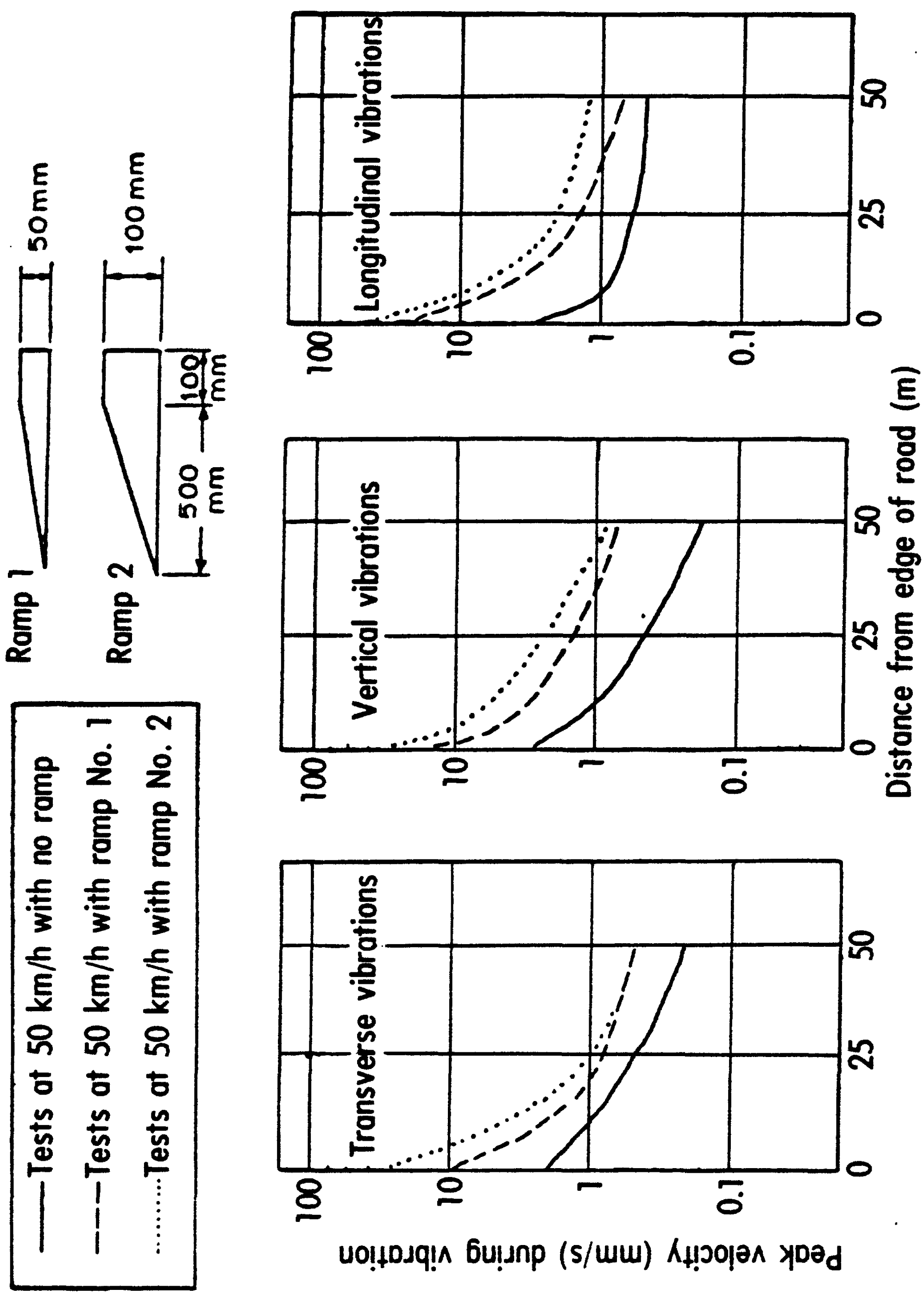

Figure 10.--Variations in peak ground velocity with and without ramps and constant vehicle speed (modified from Frydenlund, 1985).

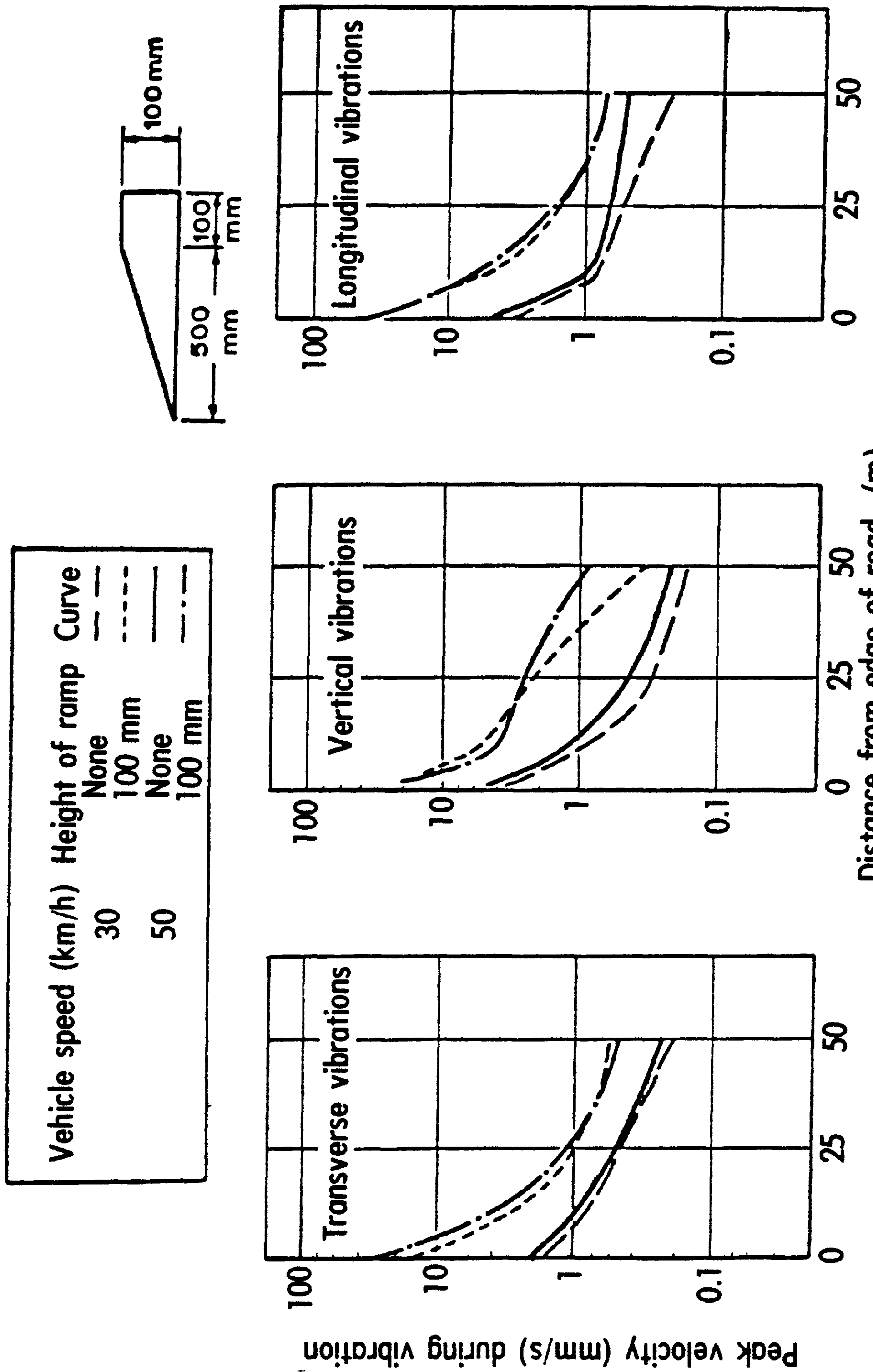

Figure 11.--Variations of peak ground velocity with vehicle speed, height of ramp and distance from edge of road (modified from Frydenlund, 1985).

FIELD TESTS

Instrumentation

The study of vibration hazards to archeological sites consists of investigations of the induced-vibration sources, transmission paths of the vibrations and, finally, the dynamic properties of the archeological structures. The field seismic equipment used to investigate the induced vibration sources and dynamic properties of the structures in Chaco Canyon were portable three-channel seismograph systems, a six-channel refraction system, and a single channel vertical motion sensing radio-telemetry seismic system. The three-channel systems recorded data from a tripartite array of seismometers. The seismometers were oriented orthogonally with the horizontal components oriented parallel and perpendicular to the energy source or the long axis of the structure. The near-surface seismic velocities and road-to-structure transmission path investigation was documented with a six-channel digital engineering, signal enhancement reflection/refraction system. The current natural seismicity was documented by a vertical sensing, single channel, radio-telemetry seismic system located near Pueblo Alto.

Vibration Sources

Induced vibrations from three types of road construction equipment were recorded at various distances from the sources. The sources were:

1) Sheep's foot, drum drive, vibrator roller. The roller is a "Bomag 210D" type which has a vibratory compactor drum with a vibration input of 18,144 kg of dynamic force at 31 Hz. The drum is 213.4 cm wide, 150 cm in diameter and weighs 5,464 kg. Vibration measurements were obtained at distances of 9, 30, 54 and 72 m from the machine.

2) Small double drum vibration roller (Wacker, W55T). The drum has a vibratory input of 3,062 kg at 48 Hz. The drum is 55 cm wide and weighs 768 kg. Measurements were obtained at distances of 9, 22 and 30 m from the roller.

3) Hand operated compactor (Wacker, GUR 151Y). Specifications indicate a vibratory input of 1,184 kg at 20.3 Hz. The dimensions of the vibrating "shoe" are 28 x 33 cm. The shoe weighs 61 kg. Vibrations were recorded at distances of 5, 10 and 50 m from the compactor.

A number of other sources of induced vibrations were monitored:

1) 18-ft motor home; 1/2-ton pickup truck, 2-ton pickup truck and various standard automobiles. Vibrations were recorded at a distance of 10 m from the canyon road near the southeast corner of the Kletso structure.

2) A 36-kg weight dropped from a height of 1.5 m in the center of the unpaved road and again on the same road after veneering the road with 15.2 cm of rock. Vibrations were recorded at a distance of 10 m from the road.

3) Coal-carrying railroad cars. The railroad investigated is at a mine approximately 19 km northwest of Gallup, New Mexico. The average weight of the cars was 90,700 kg each, traveling approximately 24 km/hr on track which was underlain by a 1-m crushed stone bed. The induced vibrations were measured at distances of 100, 200, and 1,000 m (fig. 12). The train and track construction is similar to that which may be used near Chaco Canyon.

4) A 2,543 kg quarry blast was recorded at the railroad test site northwest of Gallup, New Mexico. The recording site was located 8.6 km from the explosion. The explosion was a face row type with 60-m/sec delays between 2,540-kg shots and was typical of the shots used in strip-mining coal in this area (fig. 12). This quarry blast is believed to be similar to those that could be used for mining of coal near Chaco Canyon.

5) Four high-explosive events were recorded. Three explosions of 455, 227, and 227 kg were detonated in 15.2-cm holes at the intersection of New Mexico Route 57 and the Pueblo Alto road. The first event (455 kg) consisted of two 19-m deep holes, each loaded with 227 kg of ammonium nitrate and fuel oil. The holes were tamped with approximately 10 m of sand and silt and were simultaneously detonated with 2-1/4 x 1 sesptimes. The explosion-induced ground motions were recorded on the ground at 0.71 km near the Pueblo Alto road, at a distance of 1.8 km from the source at Pueblo Alto, and at a distance of 2.8 km at Pueblo Bonito (fig. 13). The second event was a 227-kg shot in the same location with the recording equipment in the same location. The third event was a 227-kg shot in the same location, with the recording equipment located on the ground and on a wall at Pueblo Alto, a recording system located on the ground at Pueblo Bonito, and another system located on the tall north wall at Pueblo Bonito.

The three events are believed to accurately model possible induced vibrations at Chaco Canyon should explosive devices be used for overburden removal at the coal leases northwest of the canyon.

Velocity Measurements

A 12-channel, signal enhancement seismograph was used to measure the compressional and shear-wave velocities of the near-surface unconsolidated sediments at Casa Chiquita, Kin Kletso, Pueblo Del Arroyo, Pueblo Bonito, Chetro Ketl, and Casa Rinconada. Velocities were also measured on the Cliff House sandstone float at Kin Kletso and at the sites where the induced vibrations from the construction equipment was recorded.

SEISMICITY OF THE REGION

Earthquake activity in the San Juan basin was monitored by the U.S. Geological Survey (USGS) at the Albuquerque Seismological Laboratory from January 1980 through November 1981. The recording equipment was moved to the campus of New Mexico Institute of Mining and Technology in December 1981 and operation resumed in March of 1982. The system operated until October 1,

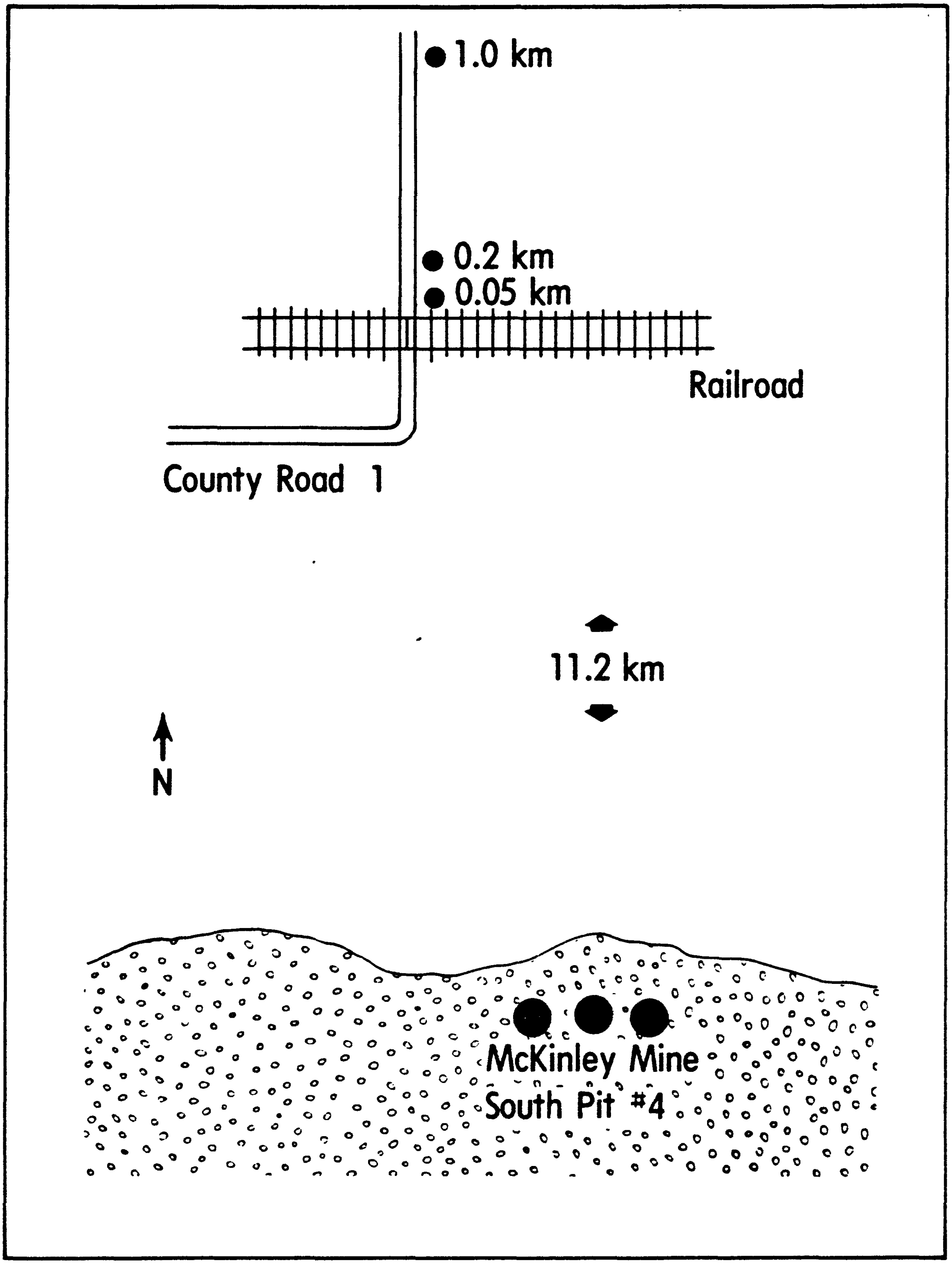

Figure 12.--Location map of quarry (explosives) and railroad vibration test area.

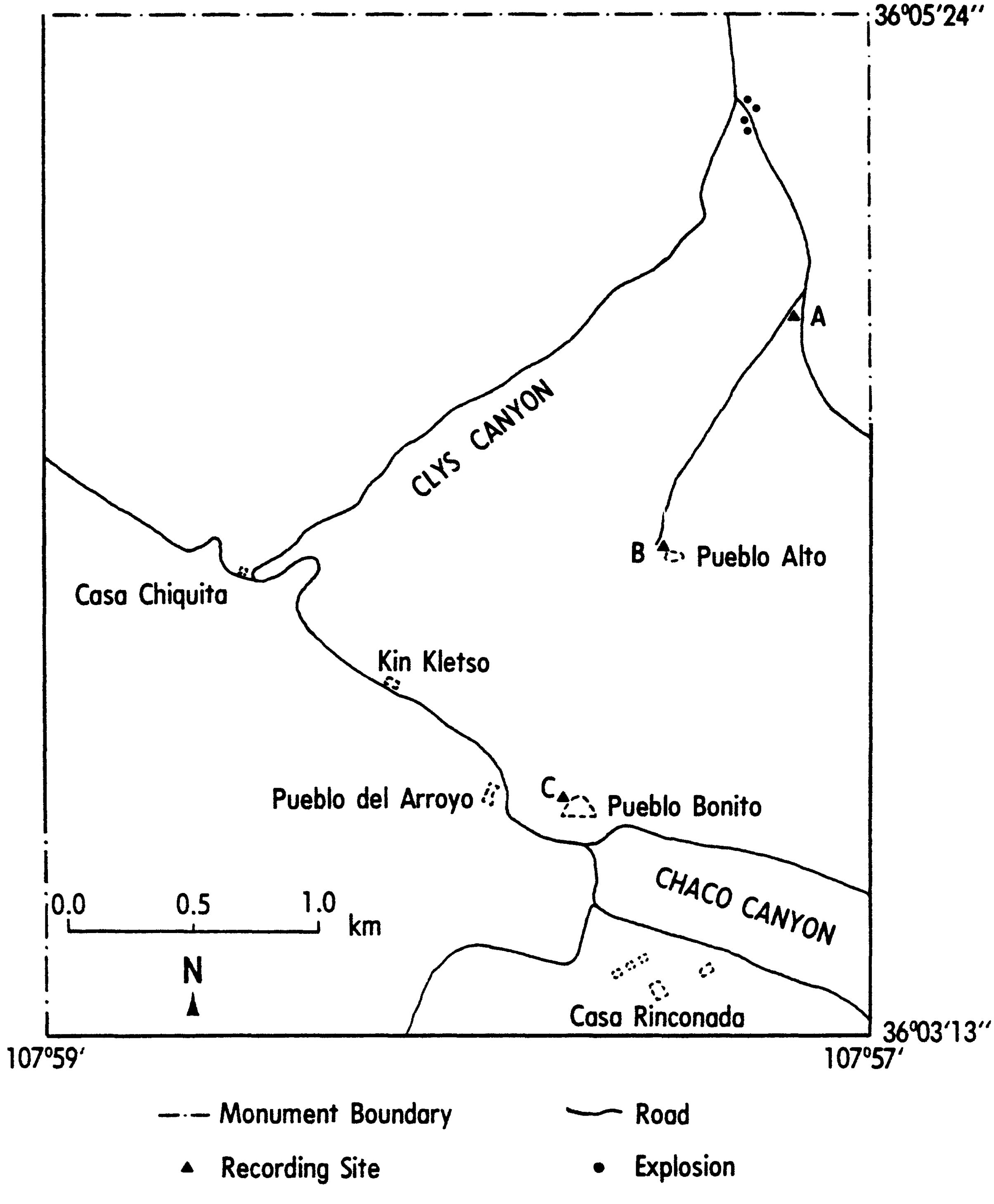

Figure 13.--Location map for attenuation study showing explosion and recording sites.

