DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

1975/146

GROUND VIBRATIONS INDUCED BY THE CONCORDE GSST-002 SONIC BOOM, ALICE SPRINGS, N.T. 1972.

by

P.E. MANN and B.H. DOLAN

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CONTENTS

SUMMARY

In June 1972 the Concorde GSST-002 made a supersonic flight in Australia, flying over a site near Alice Springs, NT. The Department of Civil Aviation was responsible for assessing the possible effects on society of supersonic flight in Australia. As part of this assessment the Bureau of Mineral Resources, Geology & Geophysics recorded the level of ground vibration induced by the sonic boom. This level was found to be well below vibration levels accepted as safe by different overseas authorities.

1. INTRODUCTION

During the Australian section of the world scales promotion tour of the British Aircraft Corporation's 'Concorde' supersonic aircraft GSST-002 the Department of Civil Aviation (DCA) was responsible for studying many aspects of its operation and the possible effects on society. One aspect detailed for close study was the sonic boom produced by the aircraft flying at supersonic speed. The Bureau of Mineral Resources, Geology & Geophysics was requested to measure the ground vibrations from the sonic boom to determine whether the air induced vibrations would be likely to cause damage to structures.

To carry out its own program to investigate the sonic boom, DCA had selected a central test site under the aircraft's planned supersonic flight path about 60 km southwest of Alice Springs on Missionary Plain. This site was also used by the BMR survey party (Plate 1). Auxiliary test sites to the east and west of the central site were also operated by DCA.

The Concorde flew from Darwin to Sydney on 19 June 1972, passing over the observing site at 07.30 a.m. at supersonic speed. It returned to Darwin from Melbourne on 26 June 1972 passing over the observing site at 10.30 a.m. at supersonic speed. On each flight two distinct sonic booms in close sequence and of approximately the same loudness were heard by the two party members.

This report describes only the work undertaken by BMR. Collation of all data relating to the aircraft operation in Australia has been done by DCA.

The measurements were carried out by a geophysical party consisting of P.E. Mann and B.H. Dolan, geophysicists.

2. GEOLOGY

The central measuring site at Missionary Plain is located on the Brewer Conglomerate of Devonian to Carboniferous age (Quinlan & Forman, 1968). At the site fine reddish brown silty sandy soil about 0.3 m thick overlies hard white recemented calcareous weathered conglomerate. The area is flat and sparsely grassed, and supports a few low trees. The approximate co-ordinates of the site are 660020 on the Hermannsburg 1:250,000 Geological Sheet.

To compare the response of different types of ground with that of the central measuring site, air shooting using gelignite charges was recorded on a sandstone outcrop and in a dry creek bed. The sandstone outcrop has been mapped as Hermannsburg Sandstone of Devonian to Carboniferous age and the sandy creek bed as Quaternary Alluvium. (Quinlan & Forman, loc cit). The approximate co-ordinates of the outcrop and creek bed sites are respectively 661012 and 660015 on the Hermannsburg Sheet.

3. BASIC CONSIDERATIONS

The sonic boom

The sonic boom is a feature of supersonic flight and it is heard by people under and to the side of the flight path. In supersonic flight an aircraft continuously builds up a pressure wavefront which spreads out from the aircraft at the speed of sound (Plate 2). A 'cone of pressure' trails the aircraft, and ultimately the pressure front reaches an observer on the ground. Although the pressure front loses energy as it expands there is a wide strip on the Earth's surface in which the sonic boom is registered, generally being more intense to an observer stationed directly under the flight path and weaker as the observer is farther away from the flight path. Normally for small military aircraft there are two distinct sonic booms with a time separation of about 0.1 sec corresponding to the difference in time between the pressure fronts originating from the aircrafts bow and tail (Maglieri, Hubbard & Lansing, 1959). The possibility of damage to structures and effect on human beings of the sonic boom must be assessed for the wave types generated.

Human response to vibration

The response of humans to ground vibration is more sensitive than is generally supposed. The subjective response of the human body to vibrations is shown in Plate 3. The vibration in buildings has been classified as quite unpleasant or annoying by some people at a particle velocity of 5 cm/sec. A similar relation exists with noise associated with air-blast pressures. The overpressure of noise from common sources, artificial sources, and the Concorde is shown in Plate 4.

Damage due to vibration

Ground

Particle displacement, velocity, and acceleration have all been used at one time or another by different investigators and authorities to determine the likelihood of damage to buildings from ground vibration. A number of references are given at the end of this report.

Most recent workers in this field consider that particle velocity is more closely related to vibration damage than either displacement or acceleration.

Nicholls, Johnson & Duvall (1971) recommend a safe vibration limit of 5 cm/sec for the particle velocity in any one of three orthogonal components of the ground motion. There is reasonable probability of damage to residential structures if this velocity is exceeded.

Air

Windes (1942) and the U.S. Bureau of Mines Research Laboratories recommend safe air blast level of 3.45 kPa for properly mounted glass panes. However, they noted that damage can occur to fractured frames at 0.69 kPa and overpressures as low as 0.018 kPa can vibrate loose sashpanes, which although non damaging could be annoying.

4. MEHTODS AND EQUIPMENT

The instruments used were a Sprengnether Engineering and Research Seismograph VS-1200 and a 24-channel seismic refraction set of equipment manufactured by S.I.E. Inc.

Sprengnether Engineering and Research Seismograph VS-1200

The VS-1200 system used comprised a recording module, an airwave detector, and a seismometer. The seismometer model S-6000 is a compact rugged instrument containing three accurately positioned orthogonal transducers in a waterproof cubic case. The cube weighs 8.8 kg and the density of 16 kg/m^3 gives a good impedance match when buried in an average soil. The natural frequency of each seismometer is 2 Hz with 60 percent critical damping, and each is fitted with a calibration coil. Throughout all recordings made at the central measuring site the position of the seismometer and its orientation remained fixed.

