COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record No. 1970 / 64

Evans Head Bombing Range Vibrations Tests,

New South Wales 1969

by

E.J. Polak

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SUMMARY

At the request of the Department of Air, vibrations due to normal bombing practice on the RAAF Bombing Range at Evans Head, NSW were measured by a party from the Bureau of Mineral Resources, Geology & Geophysics.

Sixteen 500-pound bombs were dropped. These bombs contain 300 pounds of explosives and detonation occurs at the surface of the ground. Recordings were made at seven sites at distances ranging from 4000 to 35,000 feet (1200 to 10 000 metres). Two types of instruments were used to detect the vibrations: Sprengnether Portable Blast and Vibration Seismograph, and SIE seismic refraction equipment. Two kinds of waves were recorded: the body waves and the air-blast-induced ground waves.

This report gives a short account of factors to be considered in recording and assessing the effects of vibrations due to blasting, and discusses the criteria by which the likelihood of damage can be estimated. Following this discussion the recorded data from all sites are given and the amplitudes, velocities, and acceleration of ground movement are calculated.

It is concluded that by all accepted criteria the intensities of the body waves and of the air-blast-induced ground waves from bombs dropped on the bombing range are too small to cause damage to buildings and structures at the township of Evans Head.

The intensity of air blast was not measured but was calculated to be well within safe limits. However, air blast is greatly affected by atmospheric conditions, and perhaps on days when conditions are unfavourable the psychological and annoyance effect of bombing on some people in the township may be considerable.

1. INTRODUCTION

At the request of the Department of Air, the Bureau of Mineral Resources, Geology & Geophysics measured vibrations resulting from practice bombing on the RAAF bombing range south of Evans Head in New South Wales. The Department of Air wished to establish "whether or not there exists in the Evans Head area, a geological condition which may be responsible for transmitting shock waves, generated by 500-pound or 1000-pound bombs, from the Evans Head range to the township".

The township of Evans Head is located about 2.5 miles (4 km) from the Northern Bombing Range and about 5 miles (8 km) from the Southern Bombing Range (Plate 1).

The measurements were carried out by a geophysical party consisting of E.J. Polak (Geophysicist), G. Jennings (Technical Officer), D. Tarlinton (Technical Assistant) and S. Hall (Field Assistant). The actual field work was done between 27 November and 3 December 1969.

Sixteen 500-pound (227-kg) bombs and a number of 25-pound (11-kg) practice bombs were dropped by RAAF aircraft, and recordings were taken at seven sites listed in Table 1 and shown in Plates 1 and 2.

In the interpretation of data the following textbooks were used: Parkin and Humphreys, 1969; Richardson, 1957; Sharman, 1963; Cook, 1958; Stephens and Bate, 1966; Wood, 1964; Encyclopedia of Science and Technology; Langefors and Kihlström, 1967. A complete list of references is given in Chapter 8.

2. GEOLOGY

The bombing ranges and all recording stations are located on dune sands of unknown thickness overlying soft sandstone of Triassic age, which crops out east of the mouth of Evans River.

3. BASIC CONSIDERATIONS

3.1 Waves generated

When an explosive material is detonated by a bomb striking the surface of the Earth, pressure waves are created. As the explosion occurs close to the surface of the Earth two groups of waves will radiate from the explosion: body waves through the Earth, and sound waves through the air. Since the detonation is in the boundary zone between air and ground, most of the energy will be concentrated in the air-blast wave and a lesser amount will be transferred to the ground at the detonation site.

At the start of the recording of a wave arrival there is generally one dominant frequency at which most of the energy of the disturbance is concentrated. For our purposes it is sufficient to measure the amplitude and direction of particle movement at the dominant frequency. This gives adequate data from which the likelihood of damage can be assessed.

The intensity of the wave motion may be measured as ground displacement amplitude, ground velocity, or ground acceleration depending on the type of sensor used.

3.2 Body waves

Each explosion produces several types of body waves of which the fastest and least attenuated is the longitudinal wave. This is the only wave to be recorded at longer distances, and is the only body wave recorded at Evans Head.

The frequency characteristics of the recorded wave depend greatly on the nature of the rock and overburden at the recording site and will accordingly vary from site to site. The amplitude recorded and the duration of the disturbance are also greatly dependent on terrain conditions.

For equal explosive charges and distances from the shot, rock outcrops give vibrations of lower amplitudes, higher frequencies, and shorter duration than overburden. On rock outcrops, recorded frequencies typically range from 20 to 80 Hz, whilst on overburden 4 to 20 Hz or more is typical. Amplitude variations may be as much as 30 to 1 between extremes of abnormally responsive overburden and hard rock outcrops, for recordings at equal distances from the same shot.

Rate of attenuation of waves with distance from the shot is complex and also dependent on terrain conditions. However, these conditions remain more or less constant in any one locality, and in practice several empirical formulae can be used to compute expected vibrations at a given distance. One of these is discussed in section 6.2 of this report.

3.3 Air waves

The detonation of an explosive charge in the air is accompanied by a pressure wave of very large amplitude and of very high initial velocity near the explosion, although it drops rapidly to the velocity of sound within a short distance from the explosion. With high explosives the pressure buildup is so fast that it creates a steep-fronted blast wave, and air ahead of the shock front is pushed forward. The positive pressure region persists for only a few milliseconds (except in the case of nuclear blasts) and is followed by a rarefaction phase, of longer duration; if intense enough, this second phase will result in windows being blown outwards, not inwards as might be expected at first thought.

Attenuation of air-blast waves with distance is very dependent on atmospheric conditions and may vary greatly from day to day. Wind speed and direction, wind velocity gradient with height, and temperature gradient with height are the most important factors. These can produce blind zones of no sound and zones of reinforcement where sound is exceptionally intense, and these will vary from hour to hour and day to day according to atmospheric conditions.

It is not the purpose of this report to discuss air-blast effects, but in unconfined explosions such as those on the bombing range at Evans Head it is an important consideration. For a full discussion on this subject the reader is referred to Cook (1958).

3.4 Induced ground waves

When a sound wave travels in the air it induces a disturbance in the ground below the front of the wave (Cook, op. cit. pp. 372-375). The induced ground wave normally remains completely coupled to the air shock wave, a fact which can generally be verified by the identical forms of vibration recordings of ground and air particles. The induced ground wave has a higher amplitude than the body waves from the same unconfined explosion and is therefore important in the Evans Head investigation. However, it is normally completely damped and thus not propagated away from the point of coupling. An exception occurs when the frequency of the air blast and the natural frequency of the ground are synchronised, and then the induced ground wave may travel away from the place of impact.

3.5 Perception of vibration

The human reaction to vibration of the ground depends on both frequency and amplitude, and is more sensitive than is generally supposed. Usually a vibration in a building will appear unpleasant to a human being at an amplitude much below that at which the building could possibly suffer structural damage.

Perhaps there is a growing acceptance today that the effect on persons is a matter which should be taken more seriously. The most recent article expressing this view to come to the attention of the author appears in the May 1970 edition of "Tunnels and Tunnelling". The article is entitled "Ground Vibrations from tunnel blasting" by J.V. Davies, and the curves produced in Plate 5 of this Record are taken from a diagram in Davies' article.

4. DAMAGE DUE TO VIBRATION

4.1 Body waves

The history of criteria applied to determine likelihood of damage to buildings from ground vibration shows that particle displacement, particle displacement and frequency, particle acceleration, and particle velocity have all been used by different investigators and authorities. Perhaps the first comprehensive report and the accepted reference for many years was by Thoenen and

Windes (1942) who concluded that acceleration was the most useful parameter to use. However, a more recent study by Duvall and Fogelson (1962), who applied modern statistical methods to the data obtained by previous investigators including Thoenen and Windes, has shown that velocity is the most generally useful parameter. Their findings are now most widely accepted and are probably the best available guide today.

Generally the vibration occurs at one dominant frequency, and by assuming that the motion is sinusoidal, values of displacement, velocity, and acceleration can be calculated no matter which is recorded. Values of these parameters accepted as criteria are discussed below.

Amplitude criteria. Some examples of authors and authorities who have considered the magnitude of particle movement as a criterion to damage resulting from blasting are quoted below.

(1) State of Pensylvania, U.S.A. (1947) which states, "in no case shall the ground displacement be in excess of 0.03 inches (0.76 mm) at any dwelling house, etc."

(2) Morris, (1950) states, "the limiting amplitude of 0.0082 inches gives a conservative estimate of the limiting amplitude for conventional structures".