1982, when all of the USGS seismic stations in the San Juan basin, except the one at Chaco Canyon, were removed.

The seismicity in the San Juan basin deduced from approximately 30 months of observation by this regional network of stations is very low. Exclusive of the Jemez Lineament (a volcano-tectonic structure that includes Mt. Taylor), about three earthquakes per month were located. This data set is too meager to estimate the frequency distribution of earthquakes in the basin.

During the USGS study, four earthquakes with magnitude (M_L) exceeding 2.0 were located. Two of these events were near Mt. Taylor, one was in the Chuska Mountains, and the other was about 40 km southeast of Dulce, New Mexico. The Dulce area, where the largest known historical earthquake (M_L = 5.5) in New Mexico occurred in 1966 generated only a few events during this study. The maximum magnitude attained from earthquakes in the Dulce area was ~ 1.5 (M_L). No earthquakes were located near Standing Rock, New Mexico, during the USGS study. The largest shock during the period of the USGS study was a magnitude (m_b) = 5.0 earthquake in 1976 approximately 50 km from Pueblo Bonito at Standing Rock.

An epicenter located at 35.9 N., 107.9 W., about 30 km south of Chaco Canyon, was the event closest to the national historical park during the time of the USGS observations. This small earthquake had a magnitude (M_L) of less than 2.0. The time history and spectra of this earthquake motion at Pueblo Alto are shown on figure 14. These frequencies are generally lower than the natural frequencies of the walls of the structures except for the tall north walls at Pueblo Bonito, a tall north wall at Pueblo Del Arroyo and the large rock pinnacles (Kendorski and others, 1980).

Foley and LaForge (1983) have estimated seismicity on the Southern Colorado Plateau from a 52-yr data set (1930-1981). Their recurrence relationship is

$$\mathrm{Log}\ (N) = 1.69 - 0.65\ (M)$$

where N is the number of earthquakes with magnitude M or greater per year per 10^5 km^2. This relationship suggests that one magnitude (m_b) = 5.7 earthquake will occur each 100 yrs in the study area.

Sanford and others (1981), in discussing the seismicity of the Colorado Plateau in northwestern New Mexico, noted that earthquakes tend to circumscribe the San Juan basin. They found the basin interior to have low seismicity in the range of M_L >1.5 during 1962-1977. Studies conducted at the Los Alamos National Laboratories (Cash and others, 1983) have also found the interior of the basin to have very low seismicity.

STRUCTURAL TESTING

The damping and natural frequency of the structures in Chaco Canyon are very important parameters in the analysis of the response of these historical archeological ruins. The ruins are irregular, nonengineered structures which would be difficult to model to obtain these parameters. The test procedure for obtaining the damping and natural frequency of vibration generally consisted of installing horizontal, velocity motion-sensing seismometers on the top-mid-point of walls of the structures. Several minutes of ambient seismic background and a number of induced vibration events are then recorded. The induced vibrations recorded in this study were from vehicular traffic and man-induced motion. The natural frequency and damping of the walls were also measured by recording man-induced forces on the walls. The

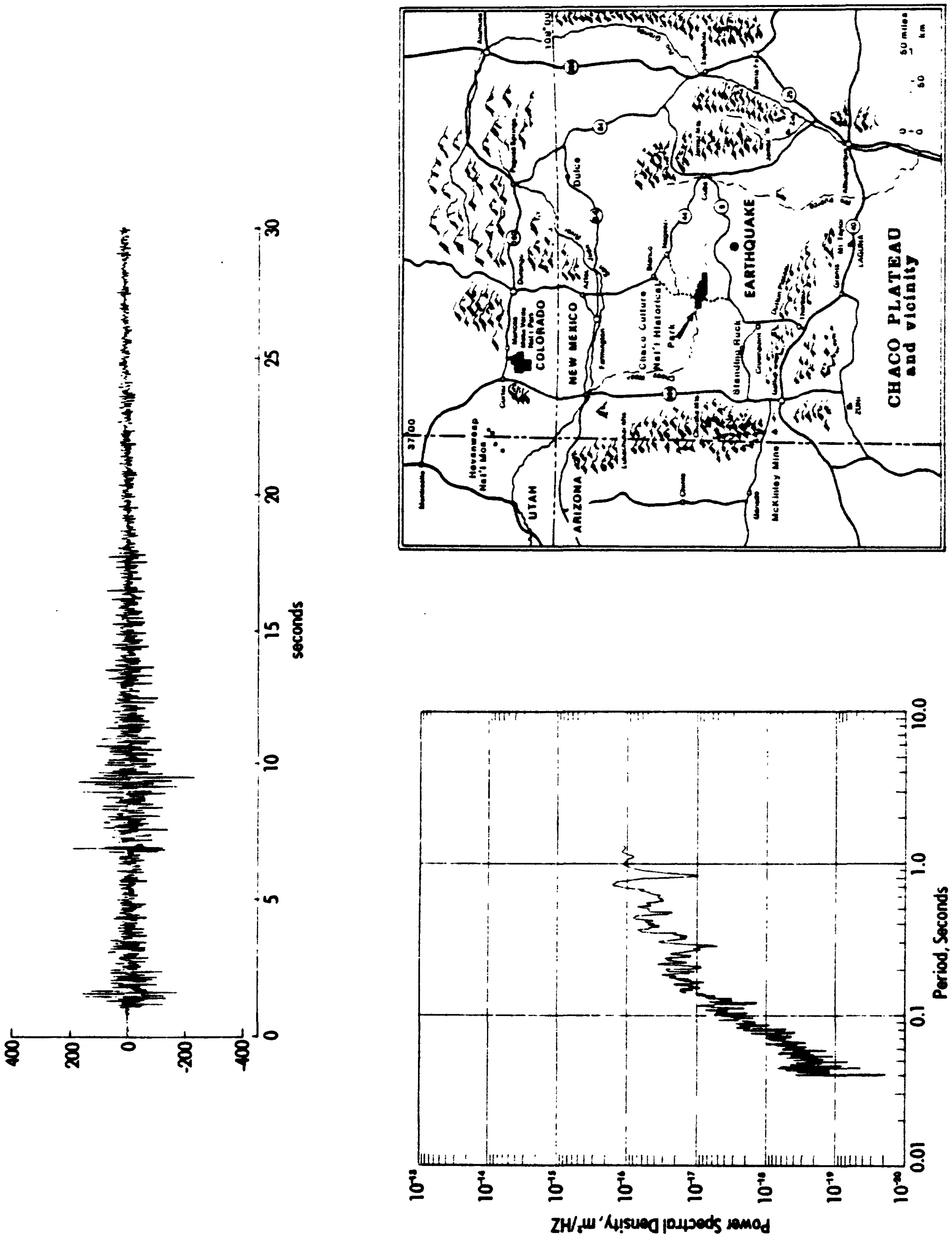

Figure 14.--Location of earthquake recorded at Pueblo Alto, recorded seismogram and computed Fourier spectrum.

man-induced forces were kept in close synchronization with the structure's natural frequency. This technique has been described in detail by Hudson and others (1964).

The tests were analyzed to determine the response spectra of the wall, to derive the structure transfer function from a site located at the base of the wall to a site located on the top-mid-point of the wall and to find the damping of the wall. The transfer function (TF) was calculated using: $TF_\tau = \frac{SW\tau}{SG\tau}$, where τ = frequency in cycles/second, Sw = spectral amplitude at the site on top of the wall and Sg = spectral amplitude at a site at the base of the wall. The spectral amplitude and transfer functions indicate those frequencies at which large amplitudes can occur at the top of the wall, since certain frequencies of the ground motion are selectively amplified by the wall. The ground motion frequencies that are amplified depend on the natural frequency and damping of the walls. The seismic records from the top of the wall were analyzed to obtain the approximate percentage of critical damping, using $\beta = \frac{1}{2\pi} (-\ln \frac{Xn - 1}{Xn})$; where β is the percent critical damping and X is the velocity amplitude for the nth cycle of motion.

Twelve walls were tested at Pueblo Bonito for natural frequencies and damping. The amplification at various frequencies of two walls, nos. 2 and 5 (see appendix), were analyzed to determine the amplification or transfer function from the base of the wall to the top of the wall (fig. 15). Twelve walls were tested at Kin Kletso for their natural frequencies and damping. Wall nos. 1 and 5 were used to determine the amplification of the walls. Seven walls were tested at Pueblo Del Arroyo for natural frequencies and damping. Wall nos. 4 and 5 were used at Pueblo Del Arroyo to determine the wall amplification. Four walls at Chetro Ketl, four walls at Casa Chiquita, and two walls each at Una Vida, Hungo Pavie, and Casa Rinconada were tested for their natural frequencies and damping.

The damping and natural frequencies (first mode) are shown in figure 16. The graph indicates a close relationship between the height of walls and the first natural frequency of the walls. The relationship was established by linear least squares regression procedures giving a coefficient of determination of 0.75. The relationship between the percentage of critical damping and the height of the walls shows more data scatter than the height versus natural frequency regression and has a lower coefficient of determination of 0.40. This lower value is considered reasonable when the deteriorated condition of the walls is taken into consideration.

ANALYSIS OF INDUCED VIBRATION DATA

Road Building Equipment

Ground motions produced by three types of ground compactors were recorded at several distances and analyzed for spectral content and attenuation rate. The spectra derived from the induced ground-motion data show that most of the ground-motion energy induced from the compactors is found in two narrow frequency bands. The largest amount of energy is found in a narrow band of frequencies centered on the input frequency specified by the manufacturer for each particular piece of equipment. A second, narrow band of lower frequencies carry approximately 6 db less energy than the first band (fig. 17). The second and lower energy set of frequencies are of interest as the center frequency of these bands are at or near the natural frequencies of several of the archeological walls.

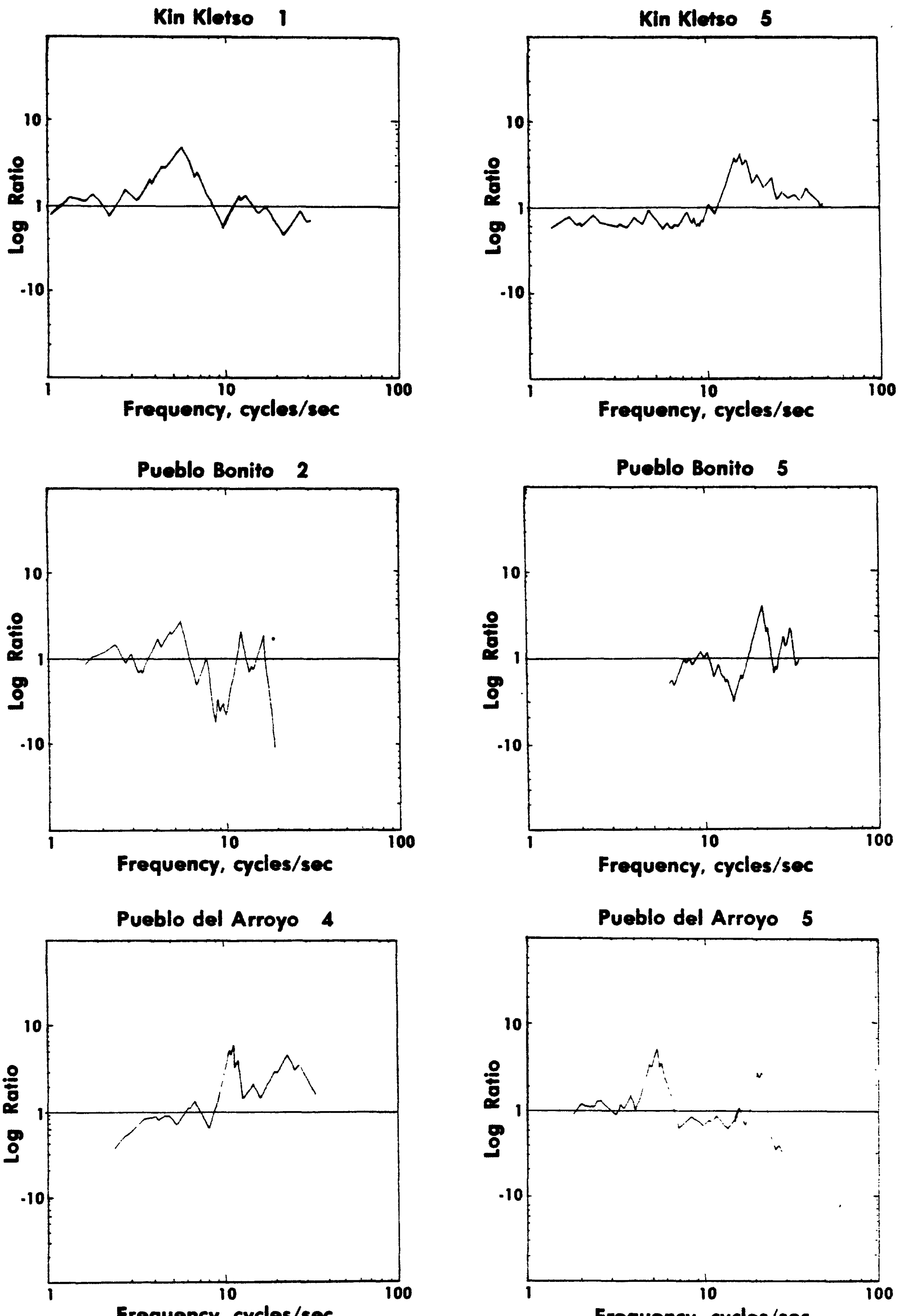

Figure 15.--Amplification ratio A_T/A_B of the top of the wall (A_T) to the base of the wall (A_B) for walls at Kin Kletso, Pueblo Bonito and Pueblo del Arroyo.

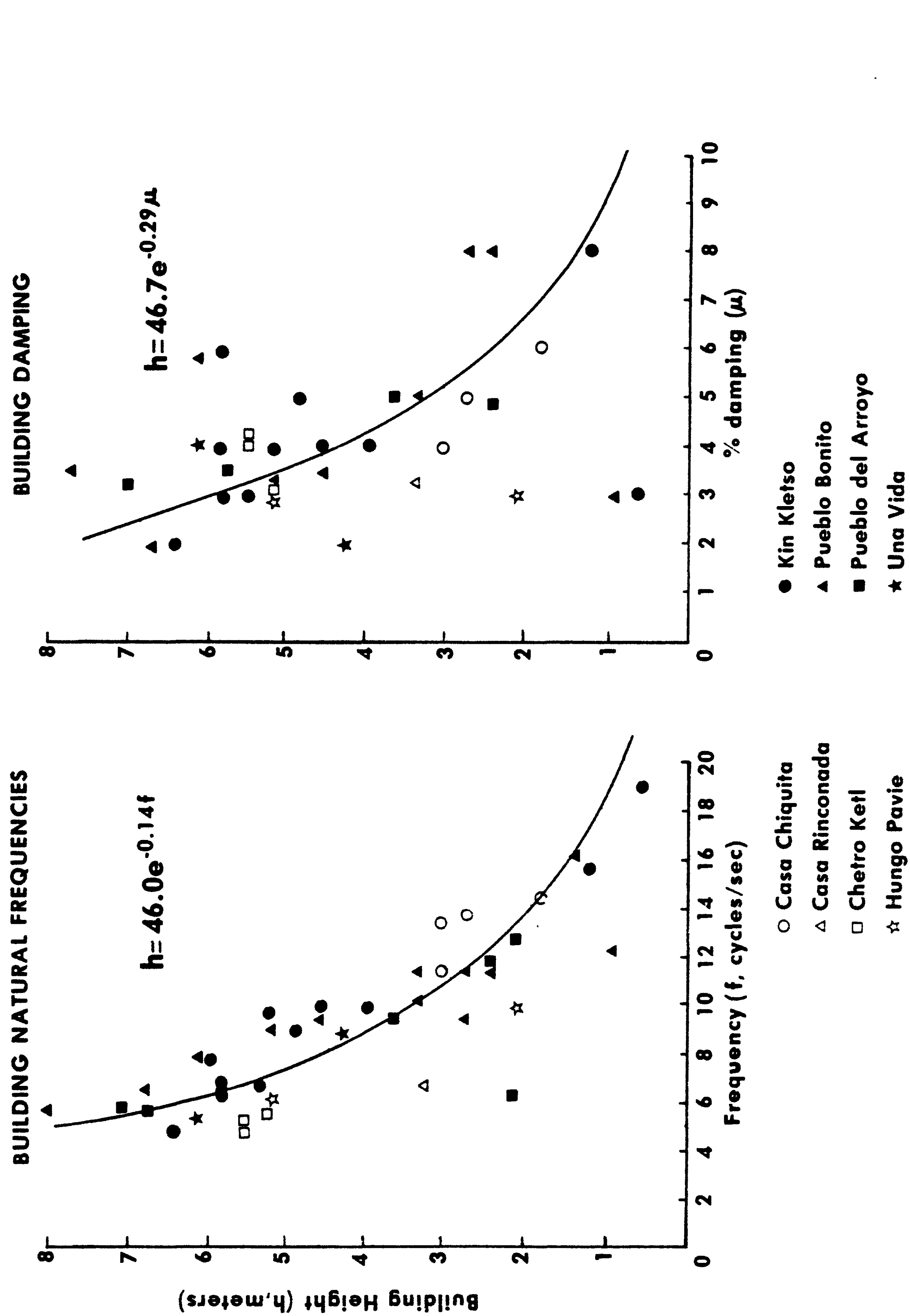

Figure 16.--Relationships among building height, natural frequency and damping for eight buildings.