The SM-1 airwave detector is an omnidirectional transducer for monitoring low-frequency acoustic phenomena. It is enclosed in a sturdy housing mounted on a collapsible tripod base that is adjustable in height between about ½ and 2 m above ground level.

The recording module contains a four-channel oscillograph accepting 70-mm direct-write or standard photographic paper. The fixed paper speed is 10 cm/sec with timing lines from a chronograph-controlled motor impressed at 0.02 second intervals. Four 200-Hz galvanometers are used to record detector outputs. Electronic circuitry are used to condition the detector outputs to provide flat response to ground displacement, velocity, and acceleration from 2 Hz to 200 Hz. The recording module contains all controls and operates from an internal rechargeable battery.

S.I.E. seismic refraction equipment

Two sets of 12-channel S.I.E. Model P-19 amplifiers and a 25-channel S.I.E. Model PRO-11 recording oscillograph with 200-Hz galvanometers were used to record the ground vibrations picked up by geophones from the sonic boom. The equipment was also used to record a conventional seismic refraction spread to obtain the seismic profile at the central measuring site.

Mark Products Model L-2 velocity-sensitive geophones with a natural frequency of 2 Hz were used to record the ground vibration produced by the first sonic boom during the Concorde's southward flight from Darwin to Sydney. The geophones were buried in the soil with the upper surface of the geophone just below the surface and covered with a thin layer of soil. The only geophone cables available for the first set of recordings had 5-m spacing between take-outs and in order to record the induced ground vibrations along the spread with maximum separation between geophones some take-outs were omitted. Four geophones were used in the north and south arms of the spread which provided a constant separation of 145 m between corresponding geophones (Plate 5). Without any prior knowledge of suitable amplification to satisfactorily record the phenomenon, the gain settings of the four amplifers were nominally set as low, medium, high, and medium to increase the probability of obtaining a usable seismogram. A signal generator was used to monitor the different amplification levels which were rechecked after completing recording.

For the second supersonic flight when the Concorde flew from Melbourne to Darwin a combination of L-2 geophones and three-component omnidirectional geophones type HS-LP-3D manufactured by Geo-Space Corporation of Houston, Texas were used. The HS-LP-3D comprises three identical geophones with 300-ohm coils, natural frequency 7.5 Hz and critically damped with their axes mutally orthogonal, in a case. Sensitivity of the geophones is constant above 10 Hz and equal to 0.016 volts per mm/sec. Two of these geophones were used in the north and south arm of the geophone spread. One geophone was buried with the upper surface of its case just below ground surface and covered with a thin layer of soil. Alongside it another three-component geophone was buried to a depth of about 1 metre. Although it was planned to place the geophone deeper to study attenuation it was not possible in the time available to have the holes drilled. The holes were manually dug with a crowbar in the tough conglomerate.

The standard refraction technique (Heiland, 1946) was used to determine the characteristic velocities and depths of the seismic refractors at the central measuring site. A spread of 24 geophones spaced 3 meters apart was laid out along the observing line. Charges of ½, 1, and 3 sticks of AN 60 25 mm x 200 mm gelignite were fired at distances of 3, 10, and 50 m from each end of the spread. From the first arrivals and geophone spacing the time-distance plot gives the depths and velocities of the seismic layers. TIC geophones of natural frequency 20 Hz were used. The velocities obtained in these measurements were used as a guide in identifying wave arrivals at the geophones and also to compute the times at which wave types should arrive. Time signals from the PMG Station VNG at Lyndhurst, Victoria, were superimposed on the records taken during the second flight.

Recording Procedures

To provide a warning system for observers operating recording equipment DCA established a radio link between the central measuring site and the Alice Springs control tower. The estimated time of arrival of the Concorde over the central measuring site was relayed to Alice Springs once the flight pattern had been established. However, to give a better indication of the arrival of the sonic boom in time to start recording equipment a secondary radio link was established, with a ground observer stationed under the flight path. On the southward flight an observer was stationed at

Hamilton Downs Station about 46 km north of the central measuring site. On hearing the sonic boom the observer radioed verification to the central measuring site. This allowed a period of about 75 seconds to start recording equipment. During the northward flight an observer was stationed about 38 km south of the central site to establish a 70 second warning. In both instances adequate warning was provided but recording was purposely delayed about 30 seconds to enable the full sequence to be recorded in the limited operating period available with each instrument. For normal use the Sprengnether and S.I.E. instruments are each equipped with a light-tight magazine adequate to handle relatively short records. Because the photographic paper feed rates are respectively 10 cm/s and 37 cm/s and it was unknown how reliable the warning period would be or how long ground vibrations would last another method had to be devised to store the exposed photographic paper. Inside a small portable darkroom tent both instruments were placed in the lids of carrying boxes and angled to allow the photographic paper to fall into the lower part of the box under guidance from the operator's free hand. Under cover of a blanket each observer crouched over the layout to operate the equipment while watching the instruments' viewing screen for the event. In the first flight the S.I.E. worked satisfactorily but the paper in the Sprengnether jammed about 25 seconds after recording commenced. On the second flight the S.I.E. and Sprengnether worked satisfactorily although the S.I.E. record is marred by fogging in three places where the paper curled up and covered the viewing screen briefly. However, it has been possible to copy some of the seismogram traces by hand. Two 46 m S.I.E. records and one 30 m Sprengnether record were processed normally. All other tests were completed using the normal take-up magazine of each piece of equipment.

Other tests

Air-shooting using gelignite charges was used to measure the ground vibration and overpressure from an artificial sonic boom. Charges of 1 and 3 sticks of AN60 25 mm x 200 mm gelignite were detonated 2 m above ground level respectively at distances of 81 and 162 m from a line of detectors (Plate 5) comprising airwave detector, seismometer, two 2-Hz geophones and two 3-component geophones approximately perpendicular to the reference line (165°M).