(3) Teichman and Westwater (1955) state, "The caution limit for property, houses, etc. closely congested is 0.008 inches (0.18 mm). This is the value for displacement adopted as the criterion in the present investigation.

Acceleration criteria. Thoenen and Windes (1942) arrived at the conclusion that ground acceleration is the best index. They did not claim that acceleration is the cause of damage, but simply that the acceleration value is a useful guide in determining the likelihood of damage. In tests carried to the damage point, they found that damage occurred frequently when the acceleration nearly equalled or exceeded 1g ($g = 32.2$ ft/sec^2 = acceleration due to gravity). They classified acceleration between 1g and 0.1g by the word "caution" and lower values by the word "safe". These criteria have been adopted in the present investigation.

If the ground motion is assumed to be a simple harmonic motion the acceleration of one component of the ground motion may be calculated from the equation

$$a = 4\pi^2 f^2 A \qquad \text{(Formula 1)}$$

where a = acceleration in in/sec^2

f = frequency in Hz

A = amplitude of movement in inches

From the three components of the acceleration the resultant acceleration is calculated from the equation

$$a = (a_V^2 + a_L^2 + a_T^2)^{1/2} \qquad \text{(Formula 2)}$$

Velocity criteria. Duvall and Fogelson (1962) found that the peak ground velocity is the most significant parameter and concluded that peak velocities in excess of 2 inches per second (5.1 cm/sec) may cause damage. This value has been adopted for the present investigation.

Several other authorities have used a factor of frequency multiplied by amplitude (a factor which is proportional to velocity) as a criterion of damage. Crandell (1949) suggests fA = 0.745 as the damaging level and fA = 0.527 as the safe level.

The State of New Jersey (1954) in USA allows a maximum vibration amplitude of 0.0305 inches (0.77 mm) for 10 Hz and amplitude of 0.0153 inches (0.39 mm) for 20 Hz, both of which correspond to a velocity of approximately 2 inches per second.

The velocity of the ground particles for a sinusoidal motion may be calculated from the formula:

$$V = 2\pi fA \text{ in/sec} \qquad \text{(Formula 3)}$$

where V = velocity in in/sec

f = frequency in Hz

A = amplitude in inches

4.2 Sound waves

When an air-blast wave reaches a vertical object the wave is brought to rest and "piles up" (Cook, 1958). The whole pressure on the object (positive and negative) may be as much as eight times the incident pressure. Under the pressure of the blast wave the object begins to move. If the natural period of the object is relatively low, the pressure may drop to zero before any damage has been done. On the other hand some brittle objects, such as window panes, may crack immediately. Windows may break under a blast pressure of about 1 pound per square inch (0.07 kgf/cm^2). Such a pressure level occurs at about 40 feet (12.2 m) from an explosion of 1 pound (0.45 kg) of TNT (Thoenen & Windes, 1942).

The Encyclopedia of Science and Technology (p. 147) gives a curve of relationship for the peak pressure of the air wave in pounds per square inch and the weight of the charge and distance. From this curve it can be estimated that at a distance of 400 feet from the explosion of 300 pounds of explosives the pressure will drop below 1 pound per square inch. A similar distance is obtained from the curve of the limits of damage given in Cook (1958) in a graph on page 356 and Table 2 (page 360). Cook suggests that at a distance of 2000 feet (610 m) the air-blast or induced ground wave resulting from the unconfined detonation of 300 pounds (136 kg) of explosives could be a cause of annoyance but could not actually be a source of damage.

5. INSTRUMENTS AND METHODS

The instruments used were a Sprengnether Portable Blast and Vibration Seismograph and two sets of seismic refraction equipment made by Dresser-SIE.

5.1 Sprengnether Portable Blast and Vibration Seismograph

The basic seismometer system consists of two inverted pendulums which respond to perpendicular components of the horizontal ground motion, and a spring-supported vertical-motion pendulum for recording the vertical motion of the ground. All three components have a natural period of 0.75 seconds and a fixed static magnification of 100. The three components are recorded on fast-moving photographic paper with timing lines at 20-millisecond intervals.

During recordings the instrument has to be placed on a hard surface, and during the Evans Head tests it was placed on a concrete block.

5.2 SIE seismic refraction equipment

Two identical seismic refraction sets installed in recording cabs mounted on two International trucks were used. Each equipment consists of a 24-channel set of SIE Type P19 amplifiers and a 25-channel SIE Type PRO-11 recording oscillograph with 200-Hz galvanometers. Velocity-sensitive geophones were used to pick up ground vibrations. The geophones were planted in the ground and connected by cables to the amplifier banks in the recording trucks. The amplifier outputs were then fed to galvanometers in the PRO-11 oscillograph and recorded photographically. Timing lines which are generated within the oscillograph at 10-millisecond intervals also appear on the records.

The SIE amplifier gains are adjustable in three-decibel steps, and amplification is stable. Nevertheless before each recording, a calibrating pulse was put through all channels to ensure reliable gain calibration.

Several types of vertical-component geophones were used, but for calculation of results only three-component omnidirectional geophones Type HS-J-LP3D were used.

The geophones used were:

(a) Three-component ommidirectional geophones Type HS-J-LP3D manufactured by Geo-Space Corporation of Houston, Texas. Three identical geophones with 300-ohm coils, natural frequency 7.5 Hz, and critically damped are fitted in one case. The axes of the geophones are mutually at right angles to each other. The sensitivity of geophones is constant above 10 Hz and is 0.4 volts per inch per second.

(b) 2-Hz vertical geophones type L2 manufactured by Mark Products.

(c) 2.5-Hz vertical geophones type HS-1 manufactured by Geo-Space Corporation.

(d) 7.5-Hz vertical geophones type 8D manufactured by Geo-Space Corporation.

(e) 20-Hz vertical geophones type HS-J manufactured by Geo-Space Corporation.

5.3 Positions of recording sites

The positions of the recording sites are shown in Plates 1 and 2 and are listed in Table 1. They are seven in all; six were placed at Evans Head and the seventh close to the northern target area. The geophone types and spreads used at each site are shown in Plate 3.

5.4 Identification of body waves

A short test to determine the characteristic velocities of near-surface layers was run in the northern target area. The standard seismic refraction technique was used (Heiland, 1946). A line of 12 geophones 17 metres apart was placed and a 22-kilogram explosive charge was fired at both ends of the line. From the time of the wave travel and the distance to the geophones a time/distance curve was plotted. The reciprocal of the slope of the time/distance curve is the value of the velocities in successive layers of the rocks.

The velocities obtained in these measurements were used as a guide in identifying the type of waves arriving at the geophone spreads, and also to compute the times at which waves should arrive at geophones, thus allowing recognition of weak arrivals on noisy records.

5.5 Recording procedures

During the tests a BMR observer was placed close to the control point of the Northern Range. He observed the moment of release of the bomb from the plane and relayed this by radio to the recording cabs. Recording was then started and maintained until the air wave arrived at the recording stations.

6. RESULTS

6.1 General

The recordings were made during five days of normal bombing practice. A total of sixteen 500-pound bombs were dropped and an attempt was made to record all explosions. However, in some instances the moment of bomb release was missed and recordings started too late. In those instances only air-blast-induced waves were obtained on the records. Table 1 summarises the data obtained.

A number of 25-pound bombs were also released during practice; some of them were recorded at Site G but not at the more distant sites.

Examination of all records shows that the only waves carrying enough energy to be recorded at the selected sites were longitudinal body waves and air-blast-induced ground waves. The transverse waves and Rayleigh waves were rapidly attenuated. The experimental shots using 22-kilogram charges (50 pounds) of gelignite referred to in 5.4 above, confirmed that these waves are rapidly attenuated and that the longitudinal waves would be the only body waves that could be expected to reach Evans Head township.

Where both body waves and air-blast-induced ground waves were recorded on the one record, the latter were invariably of higher amplitude as recorded on surface geophones. This is to be expected from unconfined shots or shots under small cover (Cook, 1958, p. 371).

The party was not equipped to measure air-blast intensity but such measurements would have added to the interest of this report. To quote from Cook speaking of unconfined explosions, "Obviously no induced wave can be more intense than its source. Air blast waves, therefore, are always a more likely cause of damage than ground disturbance". However, at Evans Head the distances involved were always well beyond safe distances by all accepted standards for air-blast damage (see 4.2).

The results at each site are discussed and summarised in sections 6.2 and 6.3 below. Not all records have been used, and at each site only those showing the largest vibrations have been selected for calculation. A plot of typical results in relation to damage criteria and human response is shown in Plate 5.