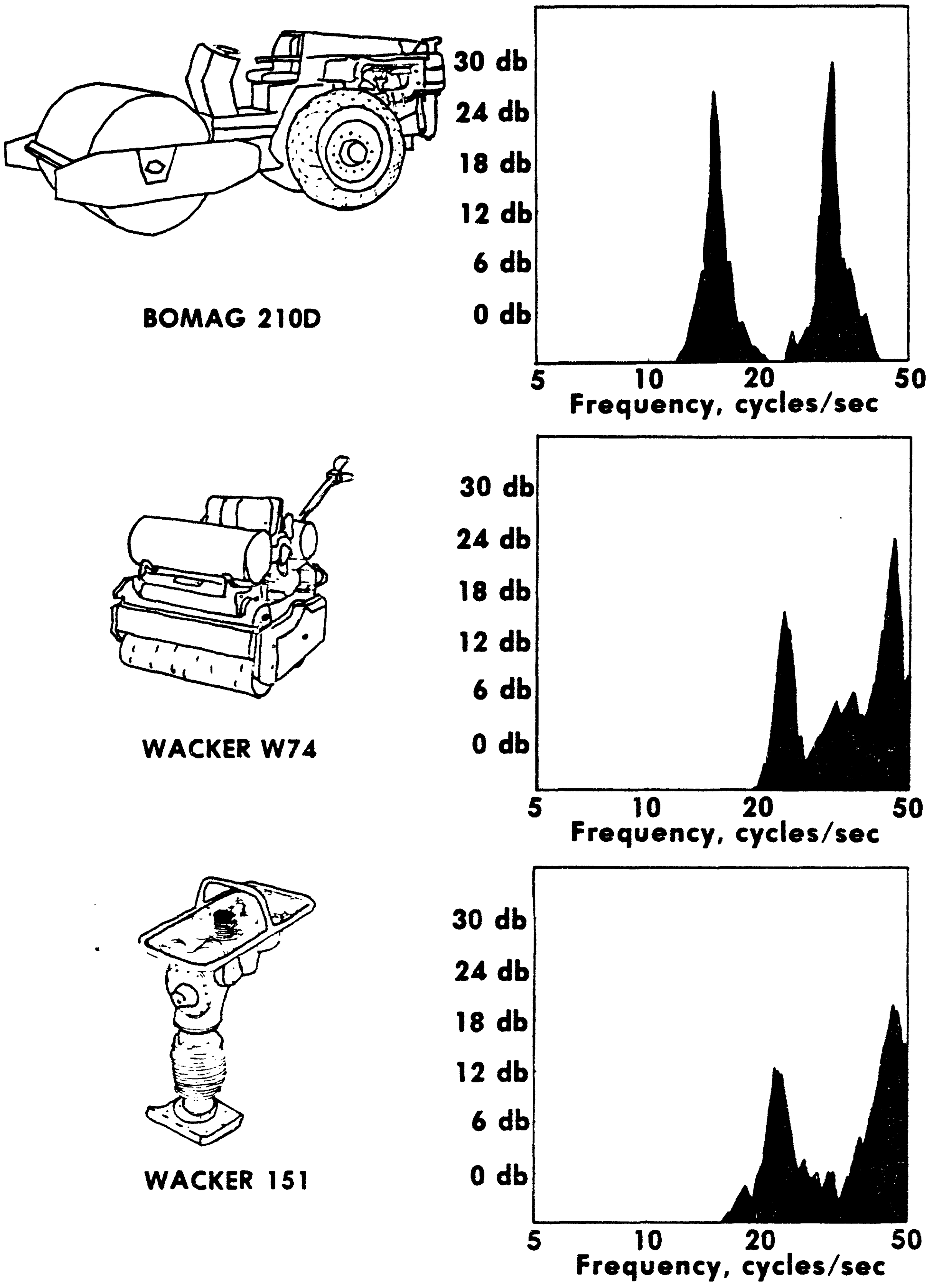

Figure 17.--Induced ground motion at various frequencies for three types of road building equipment.

The range or distance scaling function (attenuation with distance and input force) were derived by linear least squares regression (fig. 18). The induced peak particle ground motion from the compactors attenuates with distance (R) in kilometers with rates of $R^{-1.49}$ to $R^{-1.60}$. The induced peak particle ground motion scales in relation to the input force by factors of $W^{0.65}$ at 55 m and $W^{0.81}$ at 10 m (fig. 19).

Railroads

Three horizontal velocity sensing seismic stations recorded the induced ground motions from a coal-carrying train. The seismic stations were located on a line perpendicular to the track at distances of 0.05 km, 0.2 km, and 1.0 km (fig. 12). The peak particle velocity ground motions induced by the train were analyzed to develop an attenuation scaling function. The attenuation function in the 4.0-6.0 Hz frequency band derived from a linear least squares regression is $R^{-1.04}$ where R is the distance in kilometers from the railroad (fig. 20).

Explosions

Induced ground motion from three high explosions in the Chaco Canyon area and one high explosion from a quarry blast at Gallup, New Mexico, area were recorded.

The induced ground motions from explosions at Chaco Canyon were recorded at Pueblo Alto road junction, at the base and top of a wall at Pueblo Alto, and at the base of a wall at Pueblo Bonito (fig. 13). Spectra and attenuation scaling relations were developed. The peak particle horizontal velocity attenuation function shows an attenuate with distance (R) away from the explosions of $R^{-1.14}$. The scaling attenuation function for size of explosion is $W^{1.19}$, where W is the yield in pounds (figs. 21, 22). The peak frequencies at Pueblo Bonito from explosions are in the 5- to 10-Hz band width. The peak frequencies at Pueblo Alto are in the 5- to 25-Hz band width (fig. 23).

Refraction Study

Surface shallow refraction surveys were made at the southwest side of Pueblo Bonito, the southeast side of Pueblo Del Arroyo, the south side of Casa Chiquita, the north side of Casa Rinconada and the south side of Kin Kletso. A velocity survey was also made on an outcrop of the Cliff House sandstone at Kin Kletso.

The velocity of the seismic signal on the weathered sandstone outcrop is 680 m/sec. The velocities in the sediments ranged from 193 m/sec to 586 m/sec. At Pueblo Bonito a very loose layer of surface sediments approximately 1 m thick is underlain by a firmer layer of sediments at least 10 m thick. Pueblo Del Arroyo is underlain by similar sediments with a less well defined surface layer. The refraction survey at Casa Chiquita indicates that a large flat piece of weathered sandstone present at a depth of 1 to 3 m beneath the structure is similar to that at Bonito and Arroyo. The survey at Kin Kletso and Casa Rinconada indicates that a large discontinuous piece of weathered sandstone is present at a 2 to 4 m depth in the area studied. The sandstone is overlain by sediments similar to those found in the other areas tested. The buried sandstone detected at Kin Kletso outcrops within the southwest corner of the archeological complex (fig. 24).

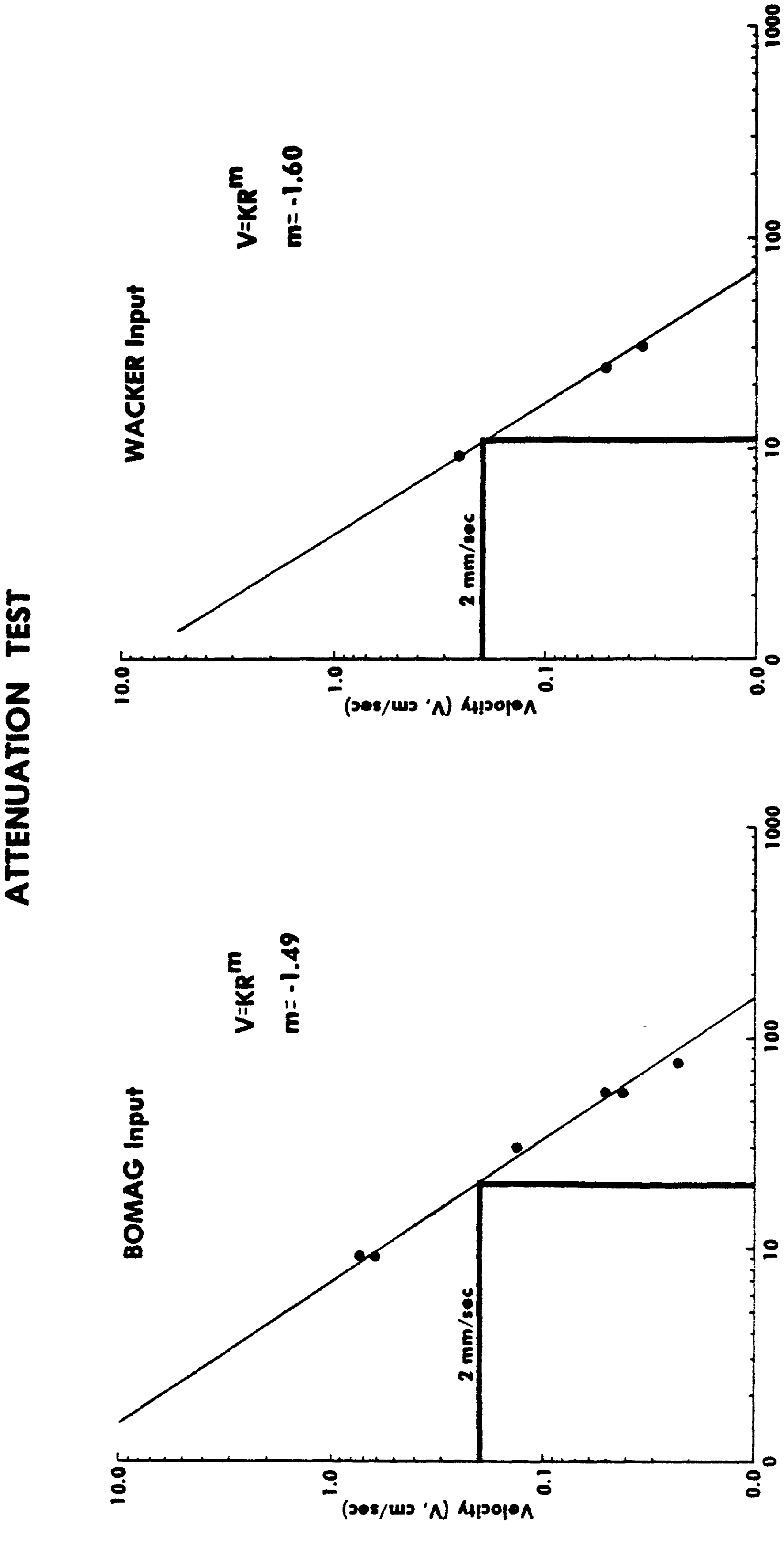

Figure 18.--Attenuation of velocity for typical Bomag and Wacker inputs.

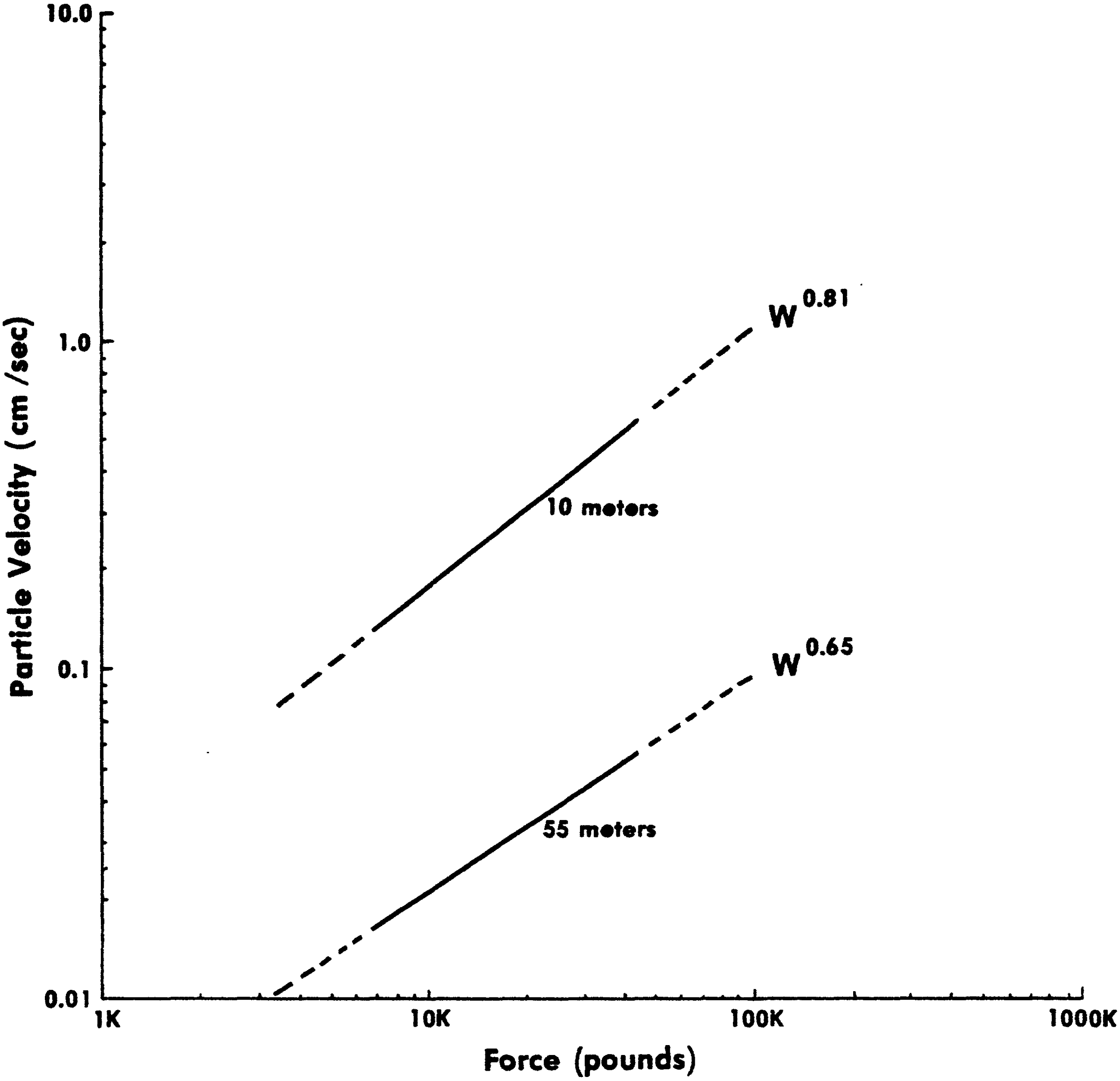

Figure 19.--Ground velocity for various input forces measured at 10 and 55 m from road building equipment.

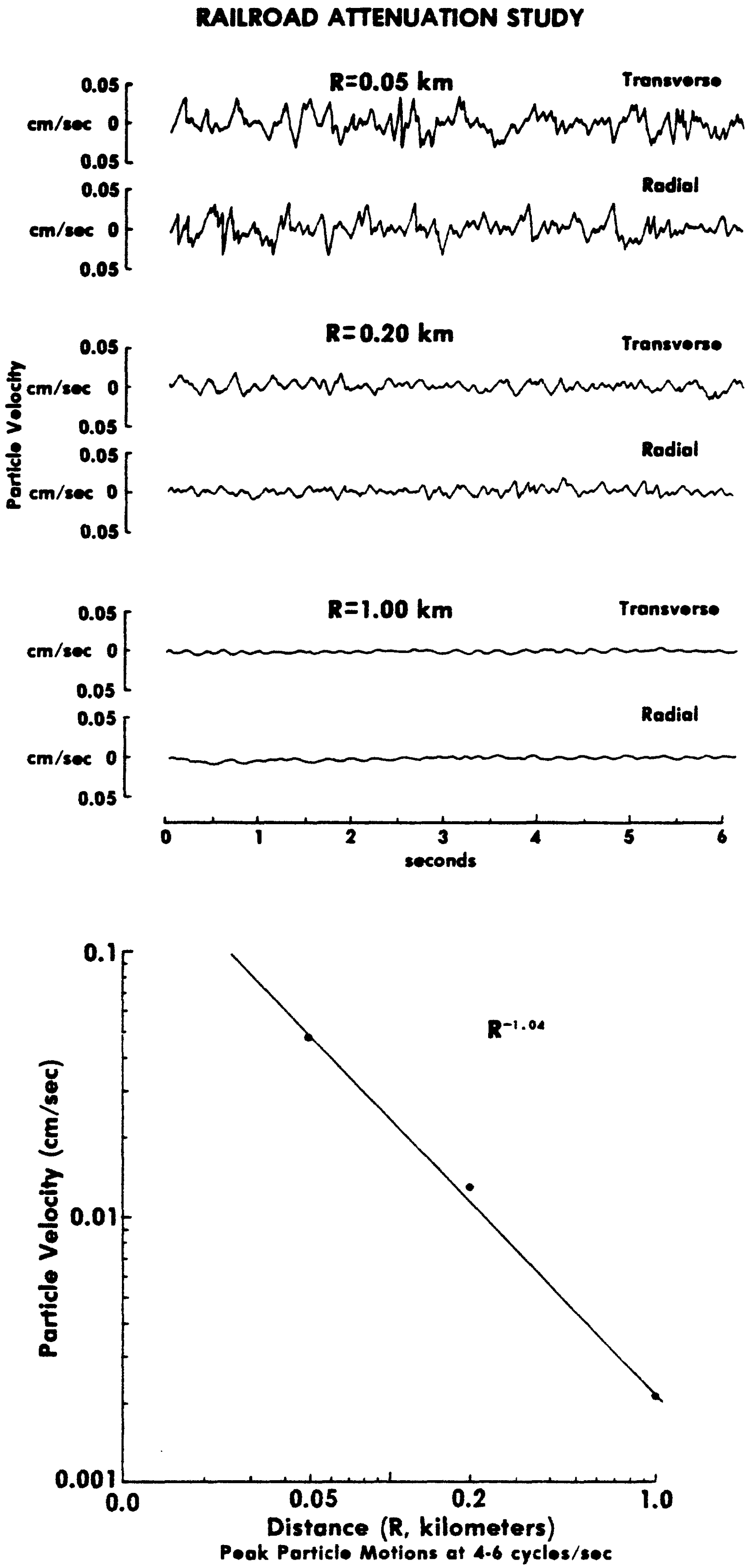

Figure 20.--Attenuation of ground velocity from a coal-carrying train.