The 2-Hz geophones and 3-component geophones were buried in the soil with the upper surface of the geophone case a few millimetres below ground level and covered with a thin layer of soil. The spacing between the detectors was about 0.3 m. Different gain settings were used for the 2-Hz and 3-component geophones. No attempt was made to measure vertical attenuation at this site. The tests also provided an opportunity to determine better recording settings for the S.I.E. on the northward flight than those used for the southward flight.

Using the same detector layout two other artificial sources were exploded to gain some idea of overpressure and noise. One was a 75 mm 'bunger' sold commercially as fireworks and the other a 'bird scarer' cartridge. The 'bunger' was exploded 2 metres above ground level 2 metres away from the airwave detector. Owing to the variable delay in the fuse the cartridge did not explode 2 metres above the ground, but at ground level 2 m from the base of the airwave detector.

Recordings were also taken with the Sprengnether equipment on a sandstone outcrop and in a creek bed. To improve coupling on the outcrop, the seismometer was placed in a hole filled with a quick setting compound cut in the surface. The airwave detector was placed two metres above the seismometer. Three plugs of AN-60 gelignite were detonated 2 m above the ground 162 metres from the seismometer along the strike of the outcrop. In this direction the ground surface was flat. At the creek the seismometer was buried to its own depth in dry sand and the airwave detector mounted 2 m above it. The shot distance was again 162 m. Neither the thickness of alluvium nor the depth of the water-table at this site is known.

5. RESULTS

The maximum ground vibration and overpressure recorded during the sonic boom are tabulated and compared with some other sources of overpressure in Table 1.

TABLE 1

Source	Distance m	Maximum overpressure kPa	dB	Maximum ground vibration mm/sec Transverse	Vertical	Along path
0.5 kg of AN 60 gelignite 2 m above ground	162	0.48	147	0.1	0.3	0.3
Bird Scarer cartridge ground level	2	0.02	120	0.03	0.15	0.03
75 mm firecracker 2 m above ground	2	0.02	120	0.03	0.13	0.3
Concorde GSST-002 sonic boom under flight path	approx. 16 000	0.029	124	0.15	0.30	0.28

The Concorde sonic boom induced the same maximum ground vibration for a much lower overpressure than the gelignite air blast. Plates 6 & 7 show the waveforms of the overpressure and induced ground vibration produced by the Concorde and some test gelignite air shots. There is a similarity between the waveforms of the ground vibrations induced by the sonic boom and those induced by the gelignite air shots at the same position, once the air-coupled vibrations have passed. These waveforms are quite different from those recorded on the creek bed site and the rock outcrop site. In the gelignite air shot tests the same incident overpressure waveform was used; hence the recorded difference in ground vibrations is due to the response of the ground.

Fourier analyses of the waveforms recorded by the airwave detector for gelignite air shots and the sonic boom air blast are shown in Plate 8. Only the first boom was analysed. The sonic boom air blast has the narrower spectrum which peaks at approximately 20 Hz. Waveforms of the induced vertical component of ground vibration from gelignite air shots and the sonic boom were also analysed and their spectra are shown in Plate 8. For the sonic boom air blast the induced vertical ground vibration response peaks at approximately 22 Hz and is small for a frequency greater than 40 Hz. The spectra of the induced vertical ground vibration from gelignite air shots at the three test sites show maximum response at approximately 33, 60 and 55 Hz. These clearly show the difference in the response of the ground at the central measuring site and the other two sites, and suggest that the response of the ground to the sonic boom would be greatest at the central measuring site.

The level of ground vibration induced by the sonic boom was 0.15 mm/s in the transverse axis, 0.30 mm/s in the vertical axis and 0.28 mm/s in the axis parallel with the flight path. These figures are below the safe vibration levels recommended by most authorities. For instance Nicholls et al. (1971) recommend a limit of 50 mm/s (2.0 in/s) for any one of the three orthogonal components of ground particle velocity; the Standards Association of Australia recommends a safe limit of 19 mm/sec (0.75 in/sec) for the resultant of the three components. The latter limit is heavily biased towards comfort and contains a sixfold factor of safety against light damage (SAA, 1967).

Hence the ground vibration produced by the sonic boom at the central measuring site was 0.02 times the SAA recommended limit and 0.006 times the US Bureau of Mines safe limit, and the results suggest that the vibrations produced would be greater at the central measuring site than at the other two sites investigated.

The records of the ground vibrations obtained from the spread of geophones show that there was no significant difference in the level of vibration recorded at the different positions along the spread, and no attenuation at a depth of 1 m below the surface.

The results of the seismic refraction work at the central measuring site are given in the form of a depth profile in Plate 9. Table 2 shows the seismic velocities and interpretation.

TABLE 2

Velocity (m/s)	Interpretation
400	Soil
1200	Weathered conglomerate and recemented calcrete lenses
2100	Partly weathered conglomerate
4700	Unweathered conglomerate

The northern end of the spread is at the seismometer recording position for the Concorde ground vibration records.

6. CONCLUSIONS

At the central measuring site the ground vibration induced by the Concorde GSST-002 sonic boom is well below the safe limits for buildings recommended by most authorities. The maximum velocity of one component was 0.006 times the US Bureau of Mines recommended limit and 0.02 times the SAA limit and also below the level perceptible by humans according to Goldman.

The ground vibration produced in a built-up area may be significantly different from that recorded during the test. The nature of the ground vibrations would be expected to be more complex owing to the reaction of buildings to the sonic boom. Similarly the overpressure generated would be more complex owing to reflection and diffraction of the wavefront by buildings.