6.2 <u>Sprengnether Portable Blast and Vibration Seismograph</u>

As mentioned in 5.1 above, this instrument has a fixed amplification of 100. This limited amplification puts severe restrictions on the possibility of obtaining measureable deflections that could be compared with the geophone and SIE seismic systems. In fact the only discernible displacements obtained with the instrument were on records from Site G which was the nearest site to the Northern Range.

Plate 4 shows a copy of the record obtained at Site G. The site was at the bottom of the slope below the control tower some 4000 feet from the target. The record shows the three traces of instrument movement in three mutually perpendicular directions. The timing lines are at 20-millisecond intervals. The record shows the barely discernible arrival of a body wave (marked A) followed by a much stronger event B, 3.8 seconds later. The later arrival is the air-blast-induced wave.

TABLE 1

Date	Bombs dropped*	Target range	Location of first recording unit: Site	Description	Blasts recorded	Location of second recording unit: Site	Description	Blasts recorded
27/11/69	4	Northern	A	South upstream side of the bridge across Evans River	2	B	North downstream side of the bridge across Evans River	2
			C	South downstream	2			
28/11/69	4	Northern	E	At the water tower of the airfield	3	D	Southeast corner of the airfield	2
						F	2000 feet southeast of site E	2
1/12/69	2	Northern	E	As above	2	G	Northern range at the bottom of the slope below the control tower	2
	2	Southern	E	As above	2	G	As above	2
2/12/69	4	Southern	E	As above	4	G	As above	4

* Bomb drops listed refer to nominal 500-pound bombs which contain 300 pounds of explosives. In addition a number of 25-pound bombs were dropped during the period 26/11/69 to 3/12/69. However, the only usable records were obtained at Site G, which was nearest the target on the Northern Range

The smallest discernable deflection of a trace on the Sprengnether record is about 0.03 inches. This deflection represents a peak-to-peak amplitude of ground movement of 0.00015 inches, which is roughly one-quarter of the amplitude of safe vibration as defined in 4.1 above.

In quarry blasting practice the approximate amplitude of vibrations due to blasting is calculated from an empirical formula:

$$A = kE^{1/2}/d \qquad \text{(Formula 4)}$$

where A = amplitude of ground vibration in inches

E = weight of explosives in pounds

d = distance in feet

k = site constant

Site constant k is normally determined on the site of actual blasting. The value for k is given by Morris and Westwater (1953) as between 0.04 and 0.4 and by Fish (1951) between 0.05 and 0.2; here the first value is for a normal ground, and the second value 0.2 is for sand and clay wholly saturated with water.

The ground conditions at Evans Head (say the recording site near the bridge across the river) can be considered normal, and an appropriate value for k would be 0.05. Then for

E = 300 pounds

d = 12000 feet

the approximate amplitude of vibrations derived from Formula 4 is 0.000072 inches (0.00018 cm). This amplitude is half the smallest vibration that it is possible to record using the Sprengnether equipment. Therefore it is not surprising that the only record obtained with the Sprengnether equipment was on Site G.

At Site G the record shows vibrations with an amplitude of about 0.000175 inches (0.0044mm) on each trace and frequency of about 6 Hz. The resultant maximum vibration amplitude of the three components is 0.00031 inches (0.0079 mm).

The body wave is followed by an air-blast-induced vibration with the following displacement amplitudes as calculated from the Sprengnether record.

Top trace: transverse, left-right - 0.0008 inches (0.020 mm)

Centre trace: vertical - 0.0005 inches (0.013 mm)

Bottom trace: transverse, to and from - 0.0008 inches (0.020 mm)

The resultant vibration has a maximum possible peak amplitude

$$A = (0.0008^2 + 0.0005^2 + 0.0008^2)^{1/2} = 0.00124 \text{ inches } (0.00315 \text{ cm})$$

This amplitude is well within safe limits. Calculation of velocity and acceleration have not been done, but they would also be very small and well within safe limits.

6.3 SIE seismograph

Geophones and spread layouts used at each site are shown in Plate 3. Records obtained at each site are shown in Table 1 and discussed below.

Recordings at Site A. Plate 6 shows a copy of an SIE seismograph record obtained at Site A from a bomb drop on the Northern Range. The record shows 24 galvanometer traces and the timing lines at 10, 50, and 100-millisecond intervals. The galvanometer traces indicate the velocity of the geophone casing (coupled to the ground) in relation to the suspended mass inside the geophone. The galvanometers that produced the 24 traces were connected as follows:

Trace Nos.	Were connected to
1-6	One ommidirectional geophone placed in a concrete block buried in the ground downstream of a bridge. To ensure that a suitable amplification was obtained, each component was recorded at two levels. The signals produced by the three components of the geophone were fed into amplifiers 1, 2, and 3 and after amplification they were recorded and at the same time fed into amplifiers 4, 5, and 6 for further amplification. As a result the following pairs of traces indicate the same direction of movement. 1 and 4 - vertical movement. 2 and 5 - left and right movement. 3 and 6 - to and from movement.
7-12	The second omnidirectional geophone located upstream of the bridge and connected in exactly the same way as traces 1 to 6. However, the amplifiers for these traces in Plate 6 were switched off as a bulldozer working nearby produced too much noise.
13-18	Six 2-Hz geophones placed in a line.
19-23	Five 7.5-Hz geophones placed in a line.
24	One 20-Hz geophone placed on the roof of one recording truck to record the arrival time and frequency of the air blast.

To relate the amplitude of the deflection of the trace to the output of the geophones and therefore to the amplitude of the velocity of the ground movement a calibrating signal was fed in parallel into the inputs of all amplifiers. Plate 6 shows a short section of the record of a calibrating signal of 300 microvolts for the following amplifier settings: sensitivity, 50%; gain, position 1.0. The same method for calibrating amplifier gain was used at other sites by choosing appropriate amplifier gain settings and calibrating signal levels.

Several arrivals of the body waves are indicated on the record. Following the first wave, arriving at the moment designated 0.0 seconds, is a wave arriving at 0.123 seconds or slightly earlier at 0.113 seconds. The vibration due to the arrival of this wave is added to the vibration from the wave that arrived at 0.0 seconds, as the two vibrations are in phase. Several other vibrations are visible on the traces, as for example the vibration at 0.250 seconds; as this arrives out of phase with preceding vibrations, the combined amplitude is lower than each would have had if they had arrived separately. At about 9.0 seconds the air blast arrives at the geophones.

Intensities of body waves at Site A. Body waves were recorded on the two records obtained at Site A on 27 November 1969.

On the record shown in Plate 6 the ground velocity that resulted from the arrival of the body wave was recorded with the following amplitudes:

Trace 4 (vertical component)	1.05 inches
Trace 5 (horizontal H1, left to right)	1.35 inches
Trace 6 (horizontal H2, to and from)	0.72 inches
Resultant maximum possible amplitude	1.9 inches
Frequency	19 Hz

As can be seen from Plate 6 where the points of measurements are indicated on the record it was assumed in calculating the resultant amplitude that the maximum of all component vibrations happened simultaneously. This is most unlikely to be so in practice, but it represents the worst possible case.

The resultant amplitude of 1.9 inches is 16 times the amplitude produced by a calibrating signal of 300 microvolts; therefore the equivalent input signal is 0.000300 x 16 = 0.0048 volts.

From the frequency response curve for the geophone (Plate 6) at 19 Hz a velocity of 1 inch per second gives an output of 0.38 volts. Then the velocity of the ground particles at site A is:

$$V = 0.0048/0.36 = 0.013 \text{ inches per second}$$

The amplitude of vibration from Formula 3 is

$$A = V/2\pi f = 0.013/(2\pi \times 19) = 0.00011 \text{ inches}$$

The acceleration from Formula 1 is

$$A = 4\pi^2 f^2 A = 4\pi^2 \times 19^2 \times 0.00011$$

$$= 1.6 \text{ inches/second}^2$$

$$= 0.004 \text{ g}$$

Air-blast-induced wave at Site A. Approximately 9 seconds after the body wave, the air blast arrived at the site. As can be seen from traces 1 to 6 in Plate 6, the air-blast-induced ground disturbance was not picked up clearly by the omnidirectional geophone. The geophone was mounted in a concrete block and buried about two feet deep in the ground in a large depression. There are several possible explanations for not recording the air-blast-induced ground distrubance:

(1) The geophone was located in a blind zone (see 3.3); (2) The geophone was protected from the air blast by its position in the depression in the reclaimed area of the main river channel; (3) At a depth of 2 feet the air-blast-induced ground motion is negligible, i.e. it is a very shallow, surface phenomenon.