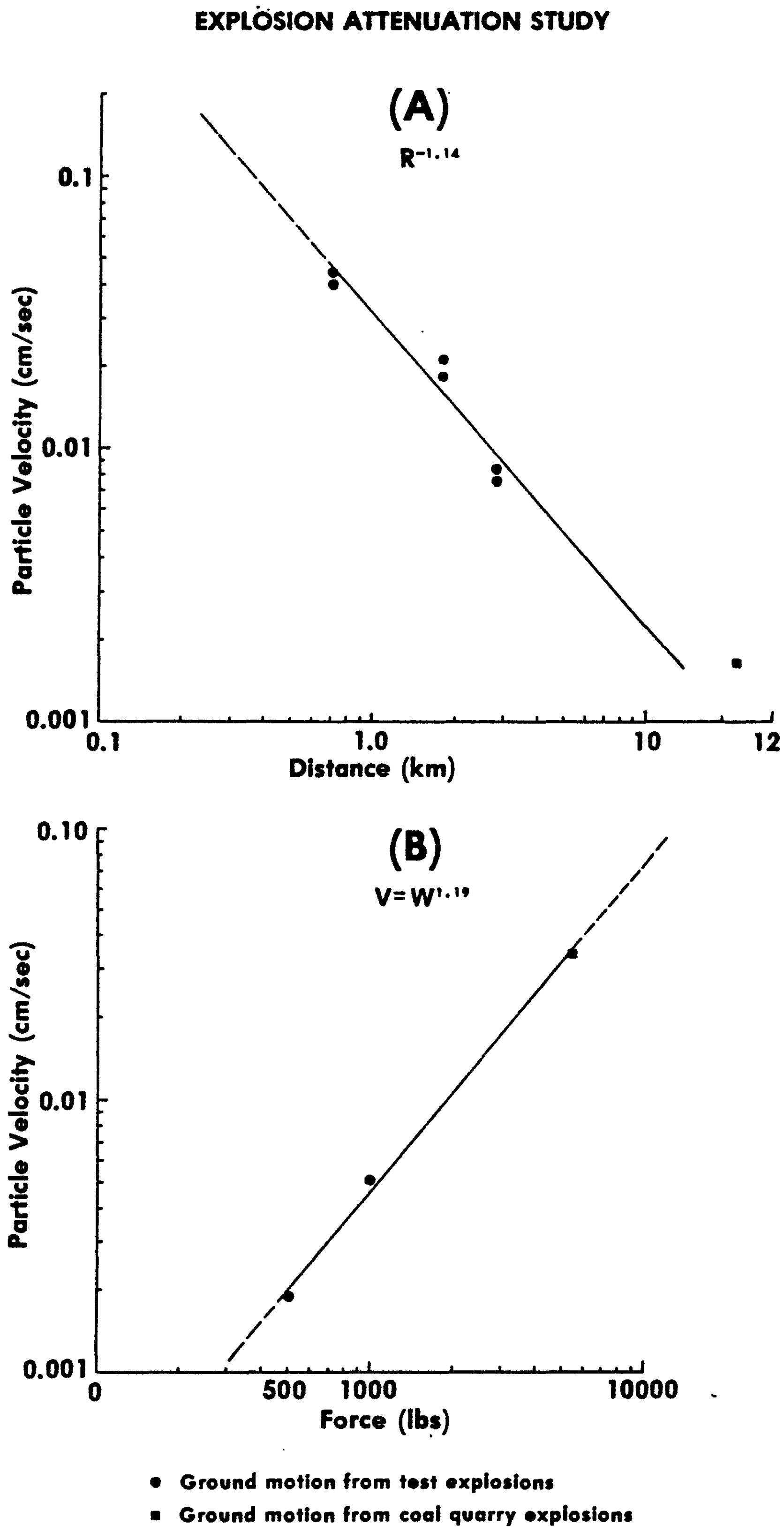

Figure 21.--(A) Attenuation of ground velocity with distance for explosions in Chaco Canyon and a quarry blast at Gallup, New Mexico;
(B) Variation of ground velocity with explosion size.

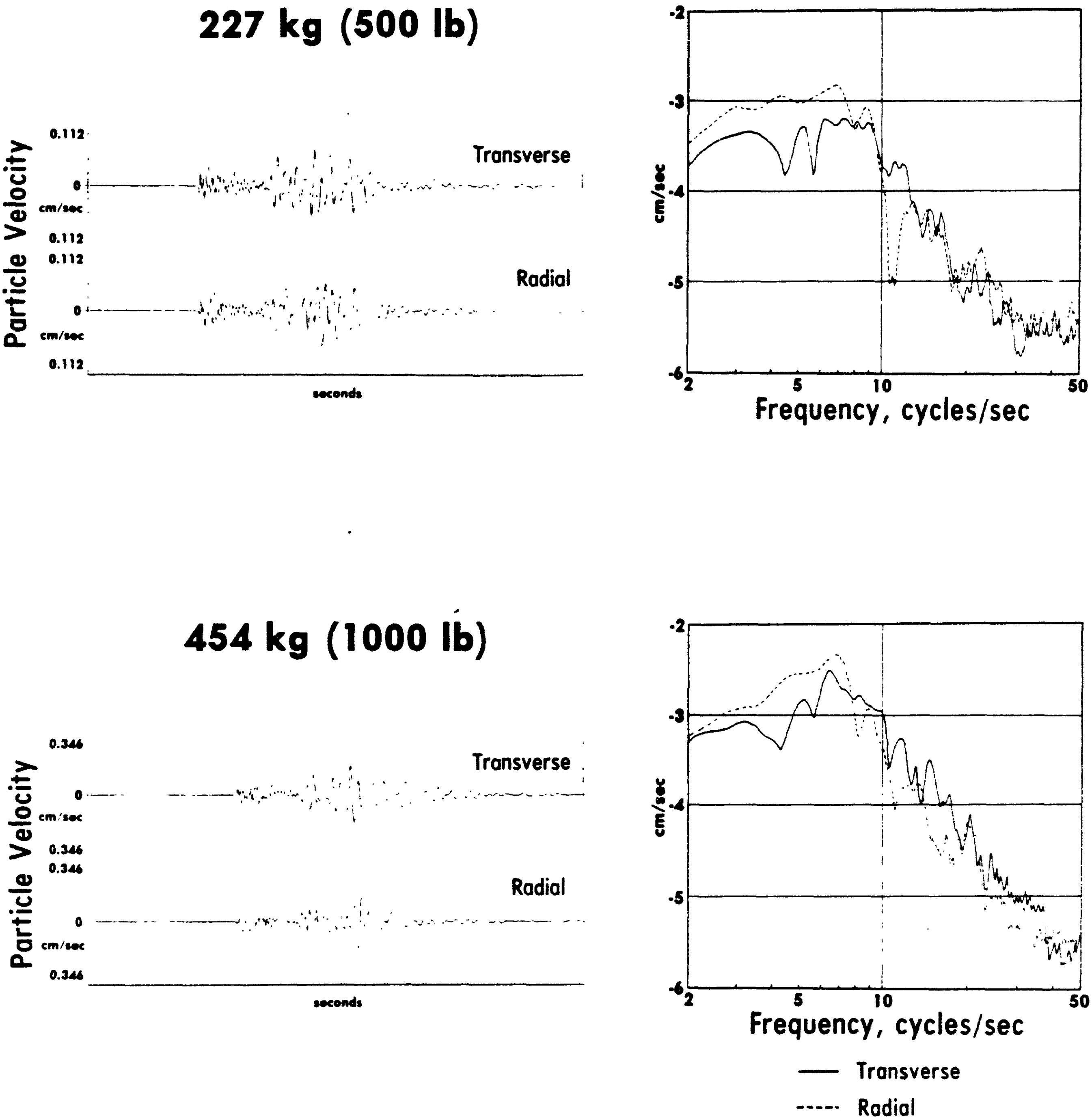

Figure 22.--Spectra at the east wall base of Pueblo Bonito from a 500-lb (227-kg) and a 1000-lb (454-kg) explosion 1.6 km NE. Explosive yield (W) scaling function to peak velocity (V) is $V = W^{1.19}$.

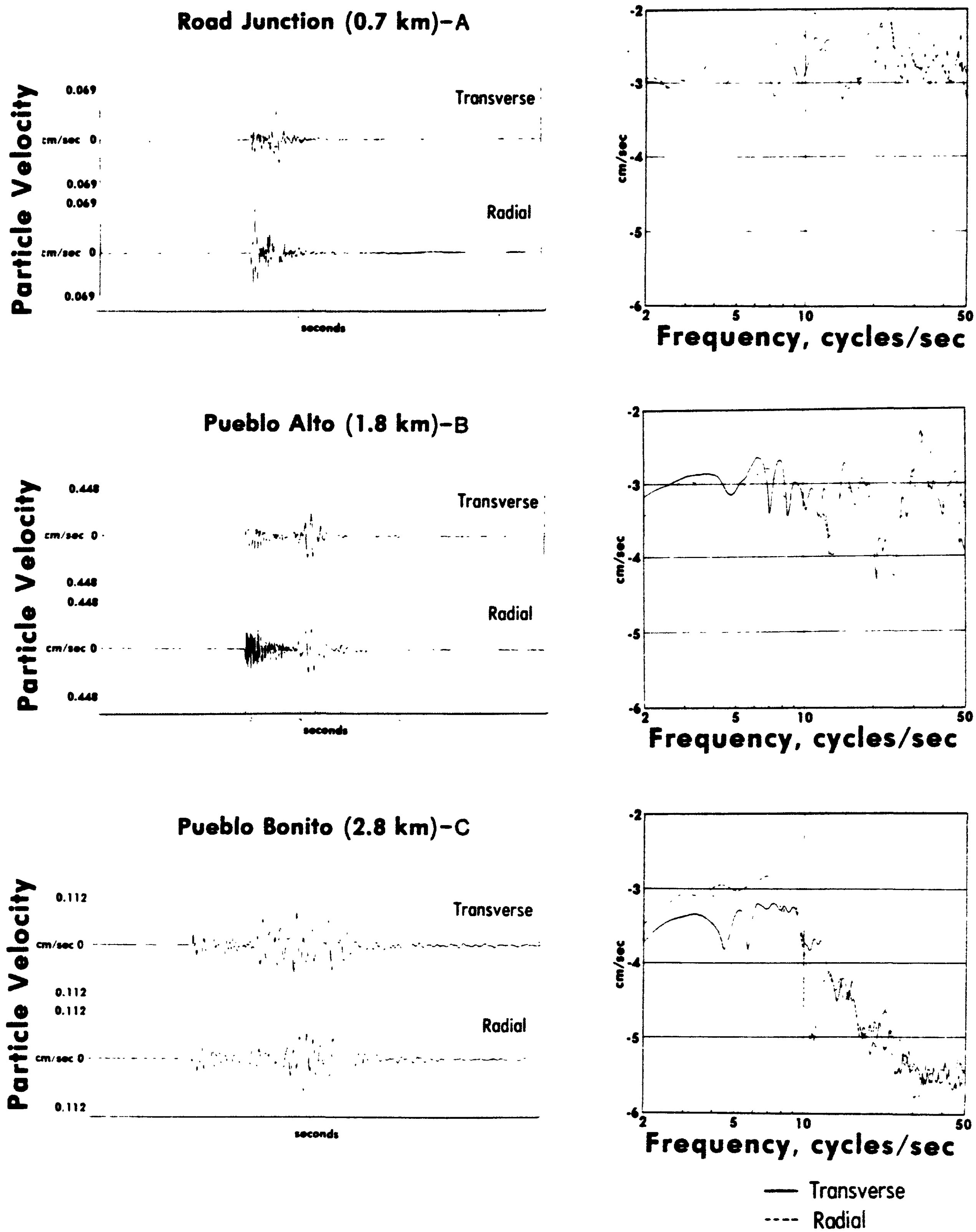

Figure 23.--Spectra at three distances from an explosion of 227 kg.

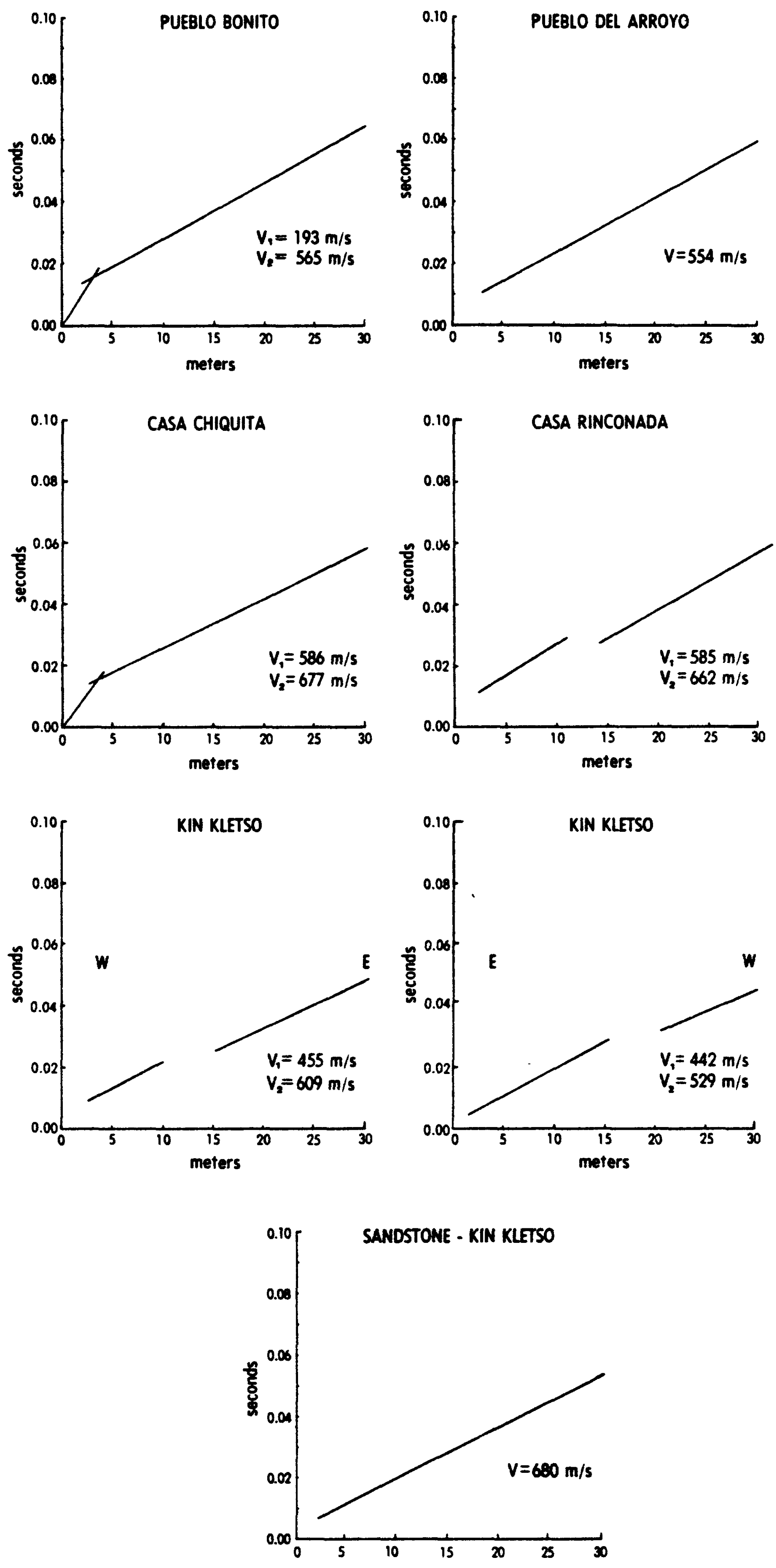

Figure 24.--Travel time curves from refraction studies in Chaco Canyon.

Traffic

Ten samples of induced vibrations from traffic were recorded at a distance of 10 m at Pueblo Bonito and Kin Kletso. Fourier spectra were derived from the 10 seismograms. The spectra derived from the samples of the induced motions were amplitude normalized and then averaged for spectral content. The averaged spectra indicated peaks at 11 and 18 Hz. The variance of the peaks from the spectra were 9.8 to 12.3 Hz and 16.5 to 20 Hz (fig. 25). The maximum peak particle velocity was measured at the Kin Kletso site.

The induced ground motions from a 1-ton pickup camper which rapidly deaccelerated from approximately 15 mph to 0 mph gave the maximum peak particle motion measured. The maximum motion was 2.5 mm/sec at 11 Hz and 1.8 mm/sec at 18 Hz.

Braces

A vibration test was made on the wall brace on the north wall of Pueblo Bonito. The large main brace had a natural frequency of 13.8 Hz and a damping value of 6.8 percent. The natural frequency of the wall that it supports is 2.8 Hz (fig. 25).

DISCUSSION AND CONCLUSIONS

A number of the peak particle velocity motions measured at 10 m from sources induced by the road building equipment and by traffic exceed the recommended maximum ground motion level of 2 mm/sec (fig. 26).

The fundamental frequencies of the walls of the archeologic structures are not, in general, "tuned" to the frequencies of these ground motions that is, they do not have the same natural frequencies as the vibrations resulting from traffic or road building equipment. However, many of the other higher frequencies of the walls are in "tune" with frequencies of the induced ground motions (fig. 27). The Kin Kletso complex has several walls which will amplify the induced ground motions from traffic and construction equipment (fig. 28). These walls as shown from the transfer function tests can magnify the induced ground motion at the base of the walls to the top of the walls by a factor of 3 to 8 with an average magnification of approximately 3 (fig. 15).

The induced seismic motion attenuation functions from the heavy road building equipment and the traffic and light road building equipment indicate that the heavy equipment at 18.2 m distance from the structures, and the traffic and light equipment at 9.1 m distance from the structures, would induce 2 mm/sec peak particle velocity motion at the structure's base (fig. 18). The average supporting wall (wall with a second floor or level) has a motion transfer function from the base to the top of the wall which results in an amplification of 2.5. We therefore recommend that the operating heavy equipment be kept at least 45 m from the structures, and the traffic and light operating equipment be kept at least 25 m from the structures (figs. 29, 30.)

The road at Kin Kletso is approximately 7 m from the structure. Since the road can not be rerouted away from the structure, we recommended the following.

(a) Add a rock bed of at least 10 cm depth using rock 2-4 cm in diameter over the existing road. The rock bed should be overlain by a smooth asphalt base road. The rock base and smooth road should extend approximately 15 m on each side of the structure.

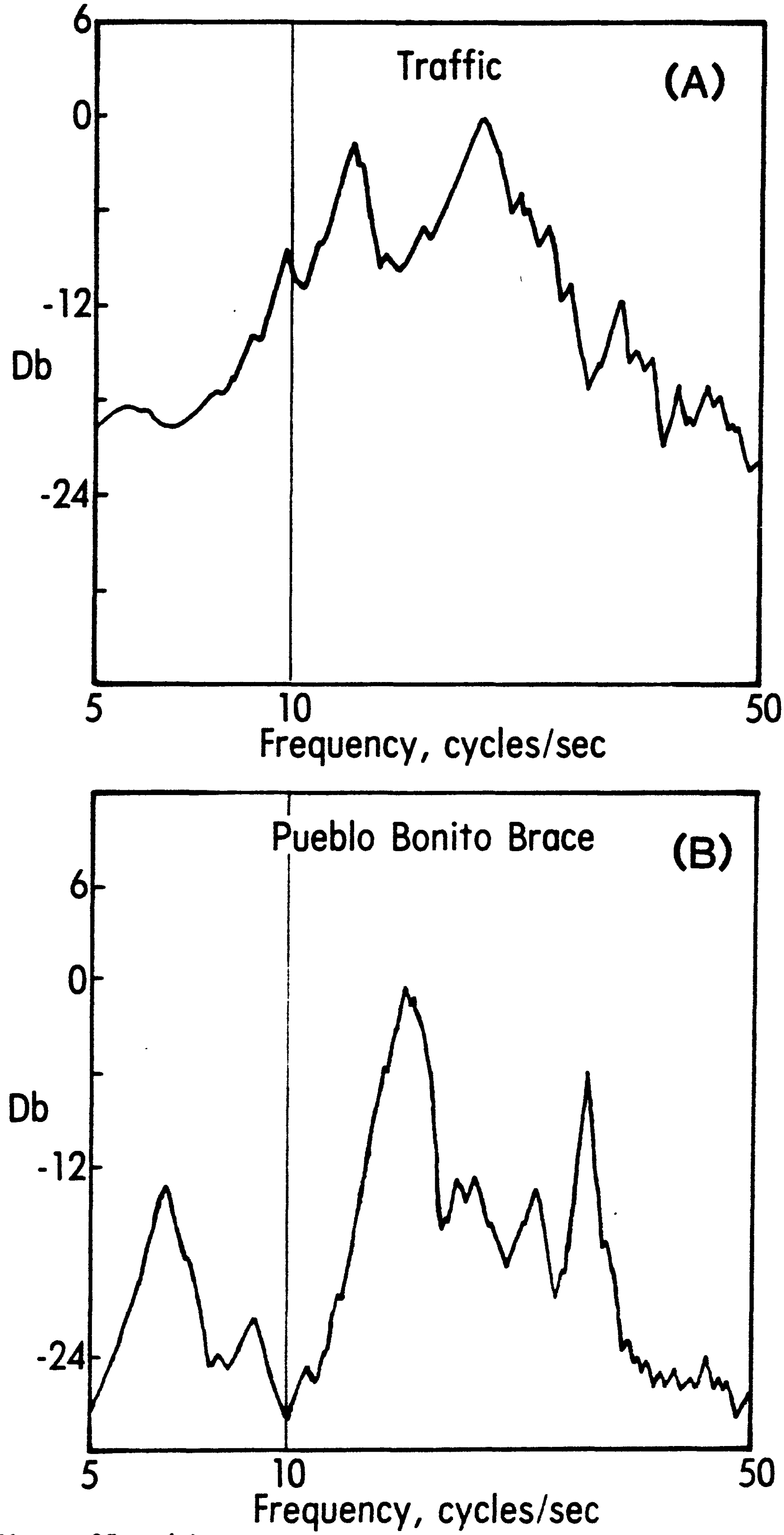

Figure 25.--(A) Averaged traffic spectra.
(B) Vibration test/spectra of Pueblo Bonito north wall brace.