If the level of ground vibration in a built-up area did not exceed that measured during the tests, there is little probability of damage to buildings.

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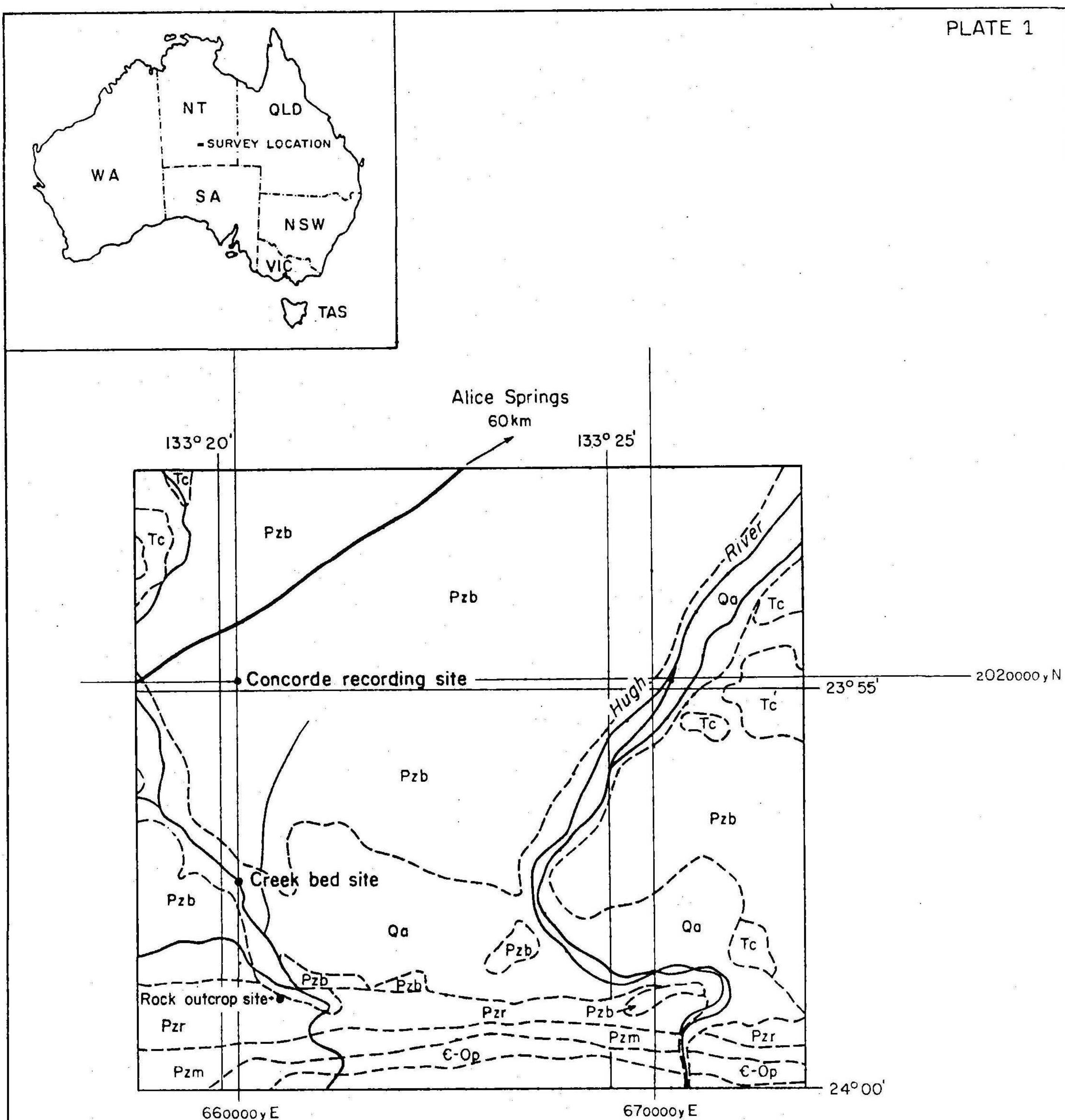
PLATE 1