However, the air-blast-induced ground disturbance was picked up by the 2-Hz geophones placed level with the ground at a higher elevation. It is interesting to note that when the air-blast-induced ground disturbance arrived at the geophones they were still recording some vibrations at about 10 Hz, indicating that this is the natural frequency of the ground in this area.

Trace 24 in Plate 6 indicates a response of the geophone placed on the roof of the BMR recording truck. The trace shows a continuous vibration of 100 Hz superimposed on sporadic deflections. The arrival of the air wave is clearly defined by an increase in amplitude and the uniform frequency of 25 Hz of the wave. The frequency of the air wave (25 Hz) is much higher than the natural frequency of the ground (10 Hz); therefore the air-blast-induced disturbance would not have been propagated through the ground from the point of impact.

<u>Recordings at Site B.</u> Two records at Site B of bombs dropped on the Northern Range were obtained simultaneously with those at Site A.

<u>Intensity of Body Waves at Site B.</u> The maximum trace amplitudes recorded from the arrival of body waves were:

Vertical component	0.27 inches
Horizontal, left to right	0.19 inches
Horizontal, to and from	0.12 inches
Calculated maximum resultant	0.36 inches

The natural frequency of the ground vibration was found to be 25 Hz. The frequency is high compared with Site A but this can be explained by the geophone being placed in the river bed in wet sand and mud.

The body wave travelled to the site with a velocity of 14,400 ft/sec. The resultant amplitude of 0.36 inches is 4.2 times higher than the amplitude produced by a calibrating signal of 800 microvolts, therefore geophone output is 0.000800 x 4.2 = 0.0034 volts. From the frequency response curve this output corresponds to peak velocity of particles

$$V = 0.0034/0.37 = 0.009 \text{ inches per second}$$

The corresponding peak displacement and acceleration are:

$$A = 0.009/(2\pi \times 25) = 0.000060 \text{ inches}$$

$$a = 4\pi^2 \times 25^2 \times 0.00006 = 1.5 \text{ in/sec}^2 = 0.004 \text{ g}$$

Air-blast-induced waves at Site B. The air-blast wave arrived at the geophones 9.55 seconds after the arrival of the body wave, and the traces recorded from the air-blast-induced ground disturbance had the following amplitudes and frequency:

Vertical component	2.4 inches
Horizontal, left to right	2.6 inches
Horizontal, to and from	1.2 inches
Calculated maximum resultant	3.8 inches
Frequency of disturbance	25 Hz

The resultant amplitude is 45 times higher than the amplitude of the calibrating signal of 800 microvolts. Geophone output is therefore 0.000800 x 45 = 0.036 volts. The corresponding peak ground velocity, displacement amplitude, and acceleration are:

$$V = 0.097 \text{ in/sec}$$

$$A = 0.0006 \text{ inches}$$

$$a = 15 \text{ in/sec}^2 = 0.039 \text{ g}$$

The higher amplitude of the air-blast-induced disturbance on this site may be explained by the fact that the natural frequency of the saturated sand and mud as shown on the first part of the record is equal to the frequency of the air-blast wave recorded at the neighbouring Site A. Under these conditions, synchronisation could take place and account for the relatively high velocities recorded.

Recordings at Site C. Site C is adjacent to the Site A. The equipment was transferred there, as Site A was found to be noisy. Two air-blast-induced waves were recorded from bombs dropped on the Northern Range on 27 November 1969.

Air-blast-induced waves at Site C. The air-blast-induced ground disturbance was recorded with the following trace amplitudes and frequency:

Vertical component	0.8 inches
Horizontal, left to right	0.4 inches
Horizontal, to and from	0.15 inches
Calculated maximum resultant	1.0 inches
Frequency of disturbance	17 Hz

The corresponding peak ground velocity, displacement amplitude, and acceleration are:

$$V \doteq 0.0041 \text{ in/sec.}$$

$$A = 0.00004 \text{ inches}$$

$$a = 0.44 \text{ in/sec}^2 = 0.0011 \text{ g}$$

<u>Recordings at Site D.</u> Two records of body waves and of the air-blast-induced disturbance were recorded from bombs dropped on the Northern Range.

<u>Body waves at Site D.</u> The trace amplitudes and frequency of the body wave were:

Vertical component	0.12 inches
Horizontal, left to right	0.22 inches
Horizontal, to and from	0.16 inches
Calculated maximum resultant	0.30 inches
Frequency	10 Hz

The corresponding peak ground velocity, displacement amplitude, and acceleration are:

$V = 0.0047$ in/sec

$A = 0.00007$ inches

$a = 0.3$ in/sec^2 $= 0.0007$ g

<u>Air-blast-induced waves at Site D.</u> The trace amplitudes and frequency were:

Vertical component	2.0 inches
Horizontal, left to right	0.9 inches
Horizontal, to and from	0.9 inches
Calculated maximum resultant	2.35 inches
Frequency	8 Hz

The corresponding peak ground velocity, displacement amplitude, and acceleration are:

$V = 0.038$ in/sec

$A = 0.00075$ inches

$a = 1.9$ in/sec^2 $= 0.005$ g

<u>Recordings at Sites E and F.</u> The two sites are adjacent and therefore the data from both will be discussed together.

On Friday 28 November, four bombs were dropped at the Northern Range and on Monday 1 December, two bombs were dropped at the Northern Range and the following two on the Southern Range. During the tests on 2 December, all four bombs were dropped on the Southern Range. Records of all explosions were obtained at Site E and of two explosions at site F.

The geophones were placed as shown in Plate 3. Two of the omnidirectional geophones were placed close to the empty tanks on an old and disused water tower, in order to measure the actual movement of the tower due to the arrival of body and air-blast waves. The records indicate continuous vibration resulting from the change of wind pressure on the tower, and the body and air-blast waves are superimposed on these vibrations.

Records from bombs dropped on the Northern Range, Sites E and F. The omnidirectional geophones placed on the tower produced the following trace amplitudes (values proportional to tower velocity) and frequency:

(a) Wind noise

Vertical component	0.1 inches
Horizontal, left to right	0.2 inches
Horizontal, to and from	0.12 inches
Calculated maximum resultant	0.25 inches
Frequency	15 Hz

(b) Body wave

Vertical component	0.2 inches
Horizontal, left to right	0.8 inches
Horizontal, to and from	0.6 inches
Calculated maximum resultant	1.02 inches
Frequency	11 Hz

(c) Air blast wave

The wave arriced at the tower 14.85 seconds after the body wave. Aproximately 200 milliseconds after the first air blast a second, stronger arrival may indicate a 'pileup' of air waves. The whole disturbance lasted 0.6 seconds as indicated by a sudden drop in the amplitude of signal level on the record. The trace amplitudes and frequency recorded were:

Initial wave

Vertical component	0.55 inches
Horizontal, left to right	0.4 inches
Horizontal, to and from	0.3 inches
Calculated maximum resultant	0.74 inches
Frequency	19 Hz

Pileup wave

Vertical component	1.5 inches
Horizontal, left to right	0.2 inches
Horizontal, to and from	1.2 inches
Calculated maximum resultant	1.9 inches
Frequency	11 Hz

On the following table the equivalent peak ground velocities, displacement amplitudes, and accelerations are summarised.

			Air blast	
	Wind noise	Body wave	Initial	Pileup
Velocity, in/sec	0.002	0.01	0.06	0.17
Amplitude, inches	0.00002	0.00015	0.0005	0.0025
Acceleration, in/sec^2	0.18	0.72	7.2	11.7
Acceleration, g	0.0004	0.0019	0.019	0.030
Frequency, Hz	15	11	19	11

Records from bombs dropped on Southern Range, Sites E and F. Northern and Southern Ranges are shown in Plate 1. From their relative positions it was estimated that the body wave should arrive at the water tower approximately 26 seconds before the arrival of the air blast. As the air blast was recorded on several records, all the records were examined and one one of them an indication of a change in frequency of the wind noise could be taken as the arrival of the body wave. This occurred 26.08 seconds before the air blast. As the amplitude of this vibration equals the amplitude of the wind noise no numerical value could be assigned to the energy of this wave. The air blast is defined clearly, and the trace amplitudes and frequency were:

Vertical component	0.55 inches
Horizontal, left to right	0.65 inches
Horizontal, to and from	0.60 inches
Calculated maximum resultant	1.0 inches
Frequency	15 Hz

The corresponding peak ground velocity, displacement amplitude, and acceleration are:

V = 0.003 in/sec

A = 0.00003 inches

$a = 0.3\ in/sec^2$

$= 0.0008$ g

Recordings at Site G. The geophones at site G were placed at the bottom of a slope on which the control tower of the range is located. The arrangement of geophones is shown in Plate 3. This is the site on which the shallow refraction spread described in section 5.4 was carried out. Two velocities were indicated in the bedrock:

(1) 8000 ft/sec which was recorded close to the road to the target on four 4.5-Hz geophones.