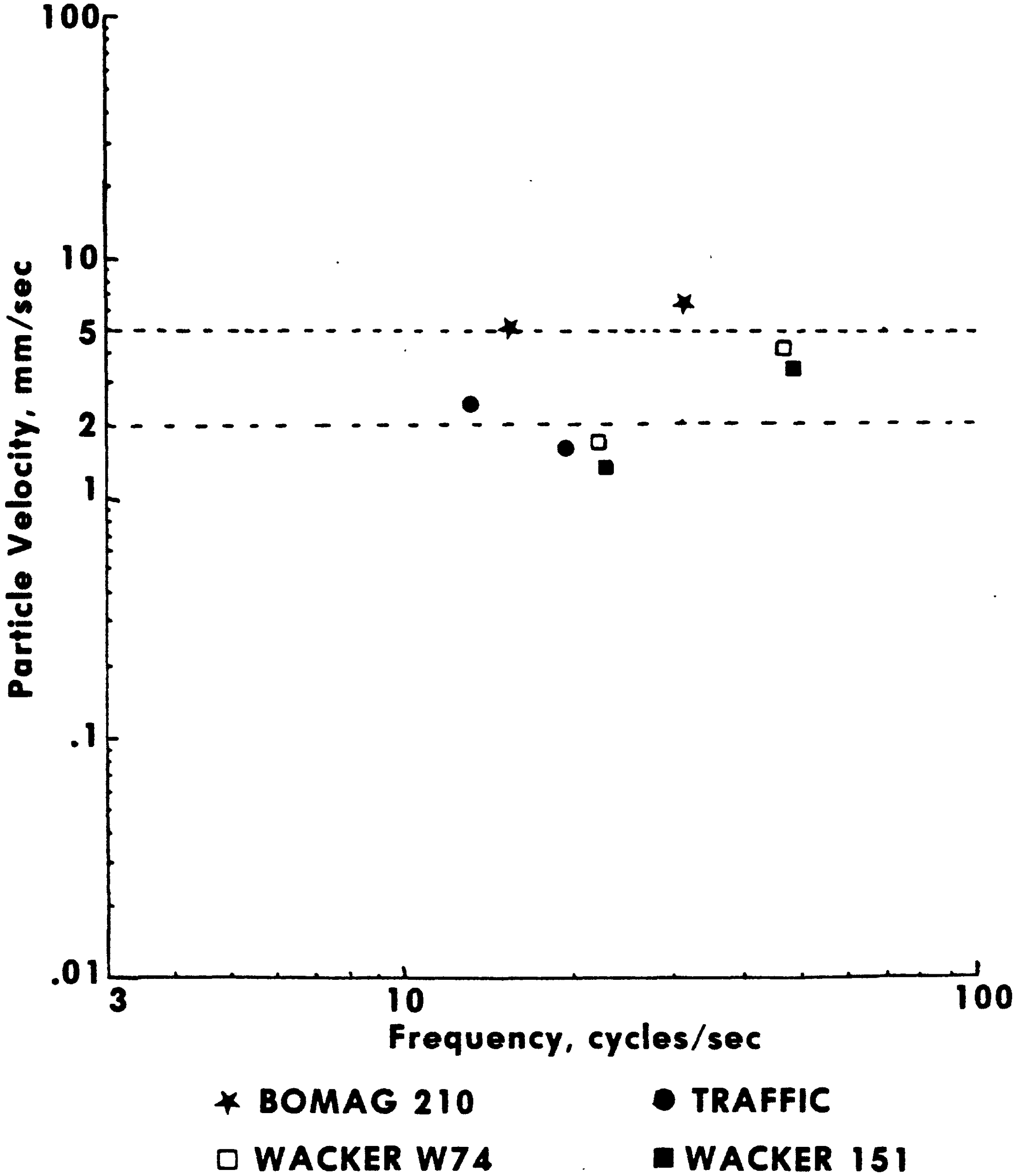

Figure 26.--Peak horizontal ground velocities at a distance of 10 m from four different types of road building equipment.

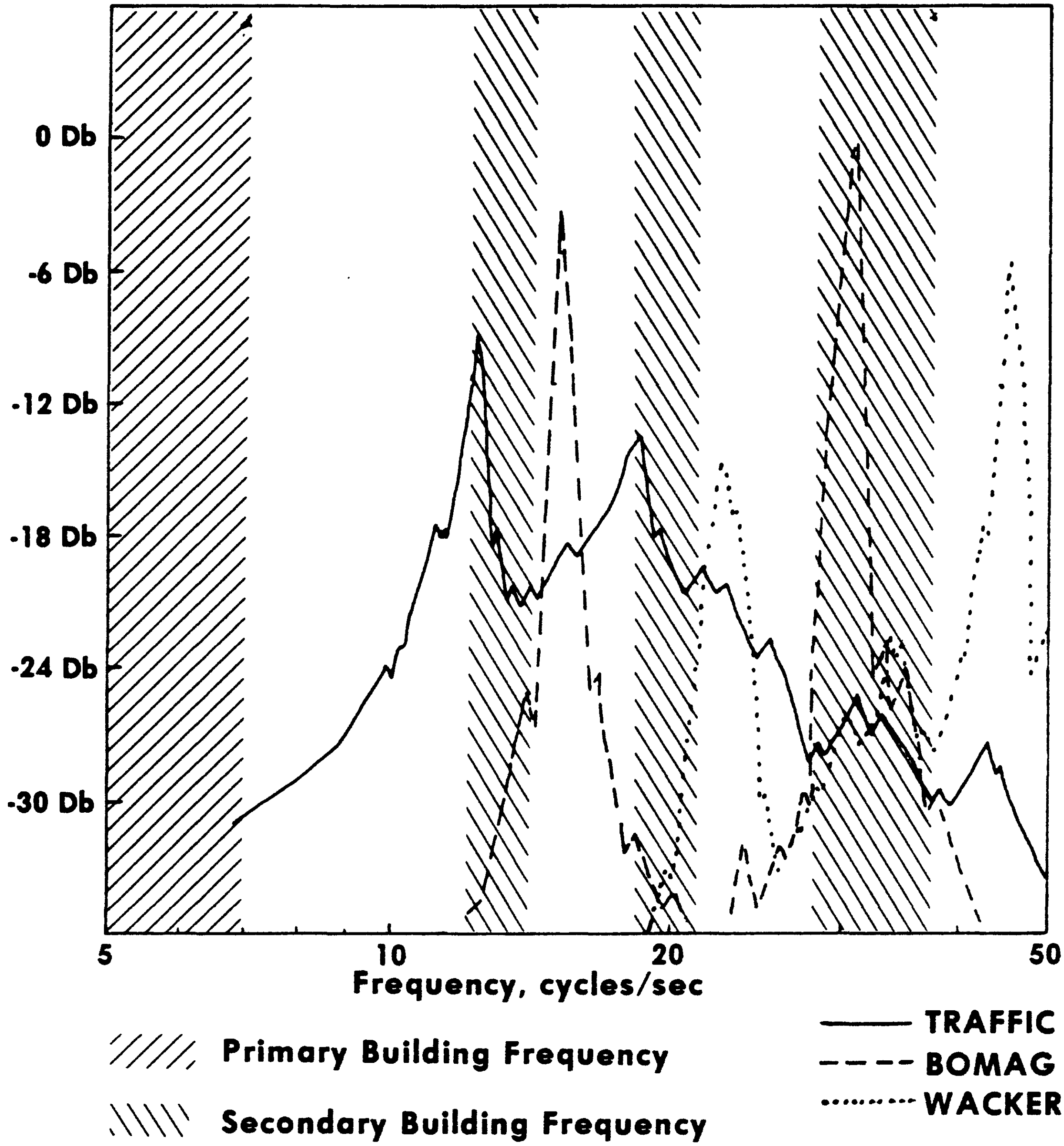

Figure 27.--Spectra of average induced horizontal ground motion from traffic and road building equipment at 10 m and the primary and secondary natural frequencies of the walls.

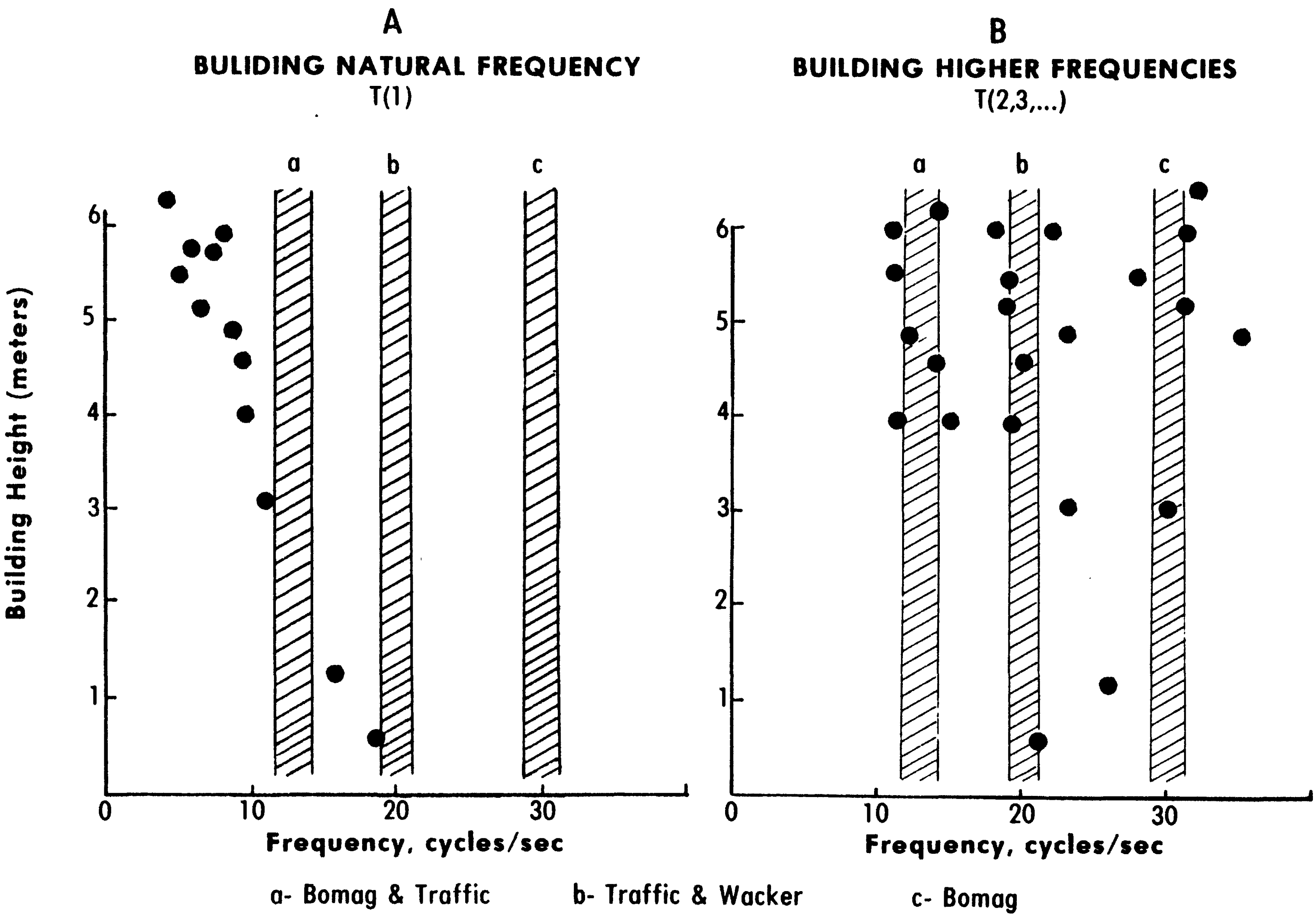

Figure 28.--(A) Comparison of frequency of induced ground motion with fundamental (first) frequency of vibration of the buildings (solid circles).
(B) Comparison of frequency of induced ground motion with higher frequencies of vibration of the buildings (solid circles).

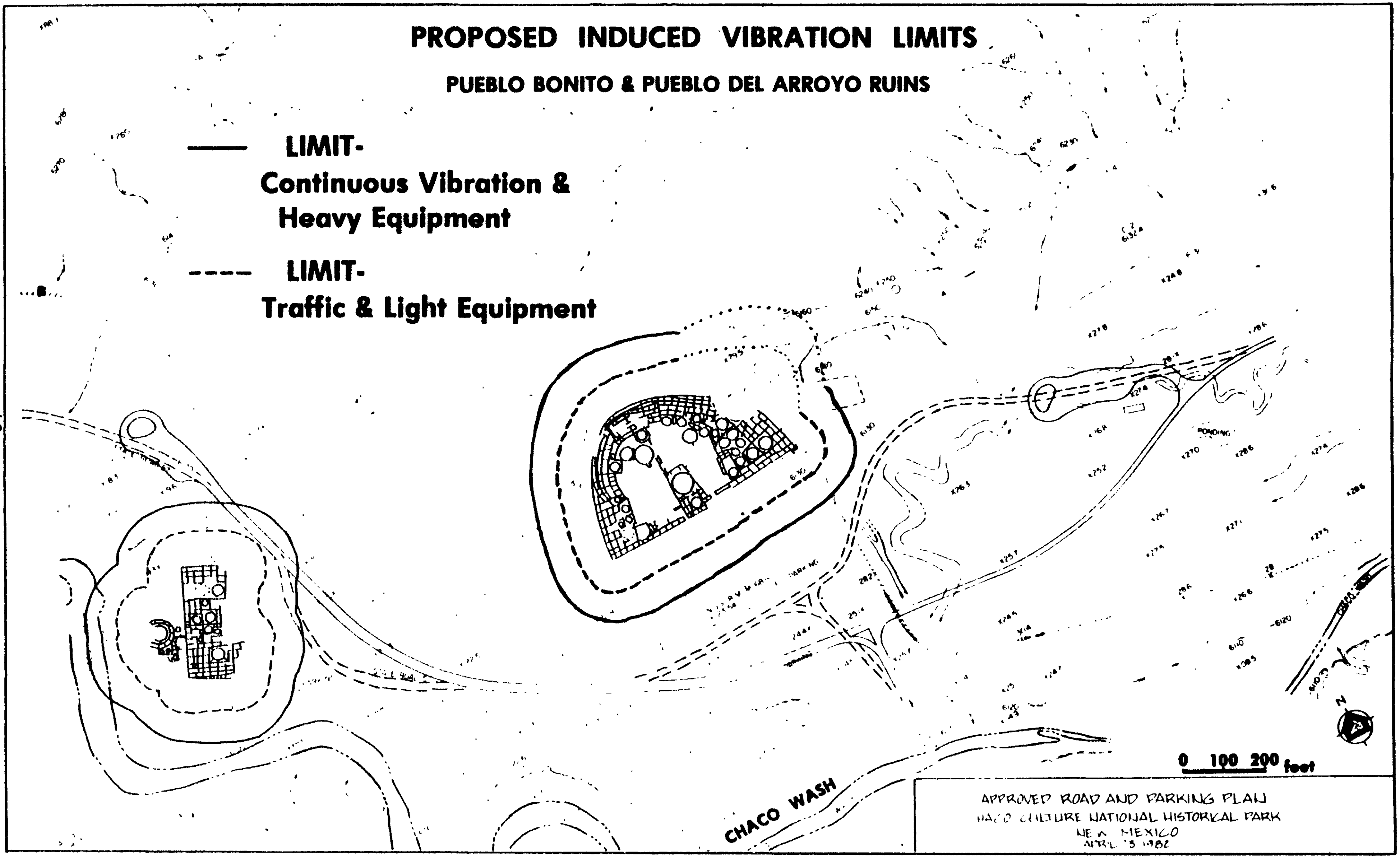

Figure 29.--Recommended minimum distances for road building equipment and traffic.

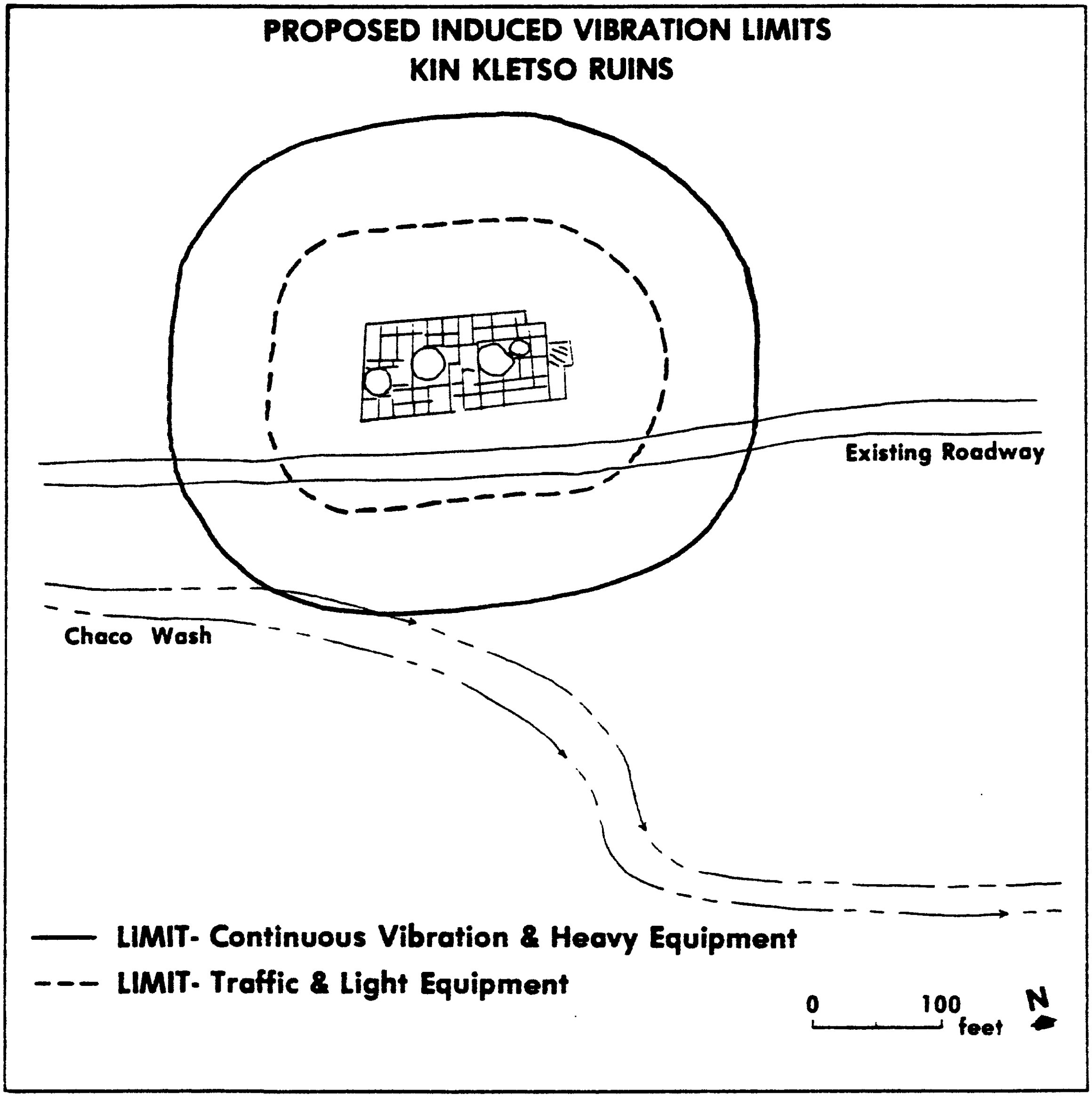

Figure 30.--Recommended minimum distances for road building equipment and traffic.