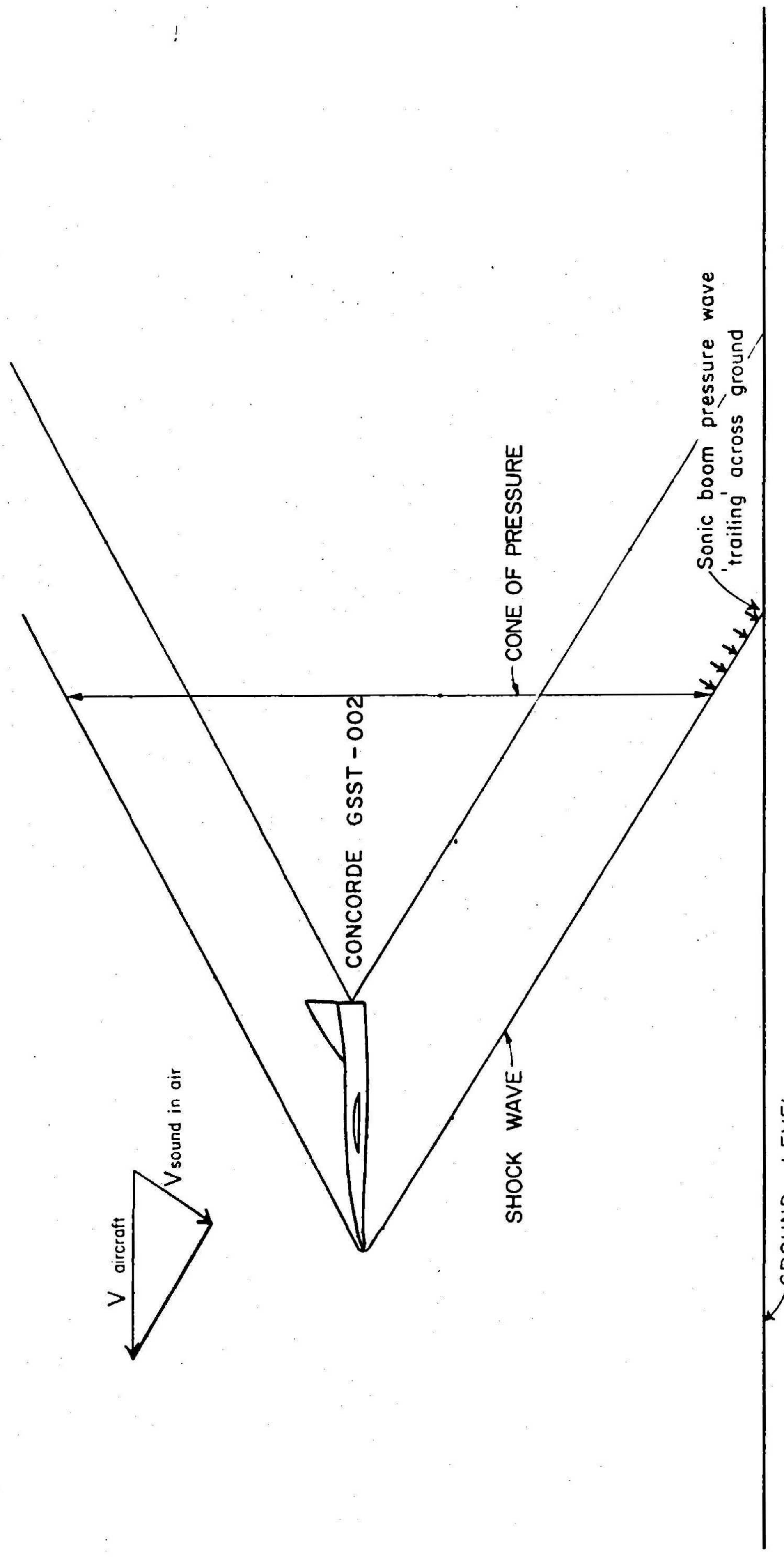


LOCATION DIAGRAM WITH GEOLOGY

0 5 10 km

LEGEND

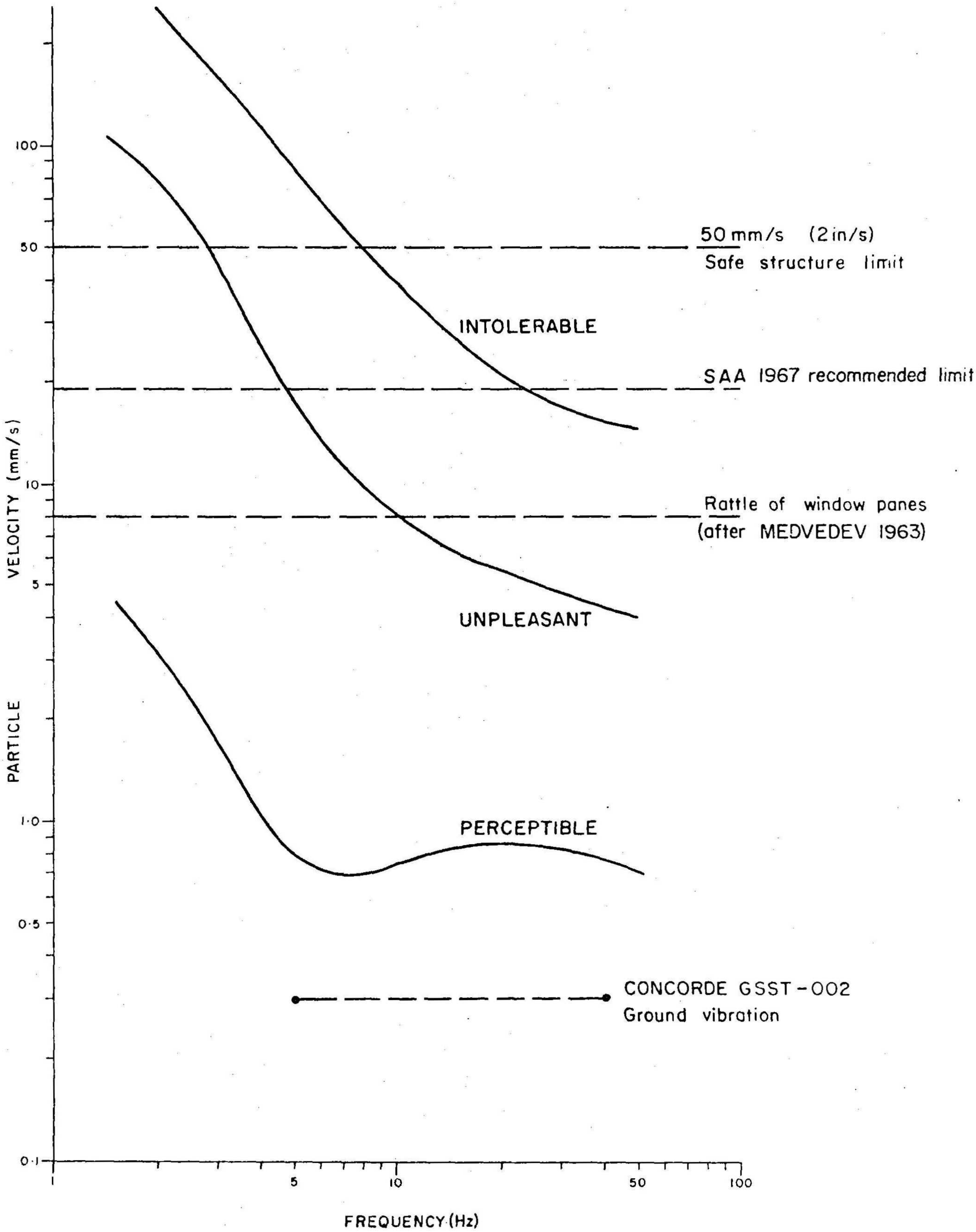
Qa	Alluvium	Pzr	Red-brown silty sandstone, pebbly sandstone
Tc	Conglomerate	Pzm	Sandstone
Pzb	Calcareous conglomerate, calcareous sandstone	Є-Op	Fossiliferous sandstone, silty sandstone, siltstone