(2) 17,000 ft/sec which was recorded on the remaining eight geophones of the spread. The velocity is higher than generally found in sedimentary rocks and may indicate igneous intrusion.

At Site G bombs dropped on both ranges were recorded.

Records at Site G from bombs dropped on the Northern Range. The omnidirectional geophone recorded the following vibrations:

(a) Body waves

Vertical component	0.1 inches
Horizontal, left to right	0.1 inches
Horizontal, to and from	0.08 inches
Calculated maximum resultant	0.16 inches
Frequency	28 Hz

(b) Air-blast-induced vibrations

Vertical component	0.6 inches
Horizontal, left to right	0.2 inches
Horizontal, to and from	0.4 inches
Calculated maximum resultant	0.74 inches
Frequency	20 Hz
Air blast arrives	3.9 sec after the body wave

(c) Records of 25-pound Bombs

Several records of the explosions of 25-pound bombs on the Northern Range were obtained. The only indication of the body waves is on 4.5-Hz geophones. The amplitudes were not calculated but they are very small. The air-blast-induced disturbance was recorded also on the omnidirectional geophone with the following trace amplitudes and frequency:

Vertical component	0.1 inches
Horizontal, left to right	0.3 inches
Horizontal, to and from	0.06 inches
Calculated maximum resultant	0.32 inches
Frequency	17 Hz

The corresponding peak ground velocities, displacement amplitudes, and accelerations for the bombs dropped on the Northern Range are summarised in the following table:

	Body waves (500-lb)	Air blast (500-lb)	Air blast (25-lb)
Velocity, in/sec	0.0025	0.008	0.005
Amplitude, inches	0.000015	0.00006	0.00005
Acceleration, in/sec^2	0.46	1.0	0.6
Acceleration, g	0.001	0.003	0.0015
Frequency, Hz	28	20	17

Records at Site G from bombs dropped on the Southern Range. On the two days on which the recording was done, conditions were very windy and low amplifications had to be used. No body wave was recorded clearly, but it was possible to recognise the moment of its arrival, which occurred at 11.07 to 11.10 seconds ahead of the air blast. Six records were obtained, two on 1 December and four on 2 December. The amplitudes and frequencies of the air-blast-induced vibration vary widely. These are shown in the Table below.

Air-blast-induced Waves - Site G

	Record No.1	Record No.2.	Record No.3	Record No.4
Vertical component	0.16	0.4	0.8	0.65
Horizontal, left to right	0.25	0.5	0.65	0.30
Horizontal, to and from	0.15	0.25	0.40	0.45
Calculated maximum resultant	0.33	0.68	1.10	0.84
Frequency, Hz	12	8	9	11
Velocity, in/sec	0.0058	0.01	0.018	0.015
Amplitude inches	0.000077	0.00020	0.00032	0.00022
Acceleration in/sec^2	0.44	0.50	1.0	1.0
Acceleration, g	0.0011	0.0013	0.0026	0.0026

Summary of results of SIE recordings

The following table gives a summary, for the Northern Range, of the results of measurements at all sites at Evans Head using SIE refraction seismograph equipment.

Location	A	B	C	D	E & F
(a) Body waves					
Velocity, in/sec	0.013	0.009	-	0.0047	0.01
Amplitude inches	0.00011	0.00006	-	0.00007	0.00015
Acceleration, in/sec	1.6	1.5	-	0.3	0.72
Acceleration, g	0.004	0.004	-	0.0007	0.0019
Frequency, Hz	19	25	-	10	11
(b) Air-blast-induced waves					
Velocity, in/sec		0.097	0.0041	0.038	0.06
Amplitude, inches		0.0006	0.00004	0.00075	0.0005
Acceleration, in/sec^2		15	0.44	1.9	7.2
Acceleration, g		0.039	0.0011	0.005	0.019
Frequency, Hz		25	17	8	19

It will be recalled from section 4 ("Damage Due to Vibrations") that the threshold criteria for likelihood of damage are: (1) Peak velocity 2 inches per second; (2) Peak amplitude or displacement 0.008 inches; (3) Peak acceleration 0.1 g. Accepting the same criteria for air-blast-induced waves as for normal body waves it can be seen from the table that the vibrations recorded do not even approach values where there is any likelihood of damage from ground motion.

Velocity, acceleration, and amplitude of vibration resulting from bombs dropped on the Southern Range also indicate that no damage can result at Evans Head from bombing on this range.

7. CONCLUSIONS

By all accepted criteria the intensity of the body waves recorded at all sites was far too small to cause damage to buildings and structures in Evans Head. The same can be said of the air-blast-induced ground motion although the amplitudes recorded are much higher than those for the corresponding body waves.

No measurements on rate of attenuation of body waves were made, but the records obtained do not suggest any exceptional geological conditions that would cause vibrations at Evans Head to be attenuated much more or less than those in other similar areas. The amplitudes of vibration at all stations were lower than those calculated from empirical formulae for the relationships between the amplitude of body waves, size of the charge, and distance from the shot.

The party was not equipped to measure air-blast intensity, but on the basis of calculations from tables and formulae available in the literature, there appears to be no possibility of damage resulting from this cause, at the distances involved. On the other hand, blast intensity can be greatly affected by atmospheric conditions and perhaps on days when conditions are unfavourable the psychological and annoyance effects of bombing on some people in the township could be considerable. This could be reduced by avoiding bombing on such days. The reader is referred to Cook (1958) Chapter 14 for a full discussion on this topic.

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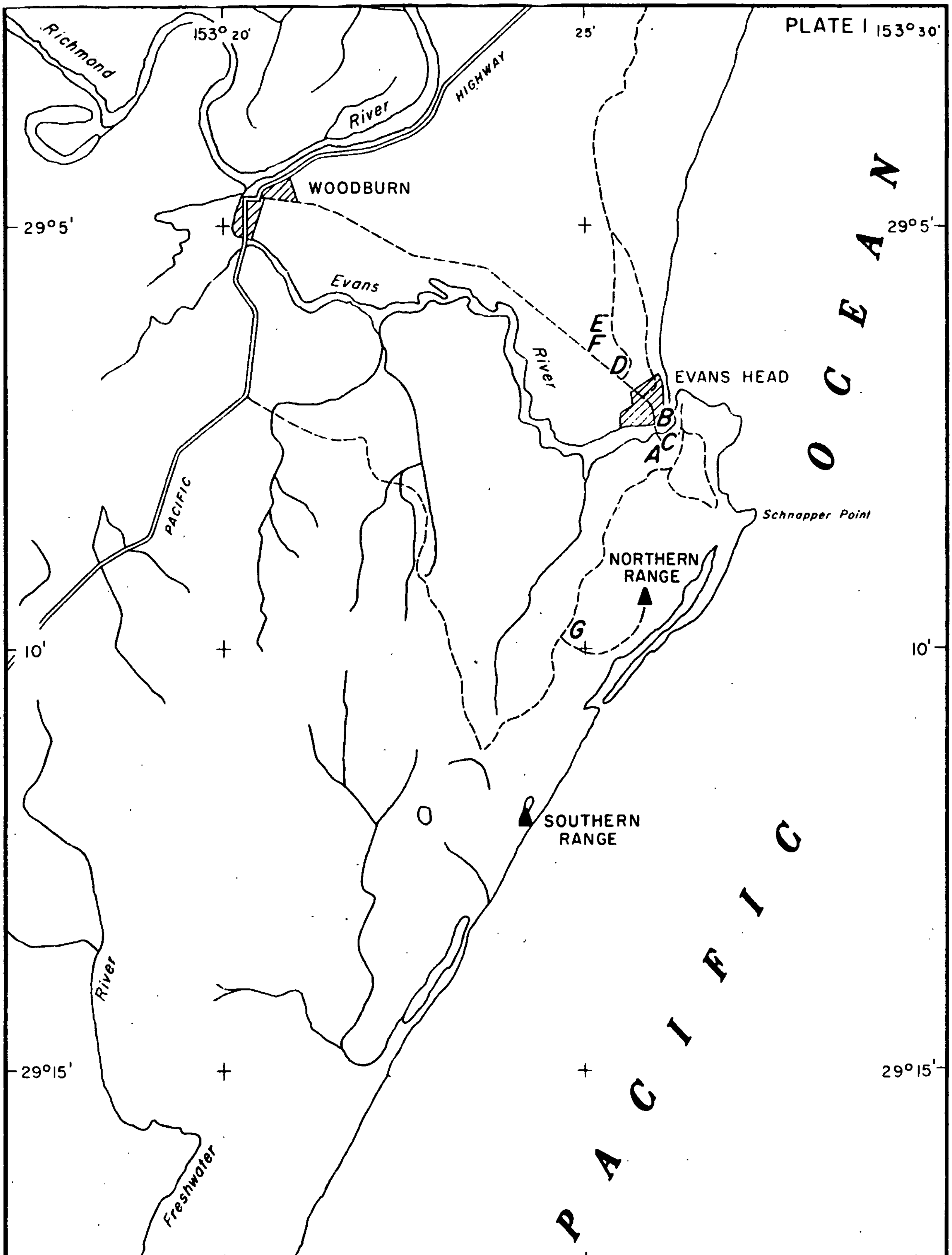
PLATE I