(b) No heavy equipment is to be used within 45 m of the structure.

(c) Traffic should be controlled within 45 m of the structure with no parking lots located within 45 m of the structure.

Induced seismic motion tests were made on the existing road before and after the rock base and asphalt topping were added. A 36-kg weight was dropped from a height of 1.5 m onto the middle of the old unsurfaced road and the rock underlain asphalt topped road (fig. 31). The peak particle ground motions recorded 10 m from the road indicate that the rock and asphalt veneer on the old road lessened the induced motions at 10 m by approximately 45 percent. This percentage reduction of motion is enough to lessen induced motions from controlled traffic to a value below 2 mm/sec peak particle ground motions, but light road building equipment such as "wackers" induced motions would be marginal and should not be used.

The seismic attenuation scaling functions of the induced ground motions from the explosions show that a 445-kg subsurface explosion should be at least 1.2 km for any pertinent archeological ruin in Chaco Canyon. A 2,225-kg subsurface explosion should be no closer than 6.3 km and a 4,450-kg subsurface explosion should be no closer than 13 km from the ruins (figs. 27, 28). A surface explosion would introduce an acoustical wave that under certain weather conditions may cause superficial damage to veneered surfaces of the archeological sites.

The seismic data from the ground motions induced by a loaded coal carrying train indicate that a similar type of railroad could operate within 1/2 km of the ruins (fig. 20). However, the operation for building the railroad, as with road construction, would need a vibration study to establish the proper allowable types of equipment and operation ranges before construction or rights-of-way are permitted.

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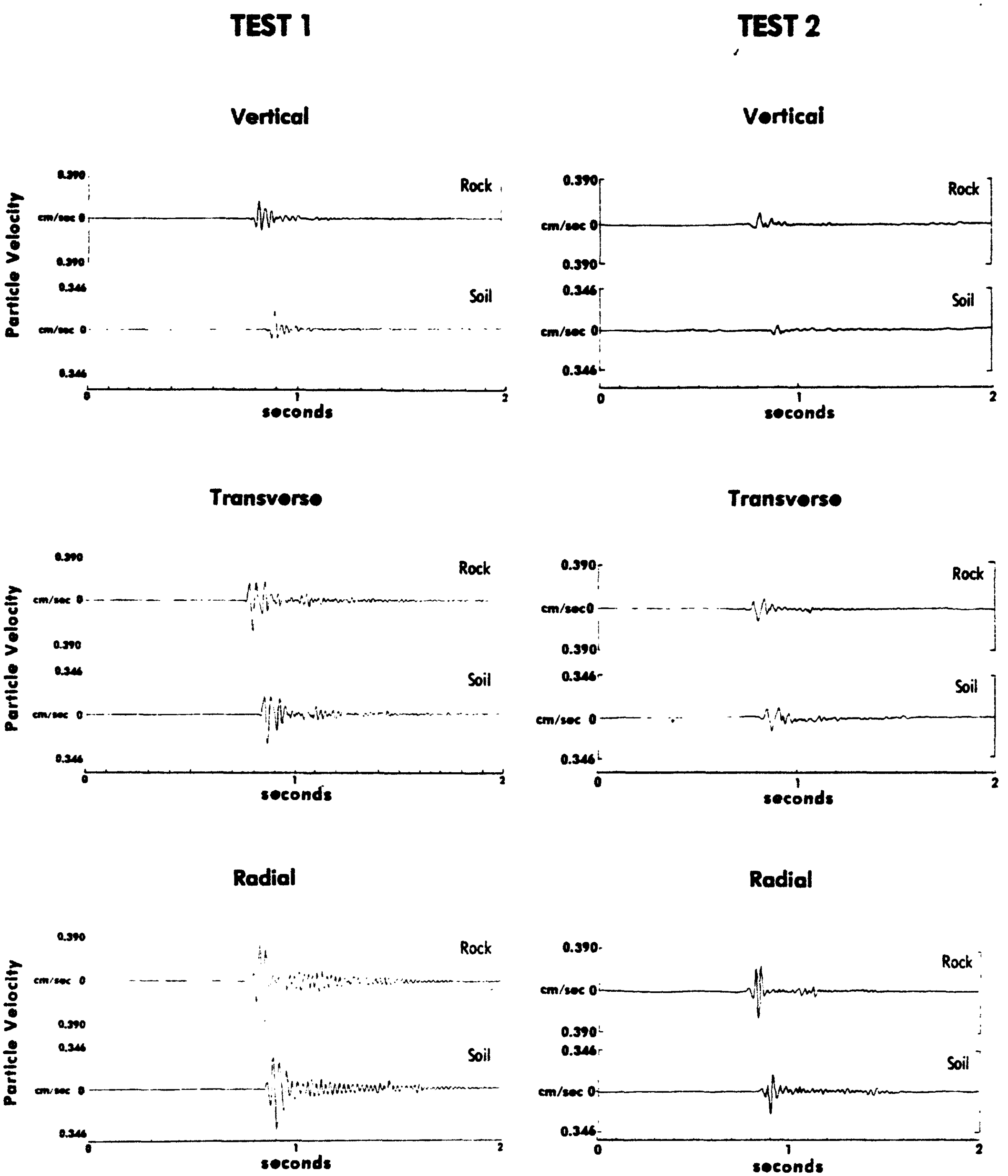

Figure 31.--Ground velocity resulting from a 36-kg weight drop recorded at Kin Kletso, 10 m from the drop. The 36-kg weight was dropped from a height of 1.5 m in the middle of: (1) an unsurfaced road; and (2) a rock underlain asphalt topped road.

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APPENDIX OF

BUILDING VIBRATION TESTS

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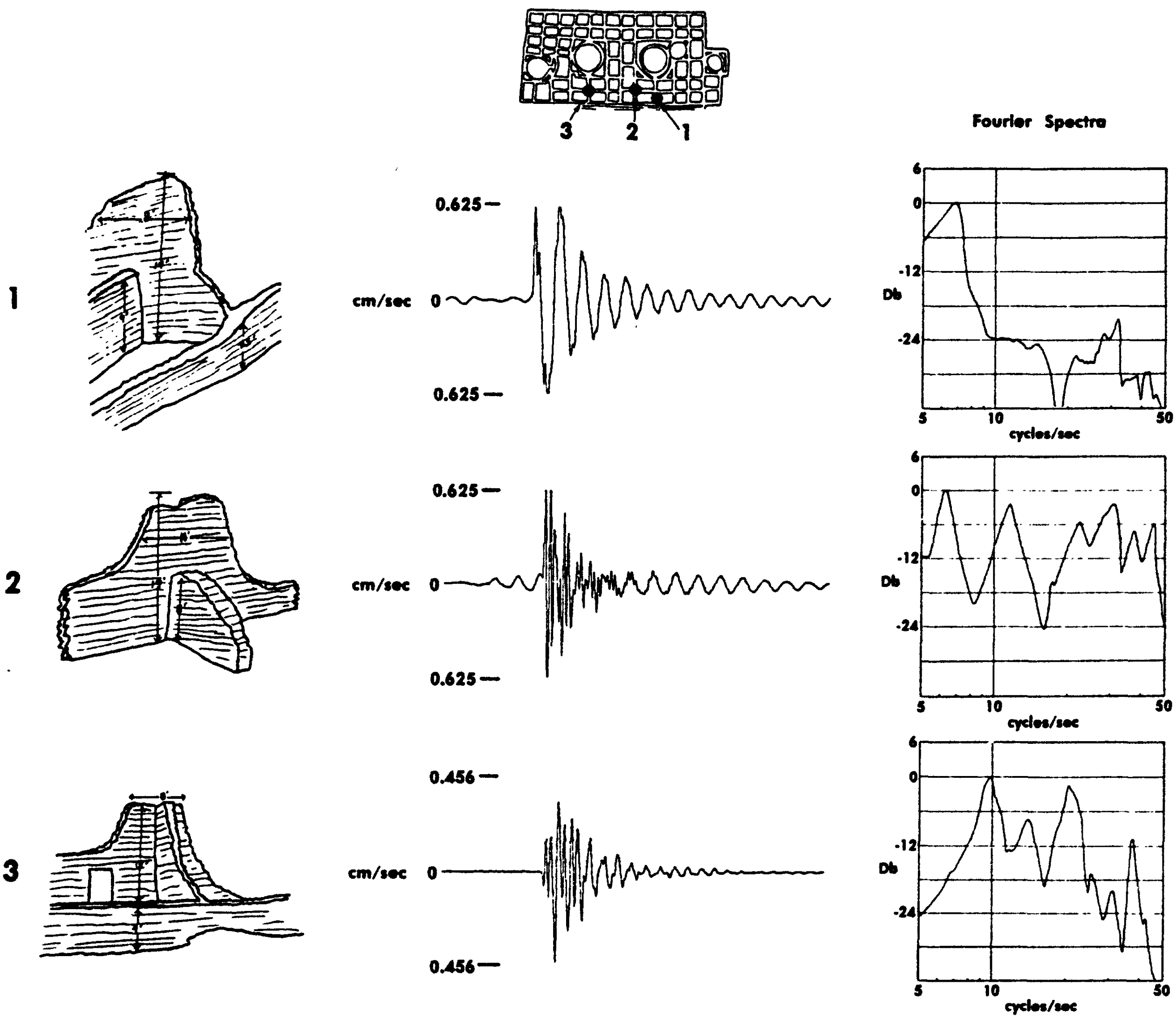
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-24
Db
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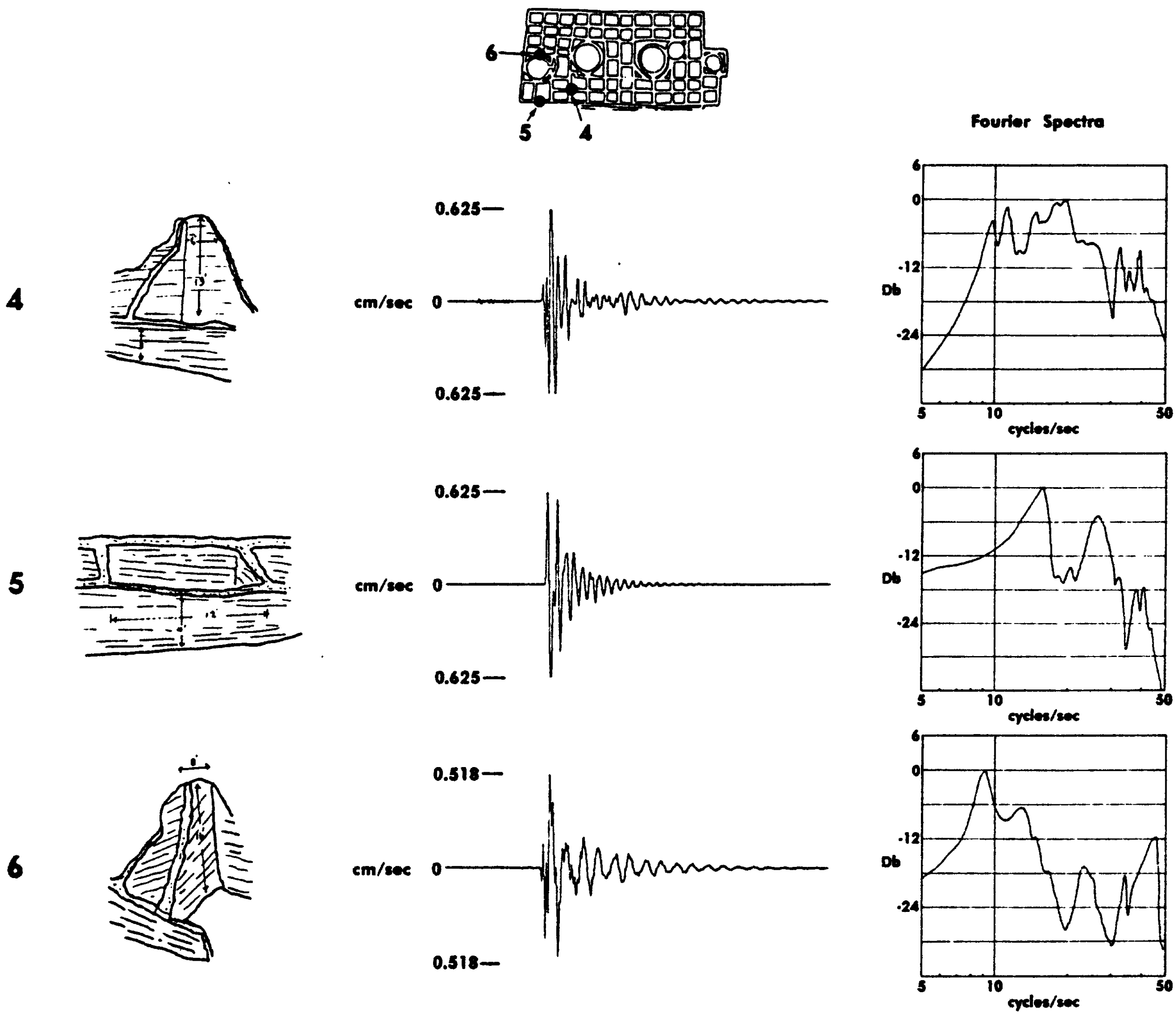
cycles/sec

KIN KLETSO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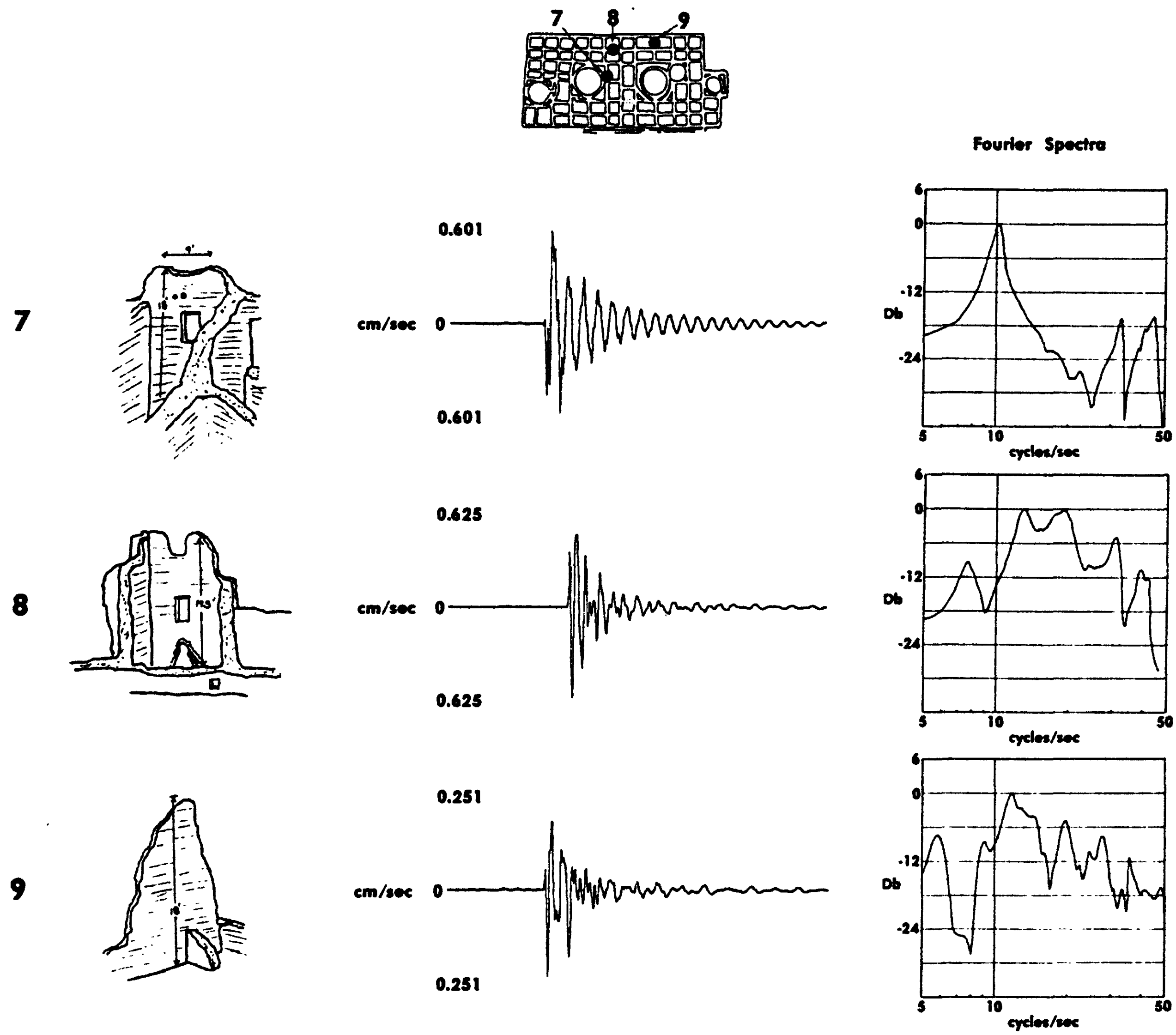
cycles/sec