SCHEMATIC OF SONIC BOOM

HUMAN RESPONSE TO GROUND VIBRATIONS

(after Goldman 1948)



HUMAN AND STRUCTURAL RESPONSE TO SOUND PRESSURE LEVEL (BOLLINGER, 1971)

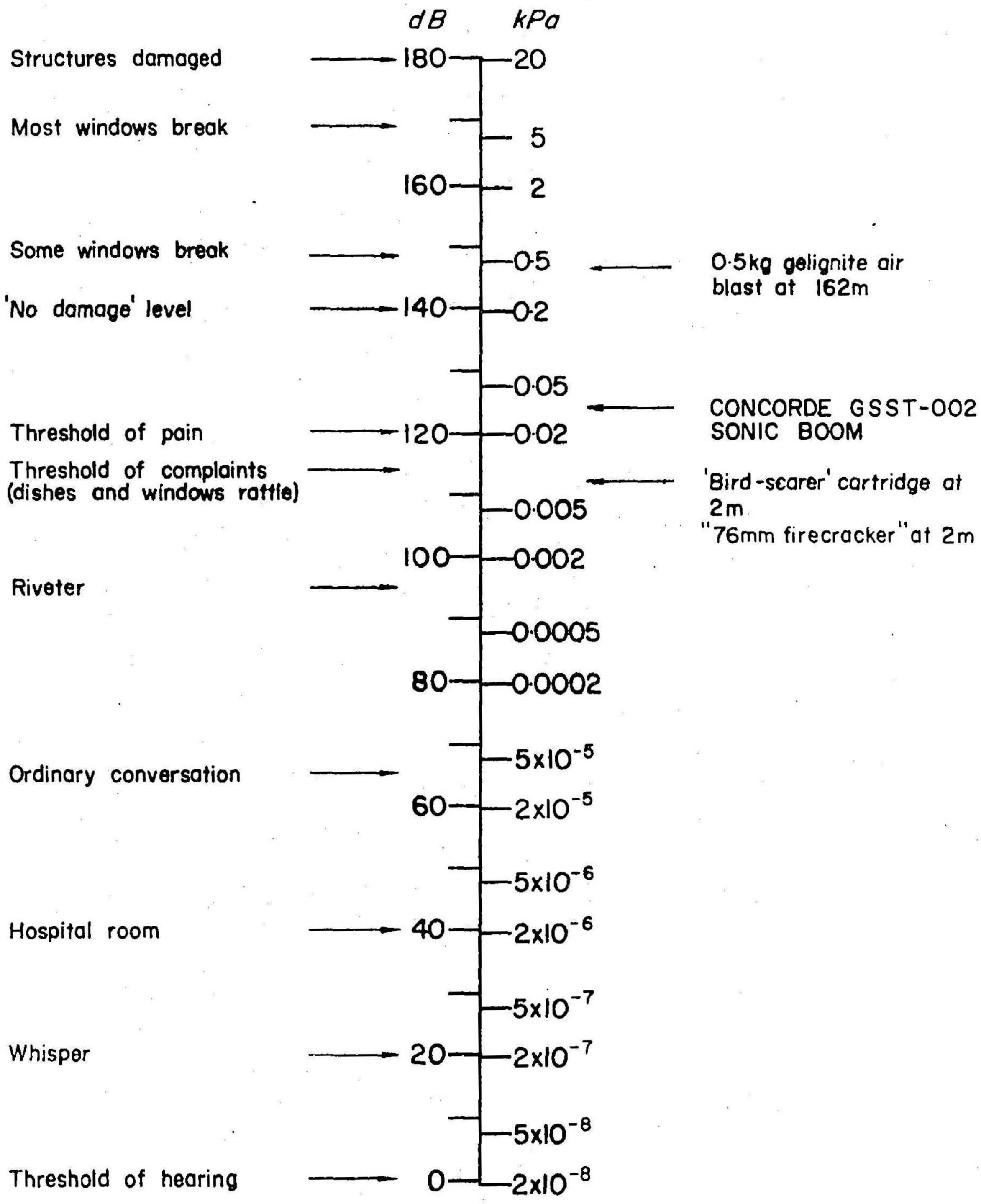
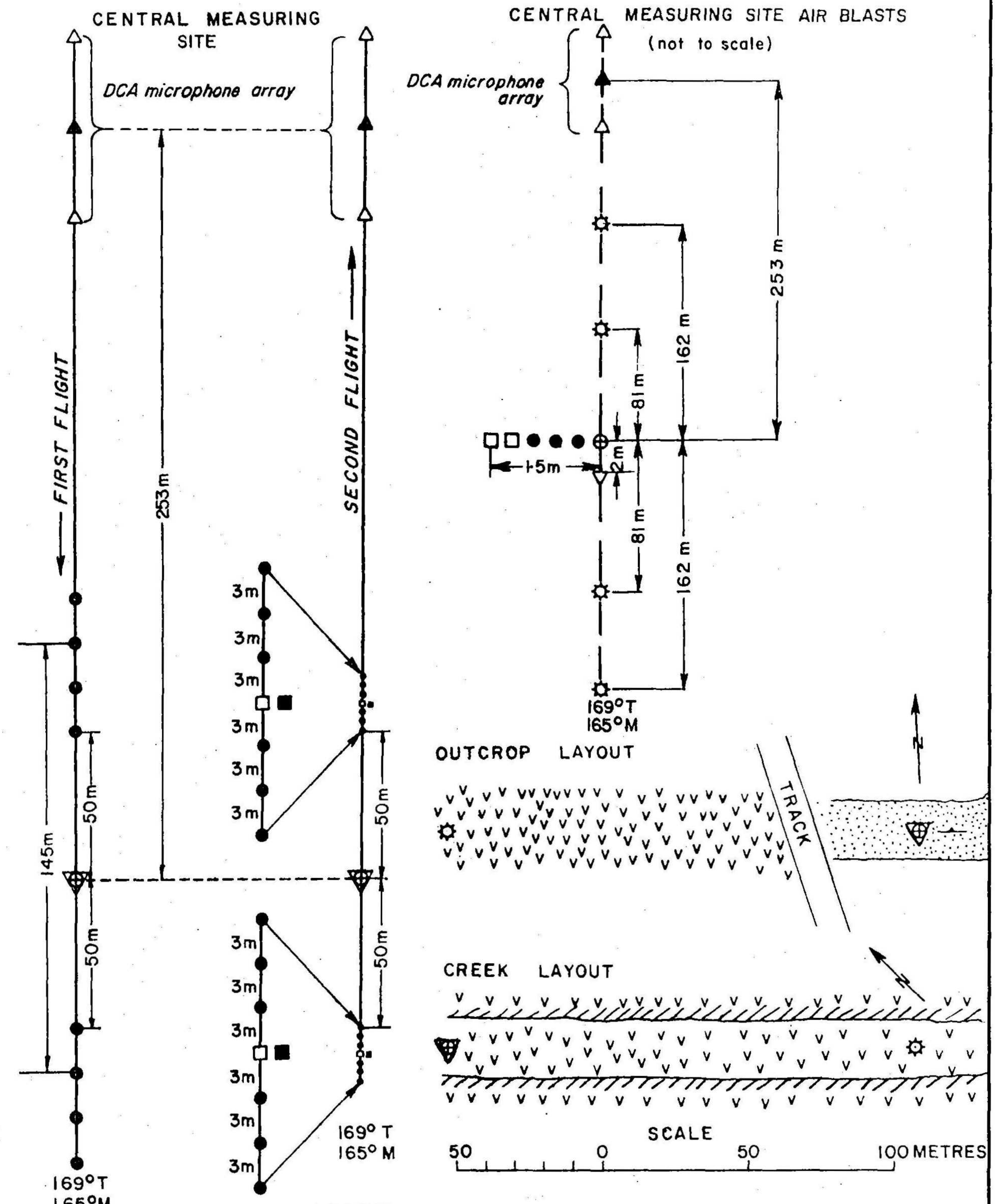