LEGEND

A–G Recording position

▲ Bombing ranges

LOCALITY MAP

Scale

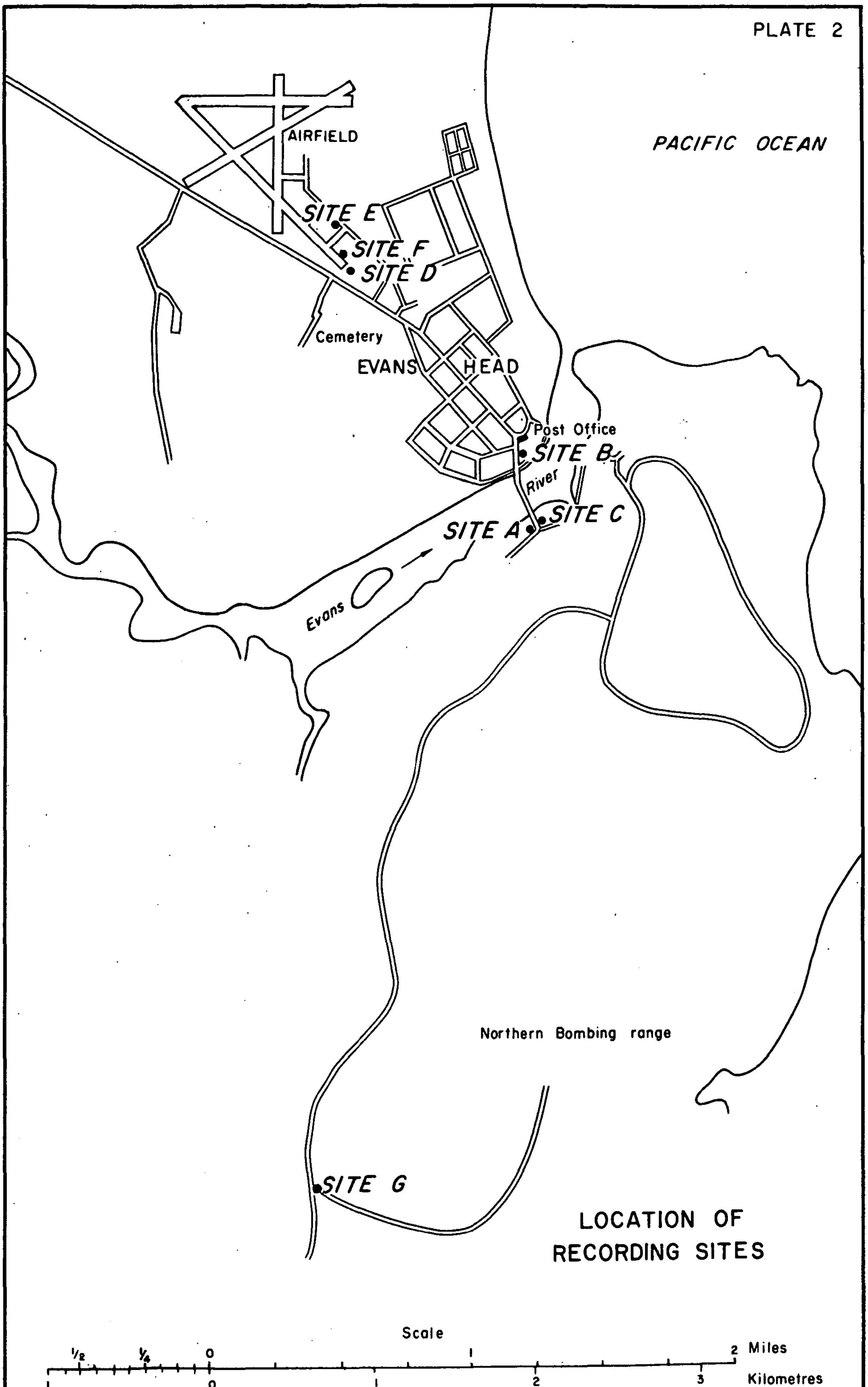
Miles: 2 1 0 1 2 3 4 5

Kilometres: 3 2 1 0 2 4 6 8

To Accompany Record No. 1970/64

H56/B5-32A

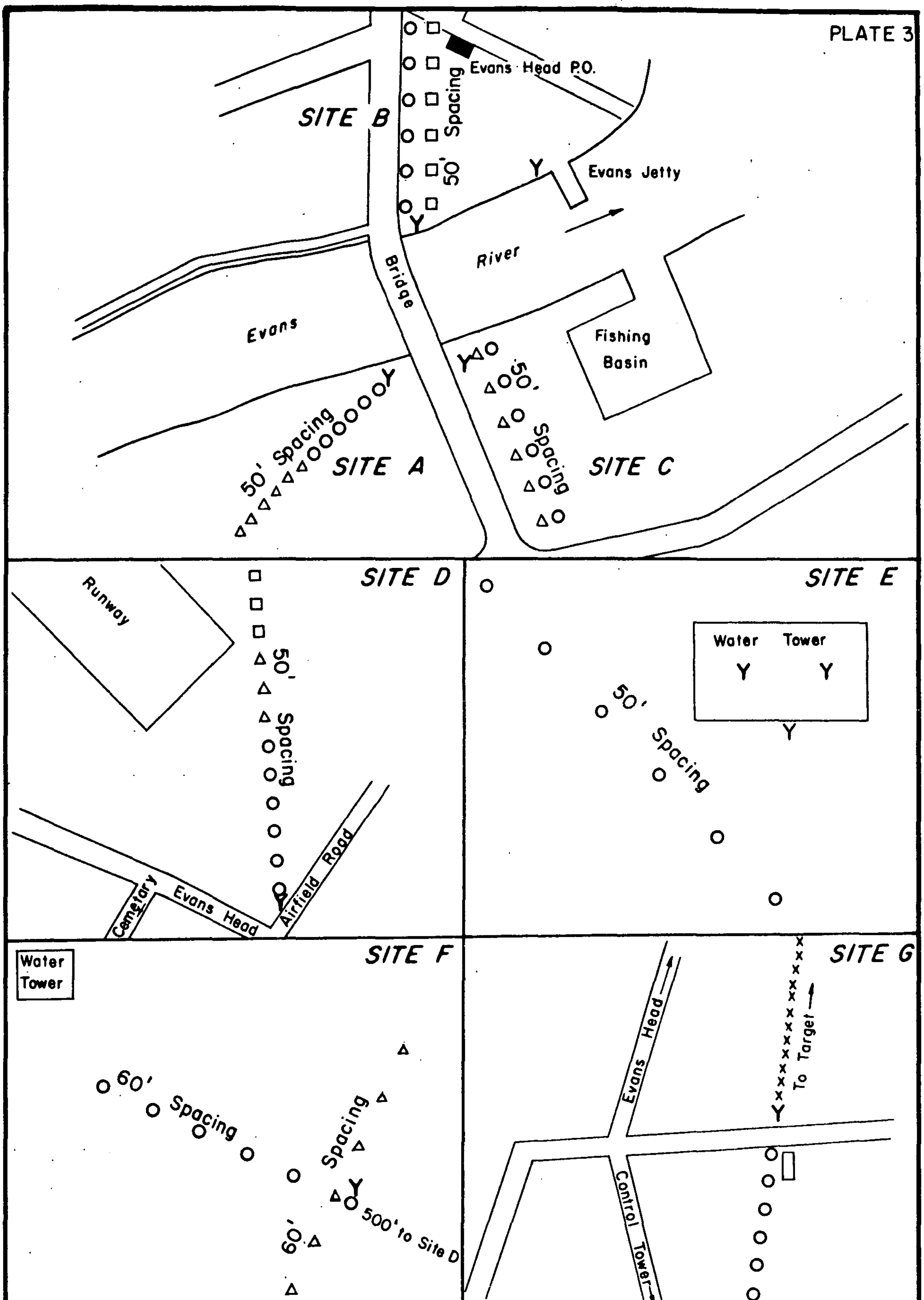
PLATE 2



LOCATION OF RECORDING SITES

To Accompany Record No. 1970/64

H56/B5-30 A



LEGEND

- Y 3 component geophone
- O 2 Hz geophone
- x 4·5 Hz geophone
- △ 7·5 Hz geophone
- □ 20 Hz geophone