KIN KLETSO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cycles/sec

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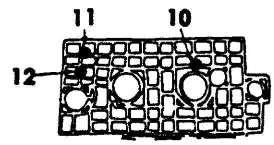
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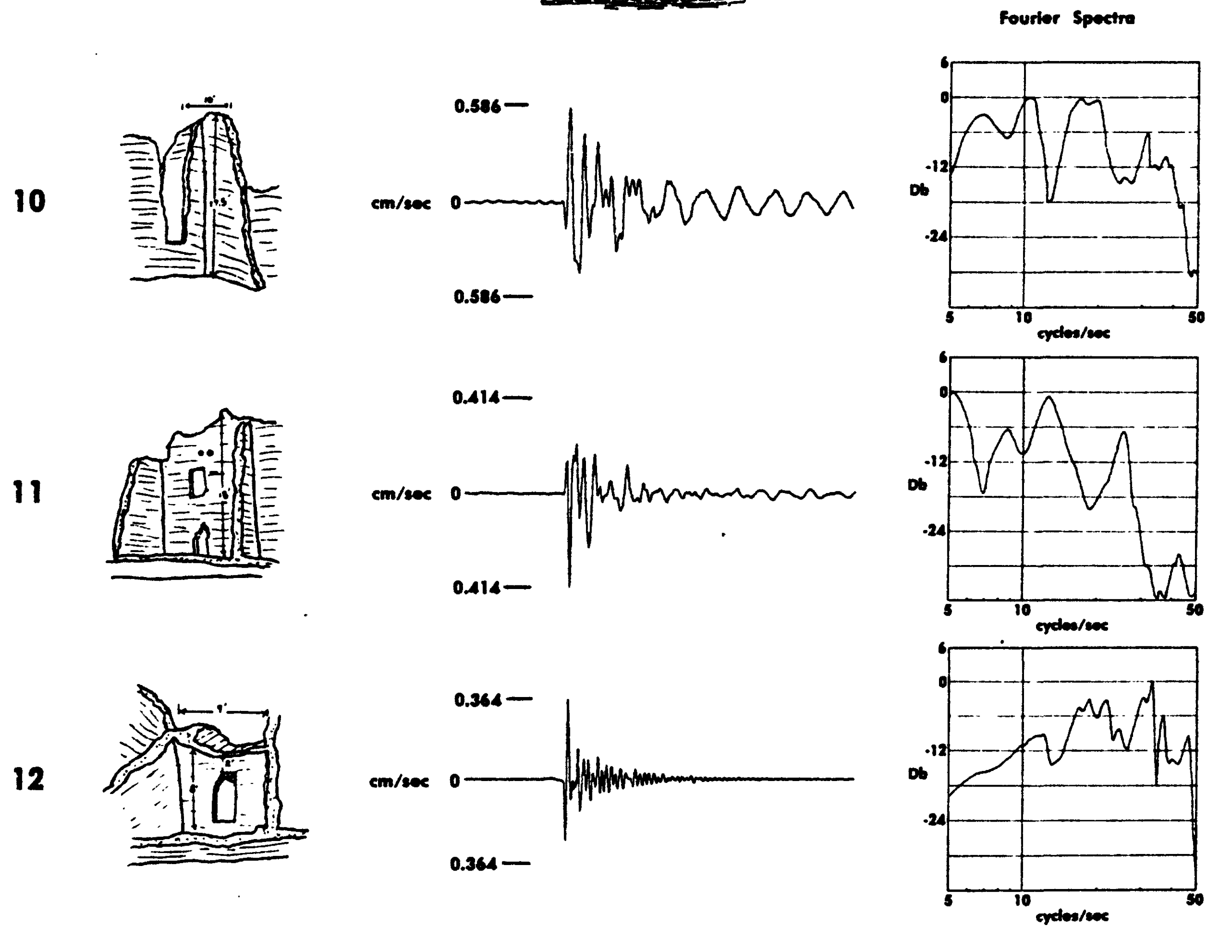
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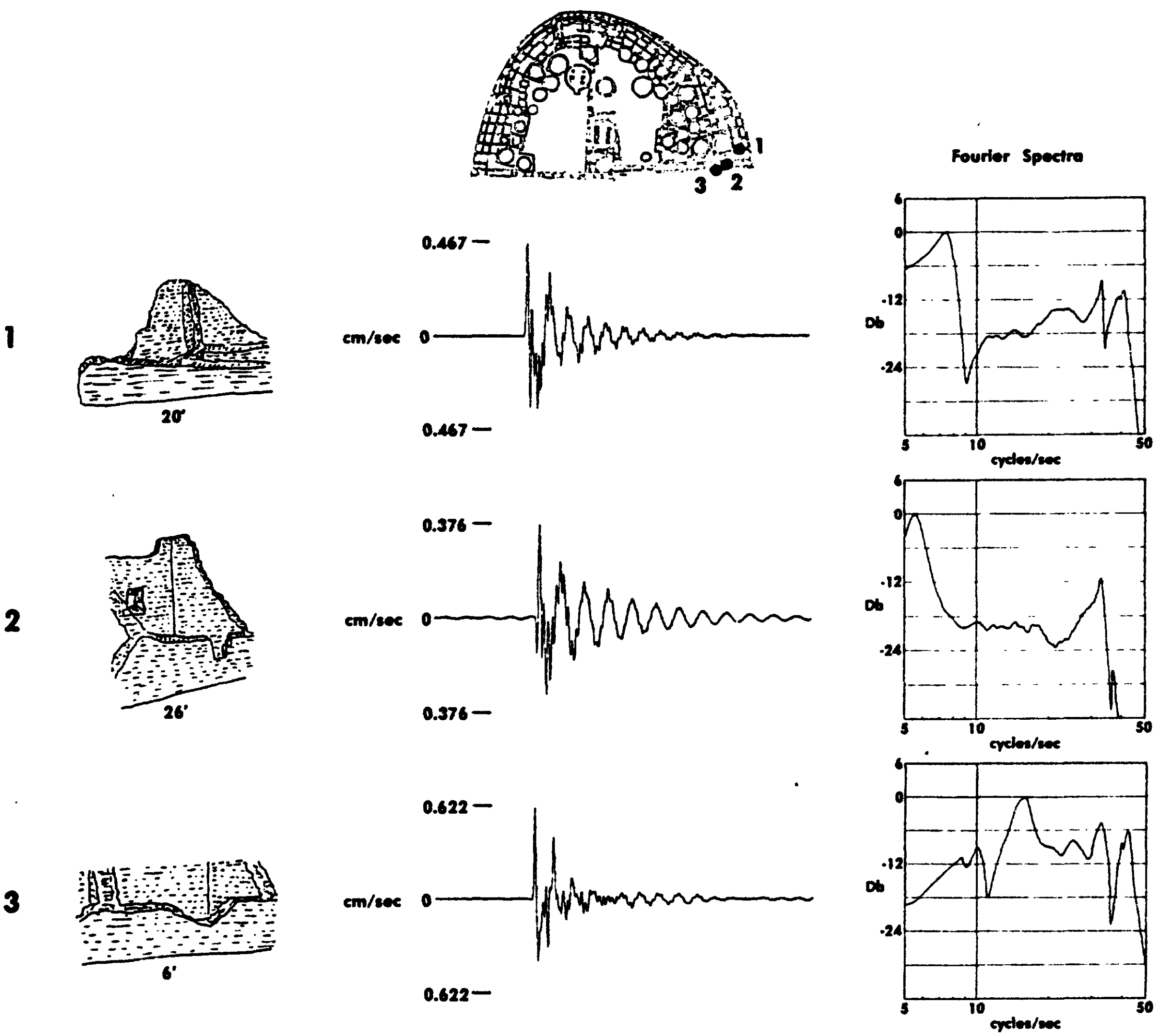

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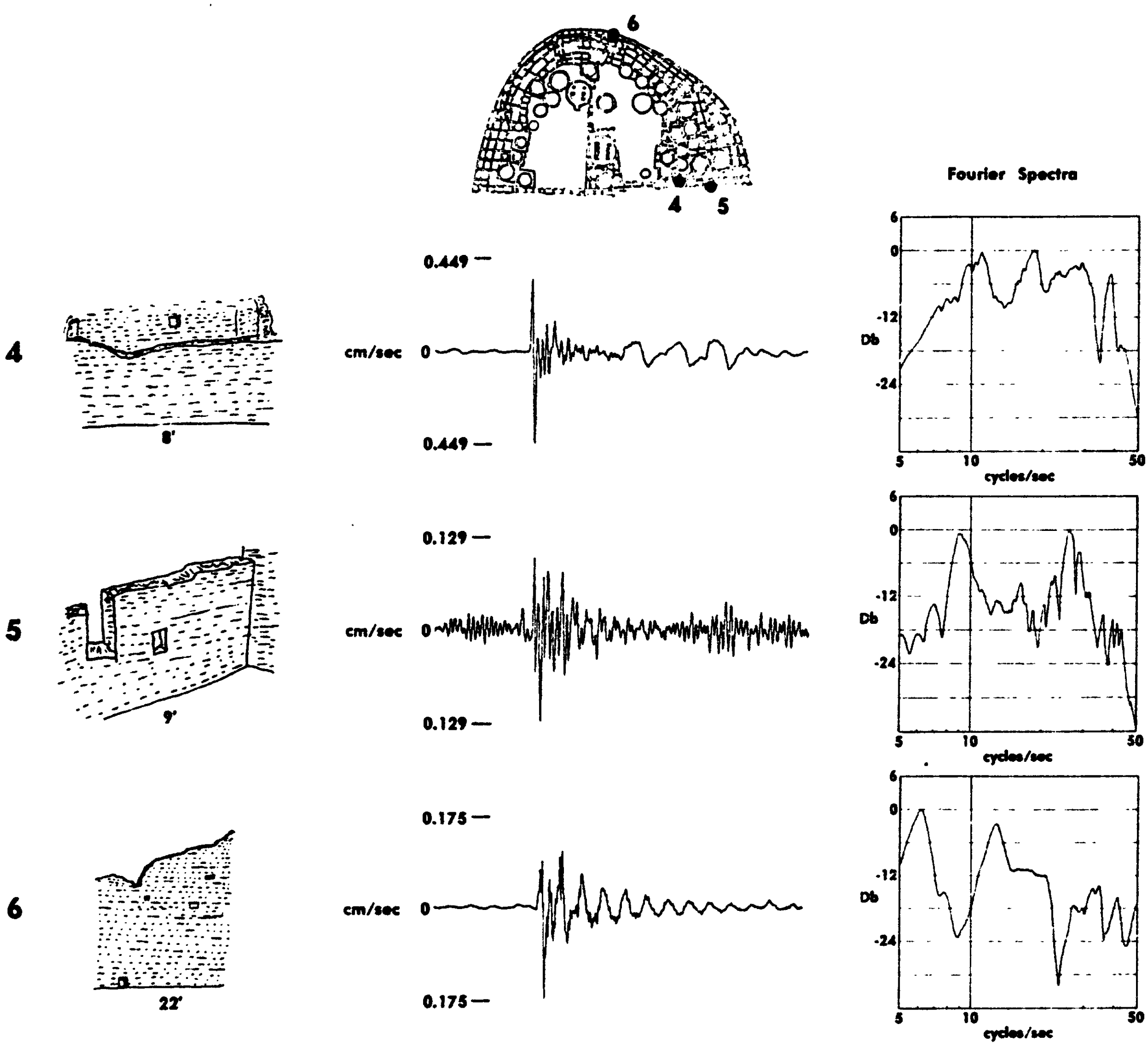

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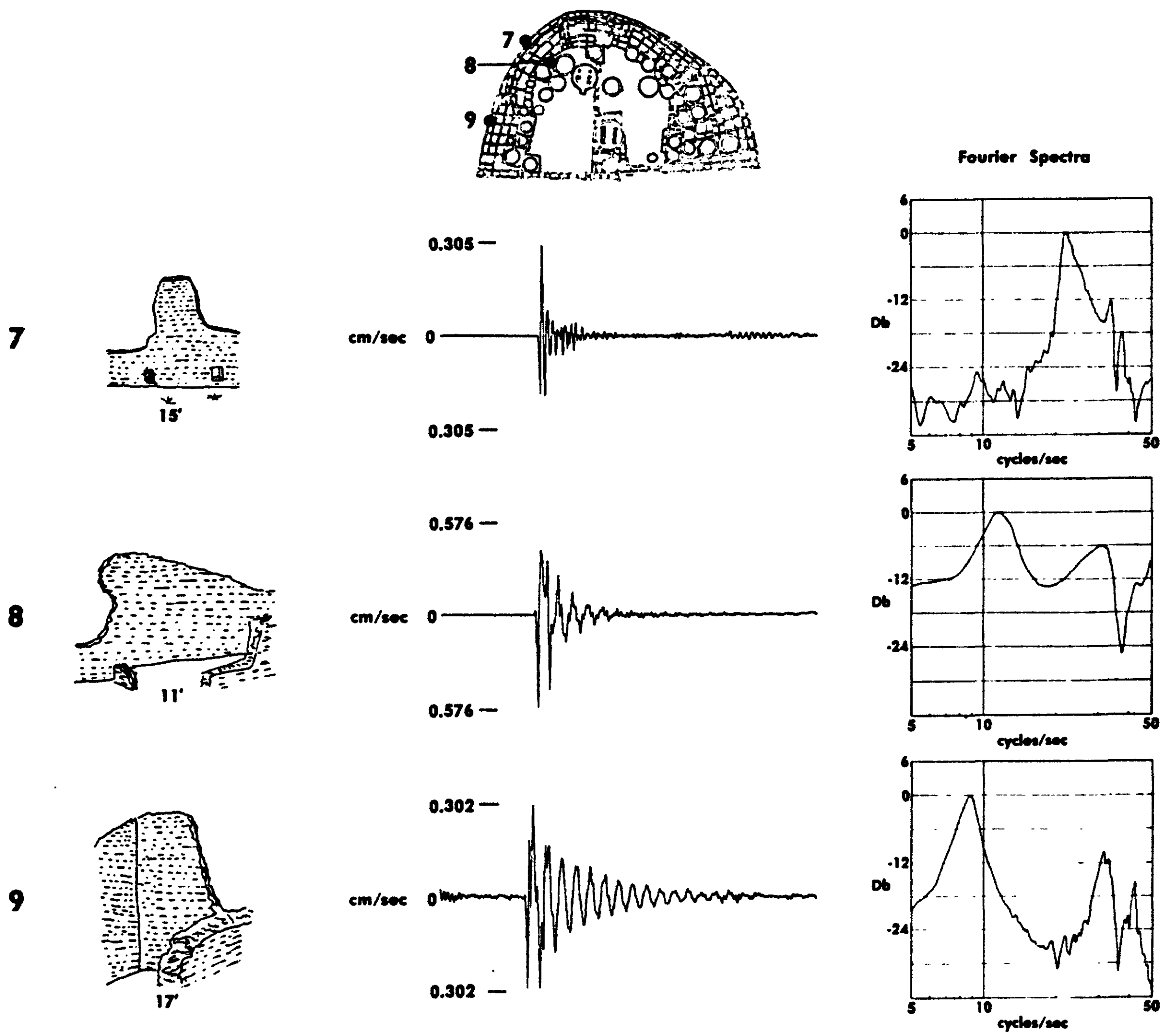
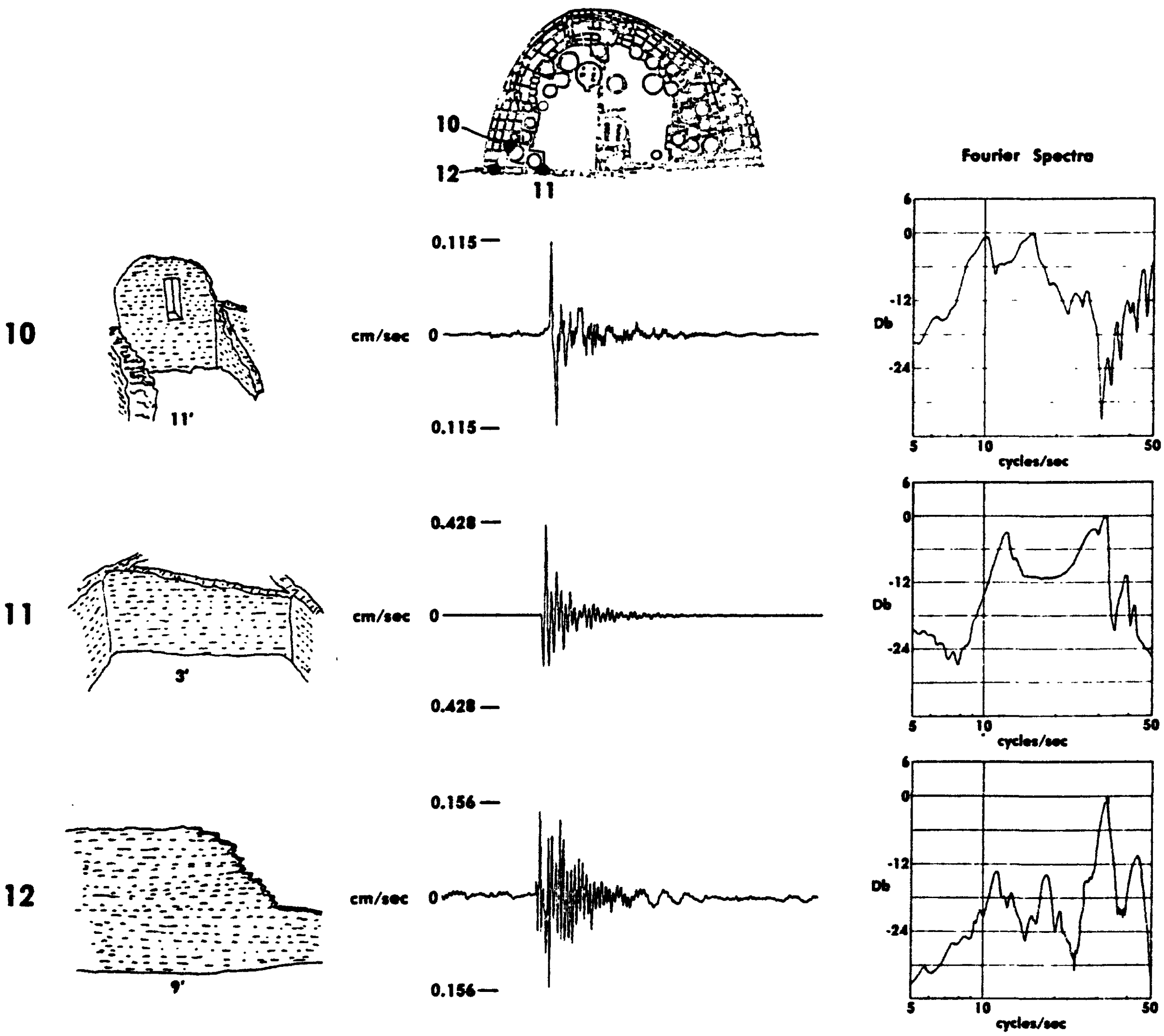
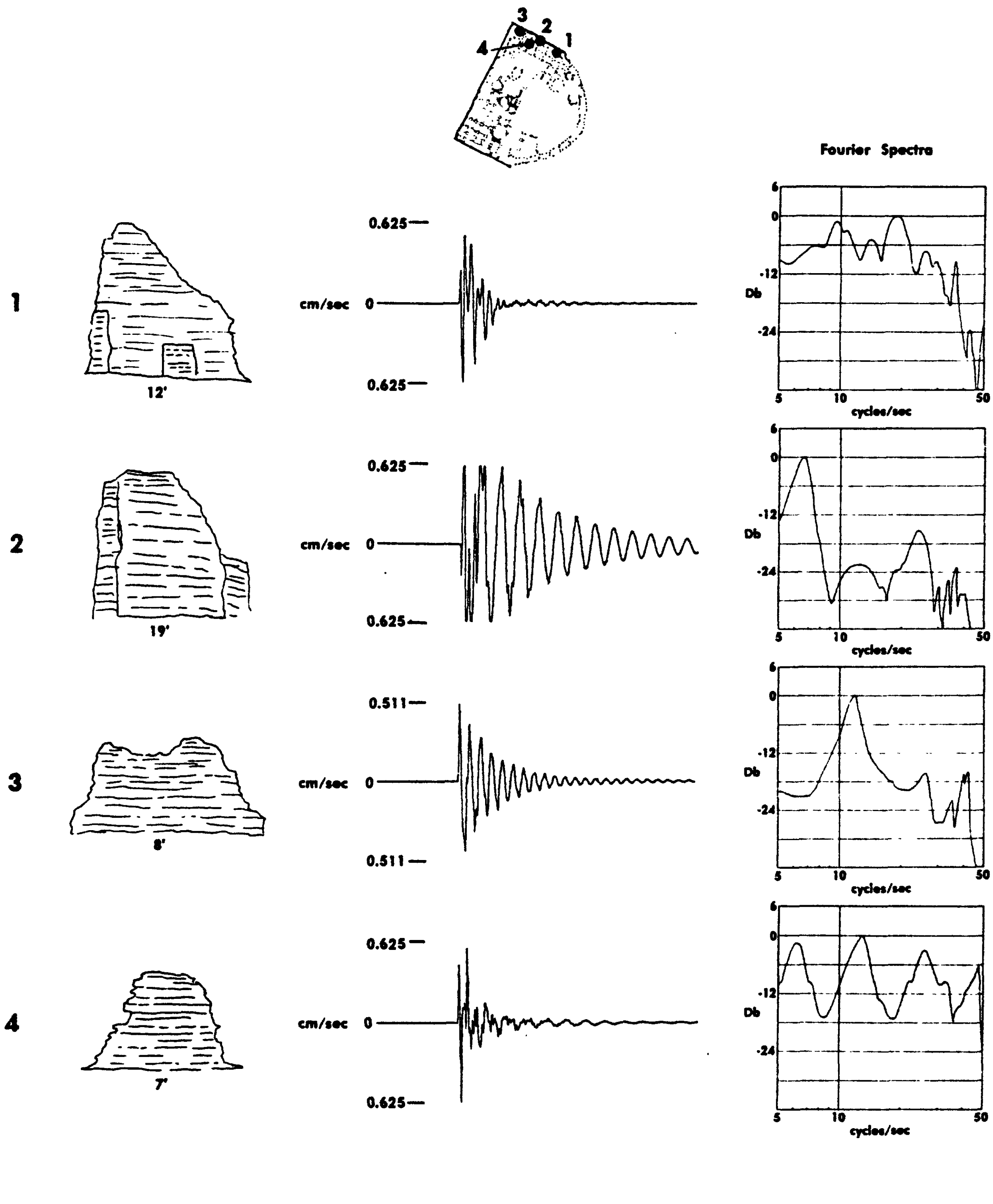