PLATE 5



LEGEND

- Sprengnether VS-6000 seismometer and SM-1 airwave detecter
- Sprengnether VS-6000 seismometer
- Mark Products L-2 vertical geophone 2 Hz
- SM-1 airwave detecter
- Geospace HS-LP-3D three-component geophone 7·5Hz at surface
- Geospace HS-LP-3D three-component geophone 7·5Hz buried 0·5m
- Airblast
- Alluvium
- Sandstone

GEOPHONE, SEISMOMETER AND AIRBLAST DETECTOR LAYOUTS

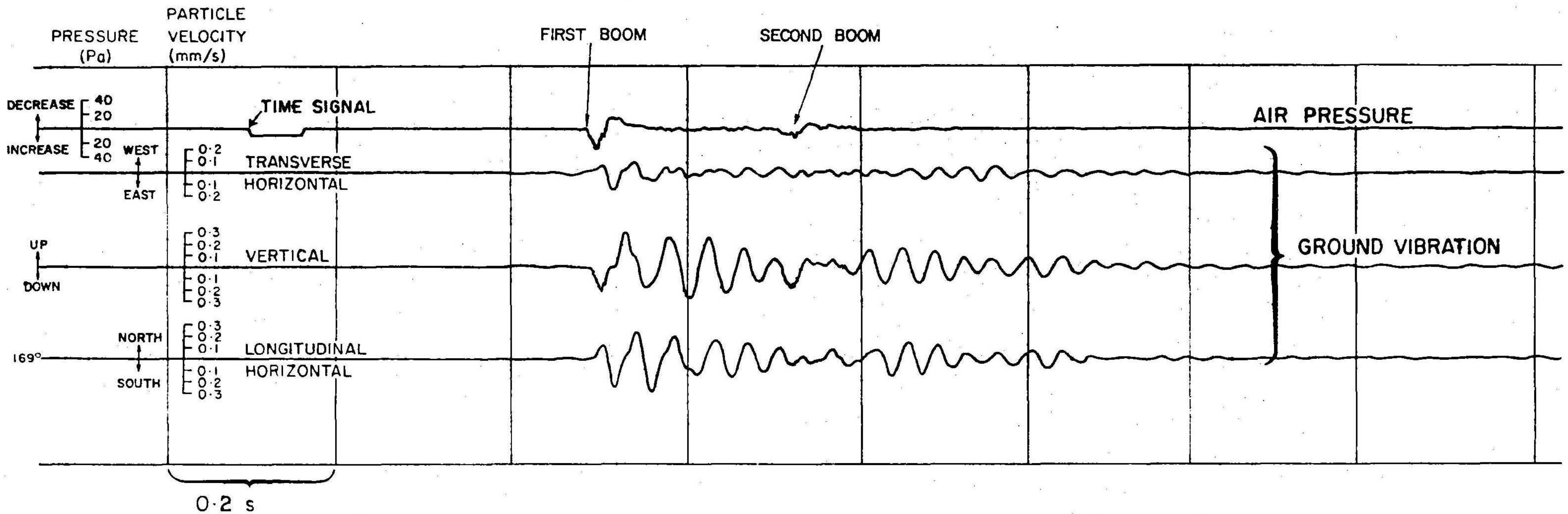
Record No.1975/146

F53/B5-1A

CONCORDE GSST - 002 SONIC BOOM INDUCED GROUND VIBRATIONS

NORTHWARD FLIGHT 26-06-1972