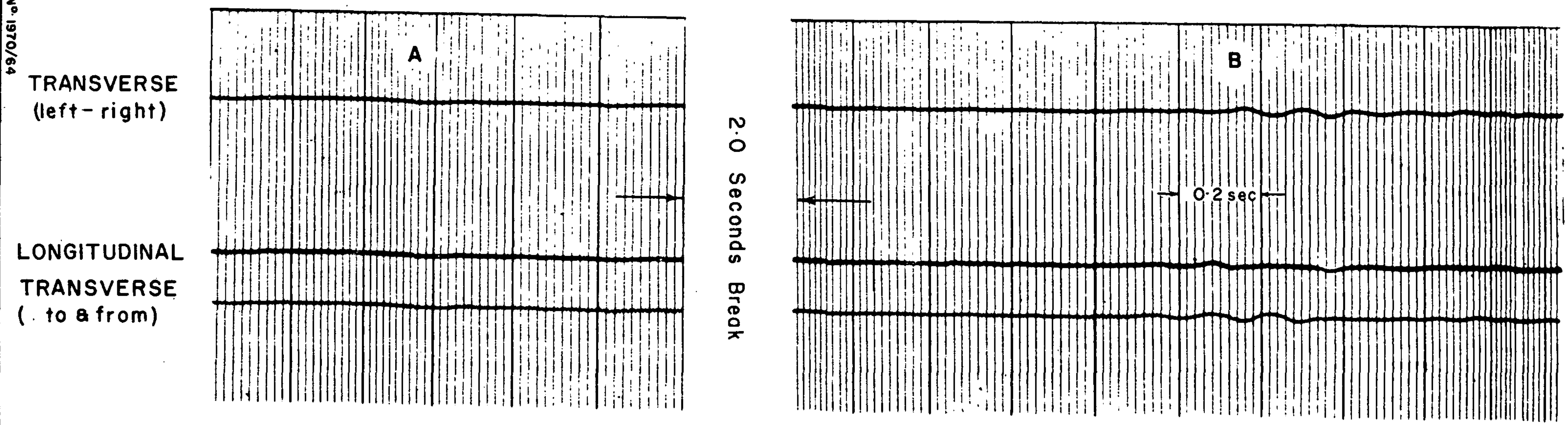
GEOPHONE LAYOUTS

DIAGRAMS NOT TO SCALE

To Accompany Record No. 1970/64

H56/B5-31 A

To Accompany Record No. 1970/64



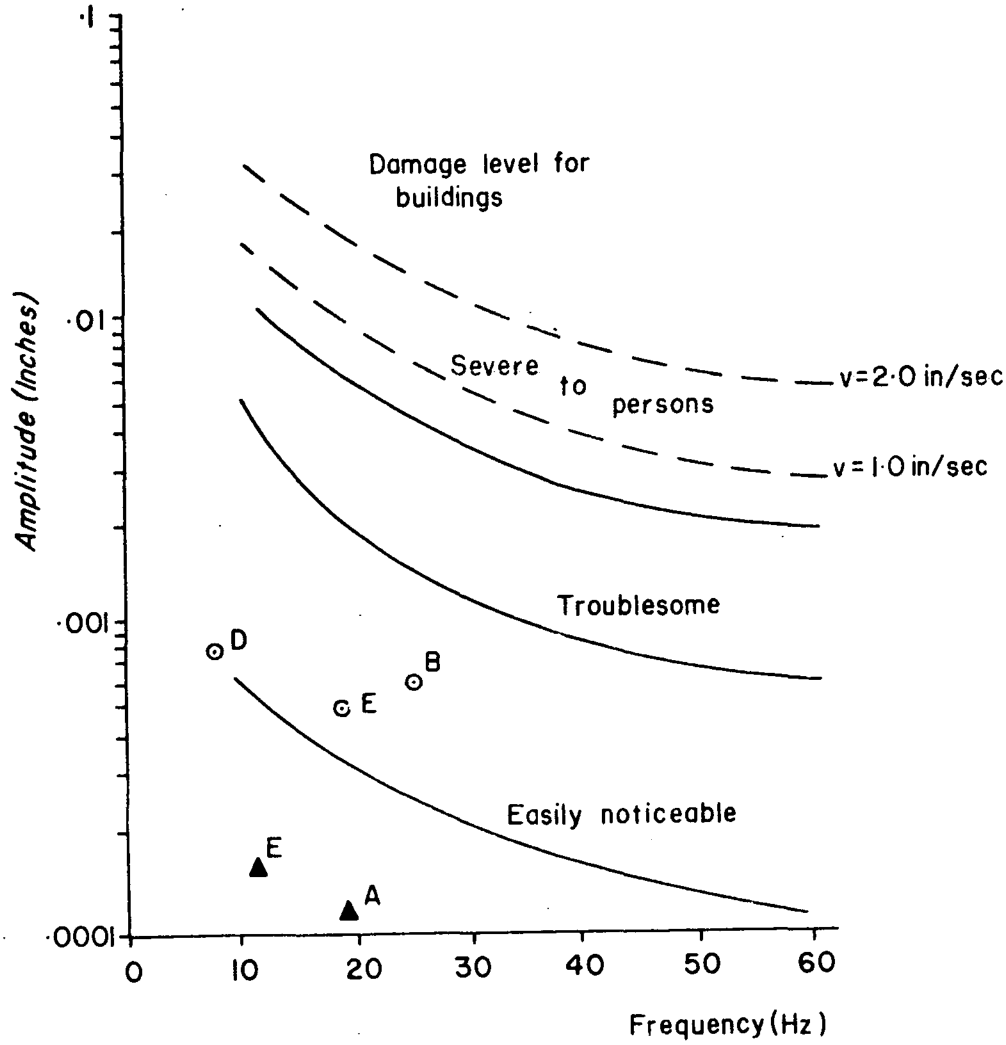
SPRENGNETHER VIBROGRAPH RECORD
EVANS HEADS VIBRATIONS 1969
SITE G

H56/B5-33 A

PLATE 4

PLOT OF TYPICAL RESULTS IN RELATION TO DAMAGE CRITERIA AND HUMAN RESPONSE

Curves after J.V. Davies, 1970
(See Section 3.5)