PUEBLO · BONITO



PUEBLO DEL ARROYO



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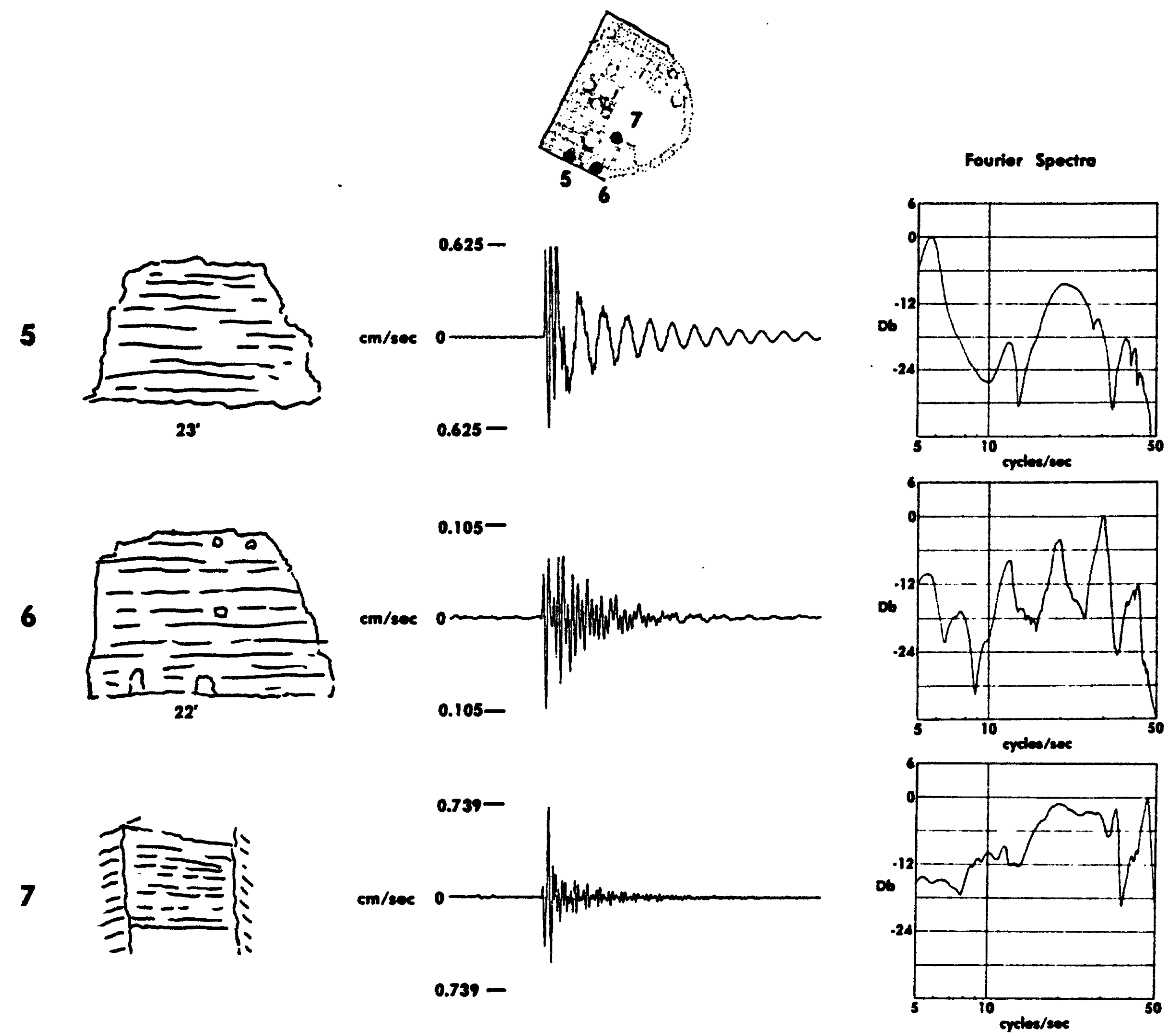

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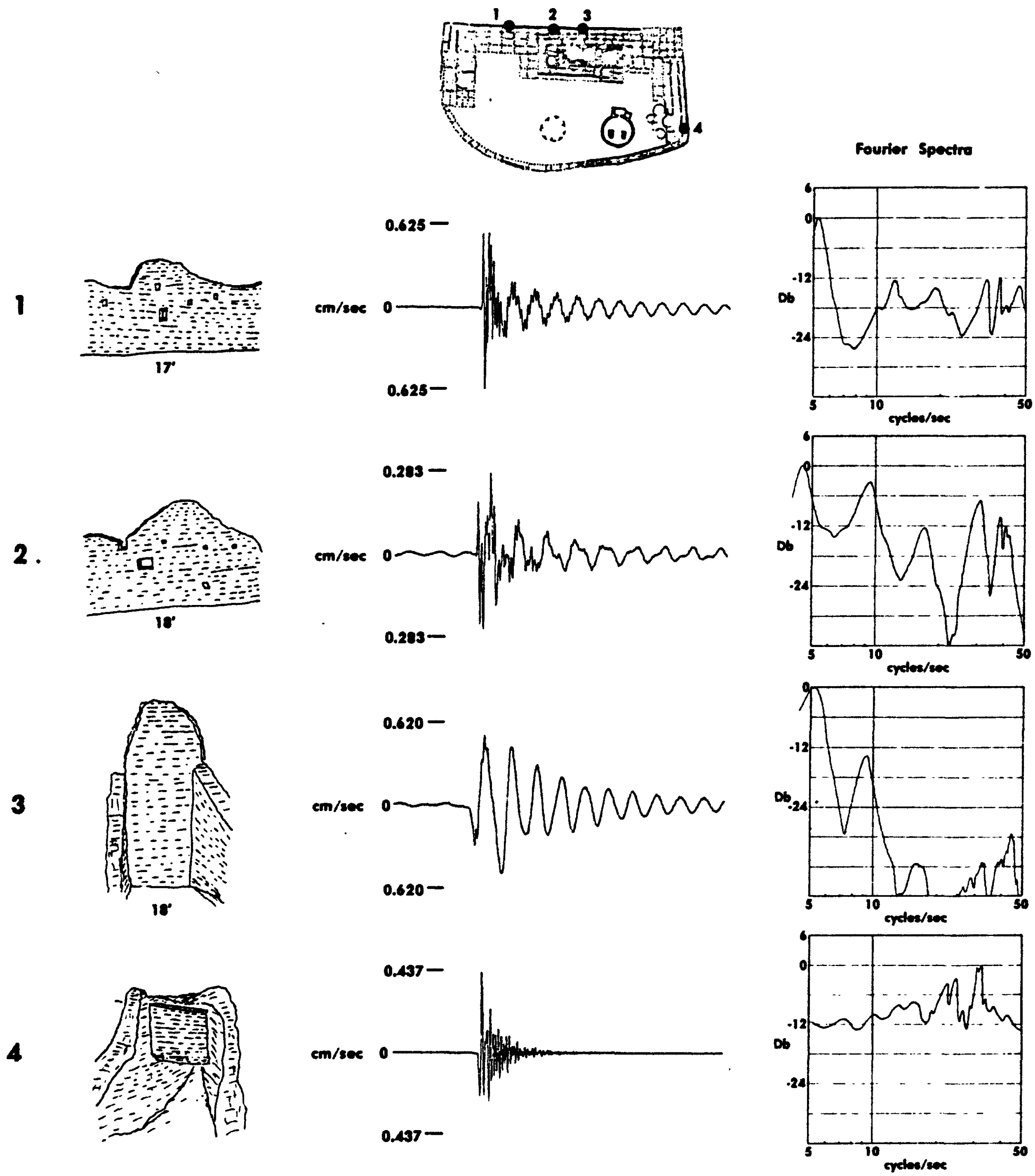
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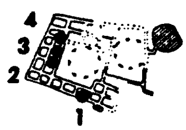

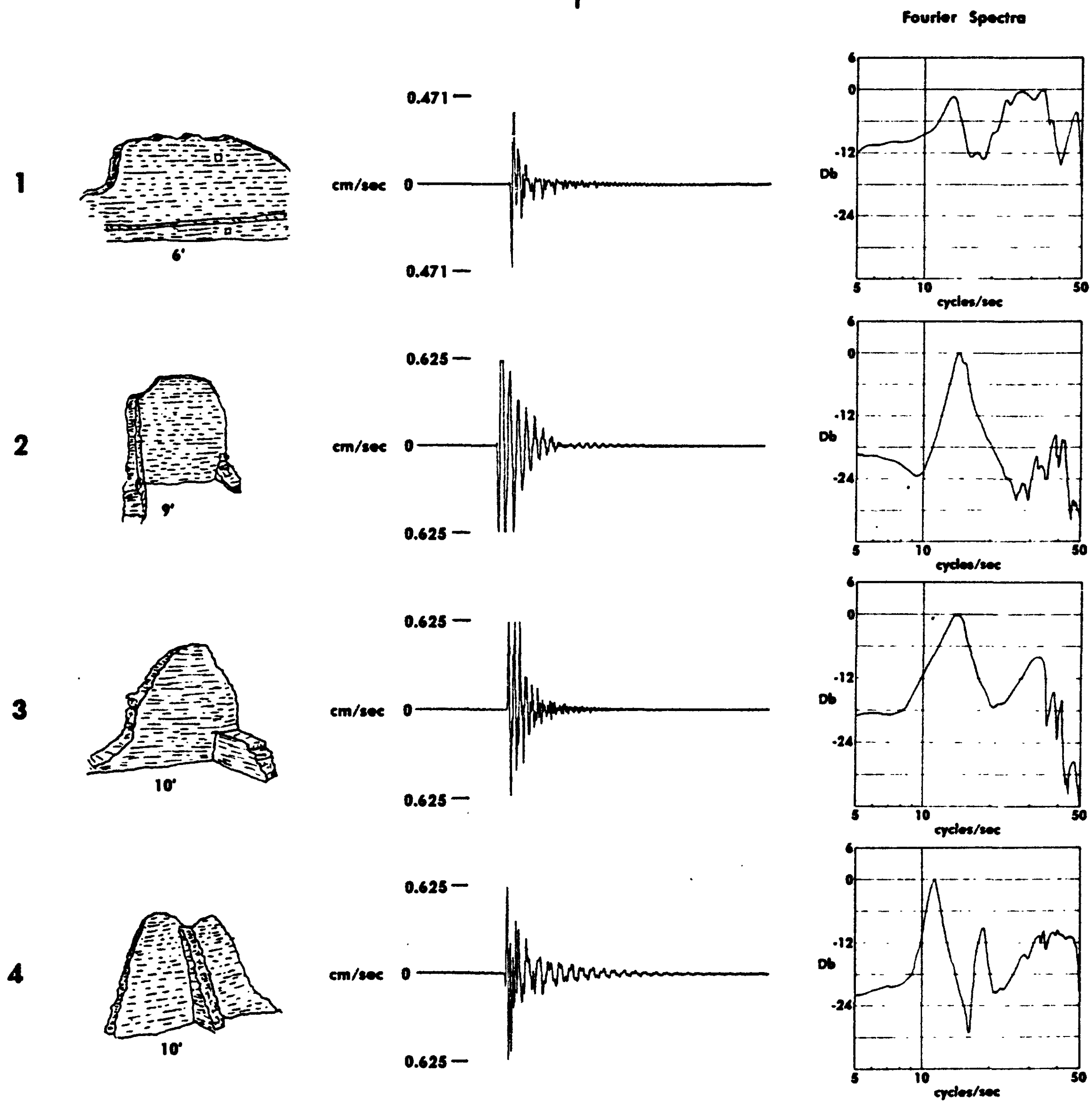

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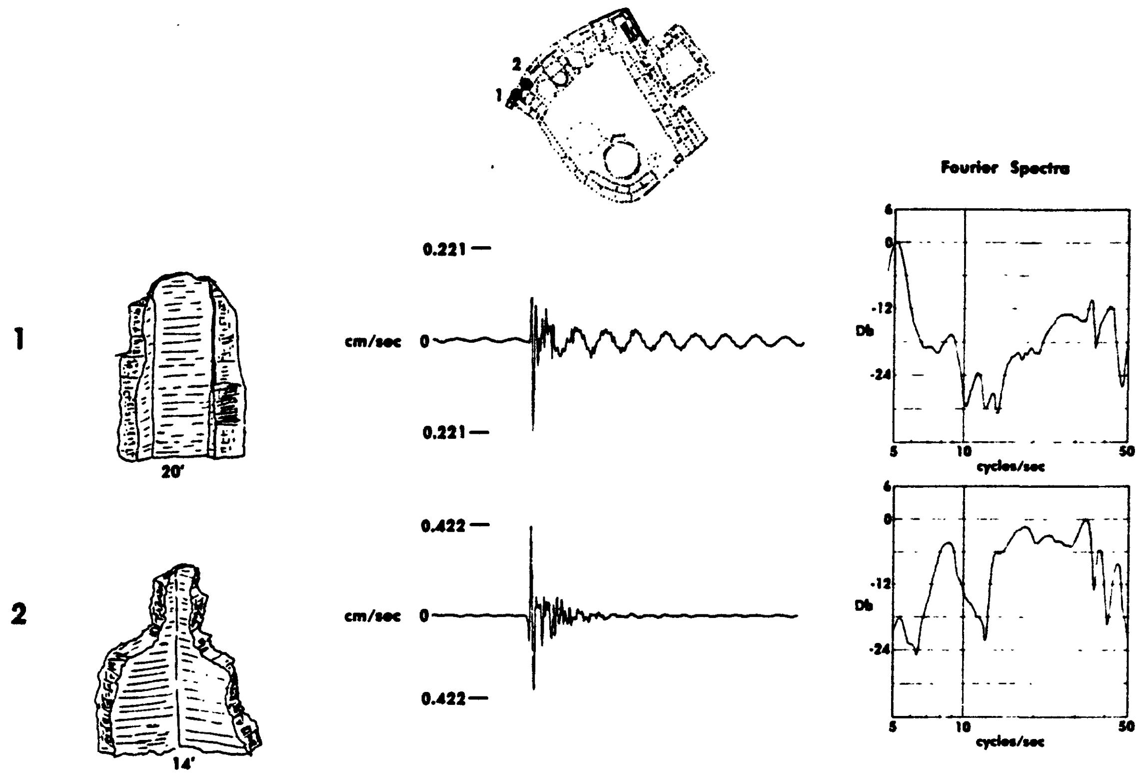

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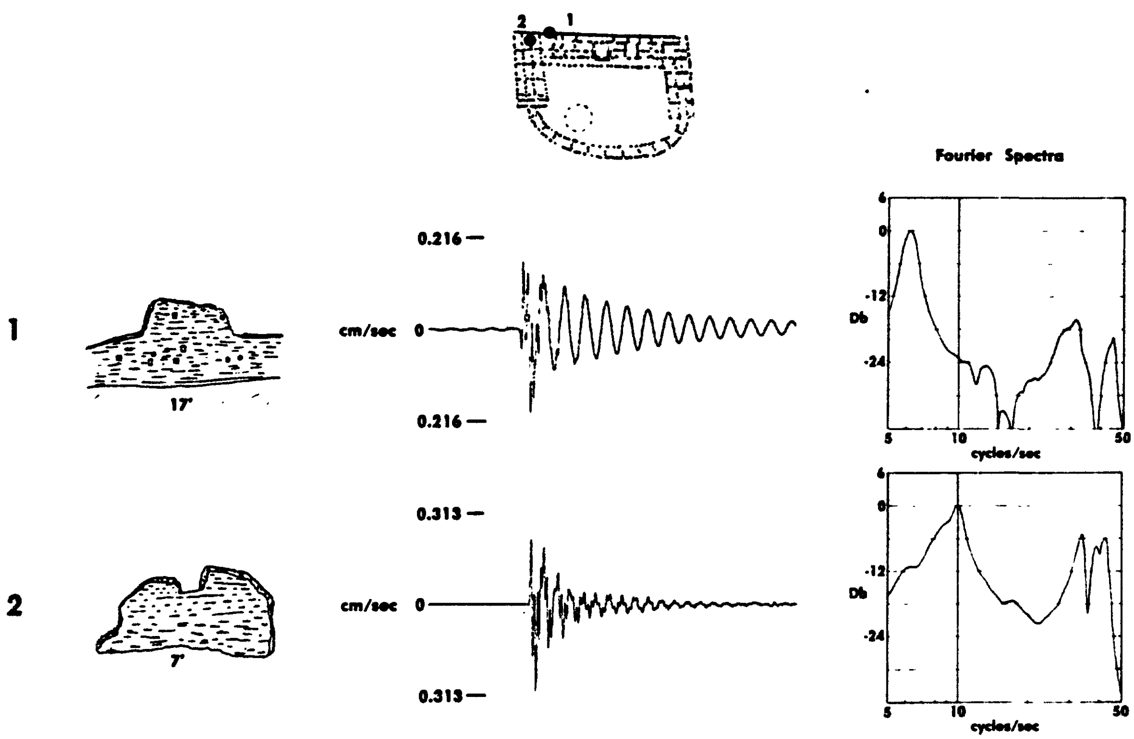

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