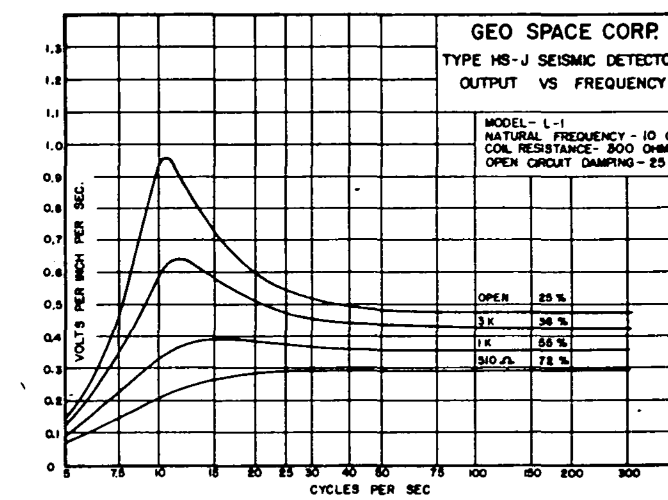


▲ Body waves

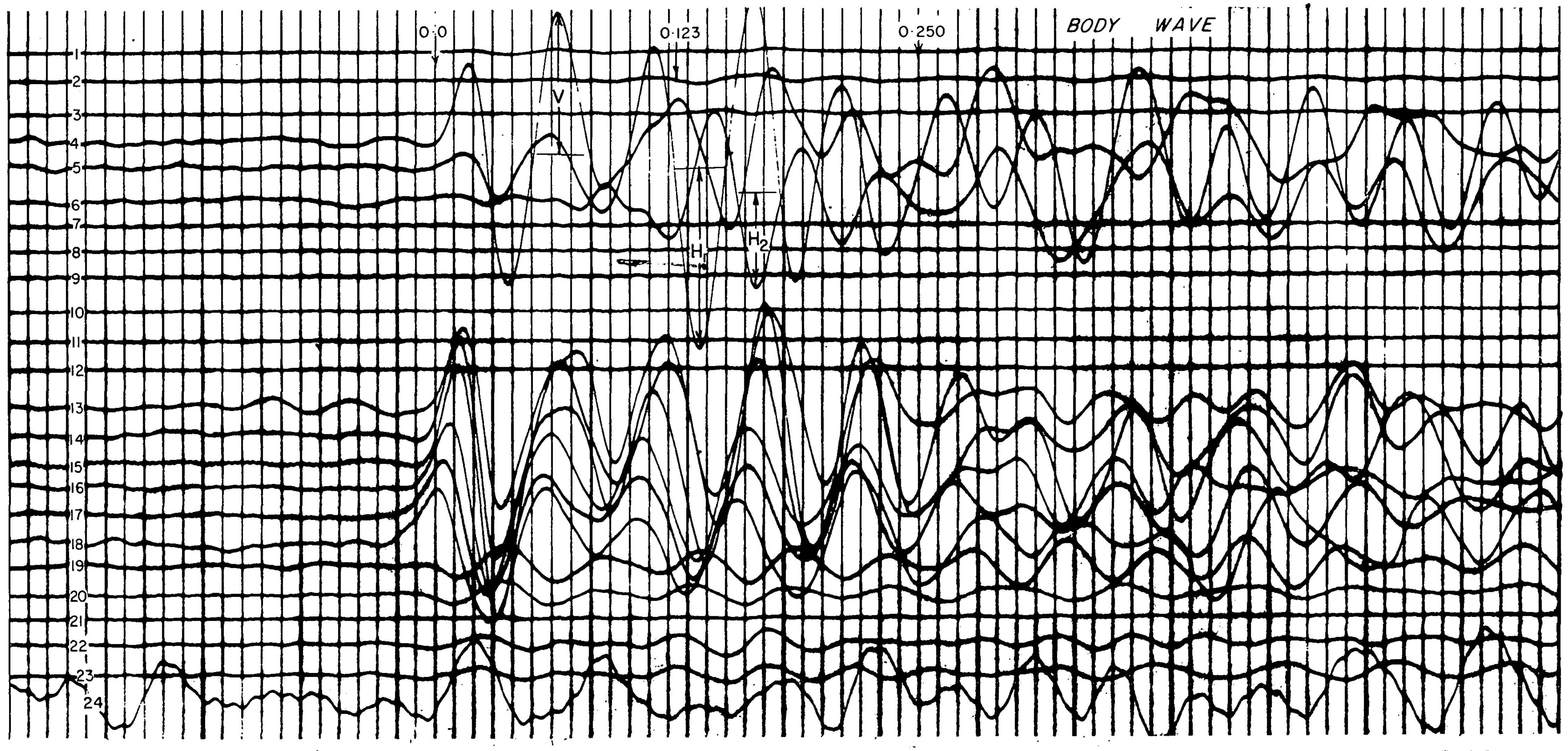
⊙ Air-blast — induced waves

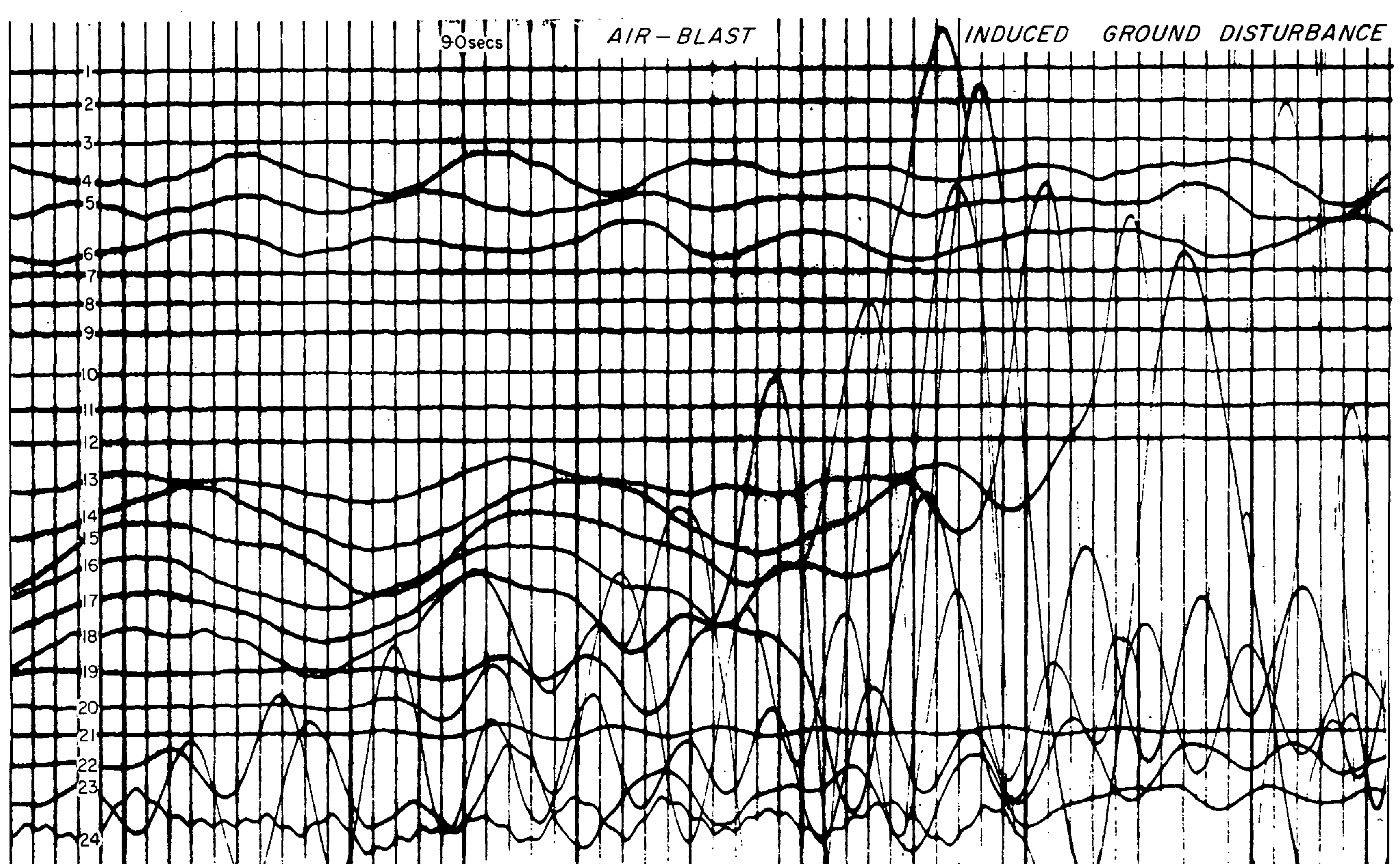
A,B..... Sites shown in Plates 1–3

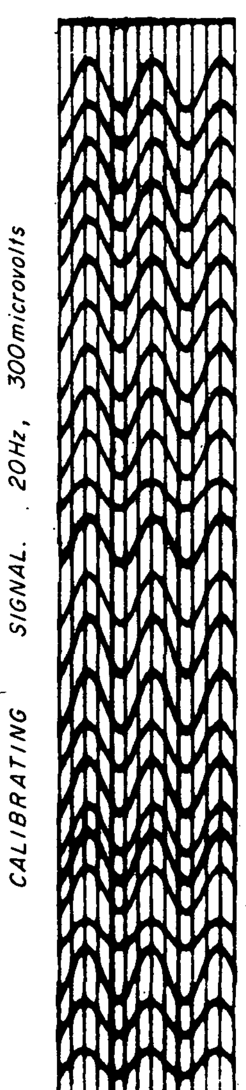
FREQUENCY RESPONSE CURVES PLATE 6



MODEL L-1
NATURAL FREQUENCY—10 cps







CALIBRATING SIGNAL. 20Hz, 300microvolts

SIE SEISMOGRAPH RECORD, SITE A

(BOMB TARGET ON NORTHERN RANGE)

EVANS HEAD VIBRATION TESTS, 1969

To Accompany Record No. 1970/64

H56/B5-34