CENTRAL MEASURING SITE



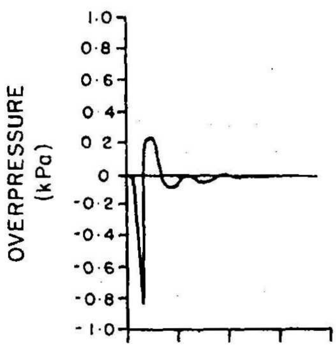
SPRENGNETHER ENGINEERING AND RESEARCH SEISMOGRAPH VS-1200 AND SM-1 AIRWAVE DETECTOR

SERIAL NUMBER 4034/4134

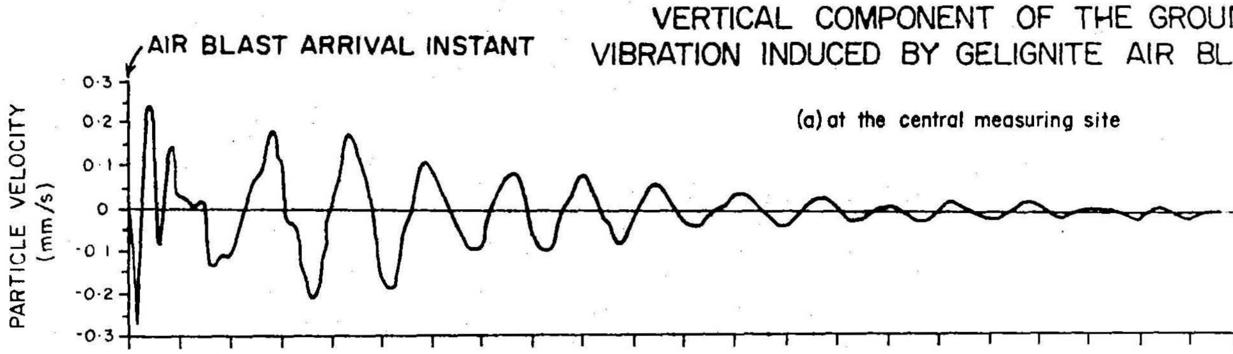
GROUND VIBRATION RECORD OF TEST BLASTS

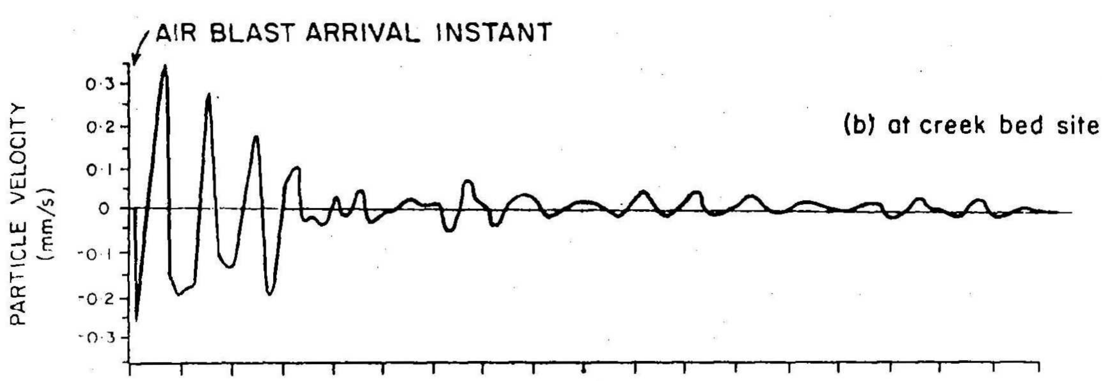
GELIGNITE AIR BLAST RECORD

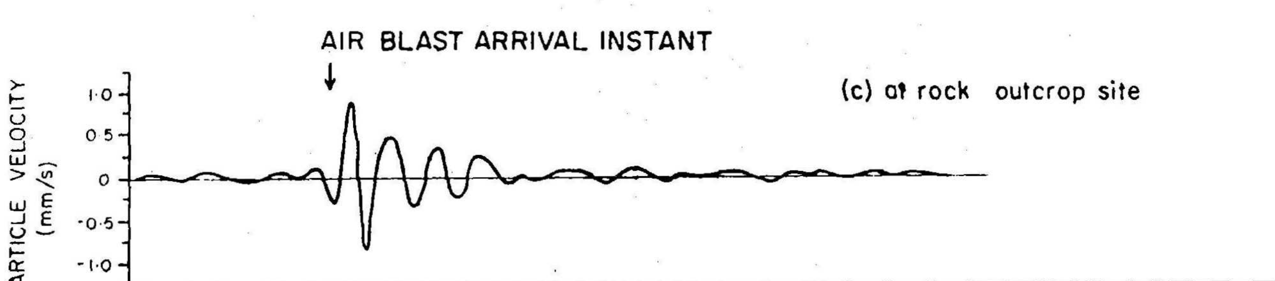
0·5kg of 'AN60' polar gelignite at 162m, detonated 2m above ground at the central measuring site



VERTICAL COMPONENT OF THE GROUND VIBRATION INDUCED BY GELIGNITE AIR BLAST







TIME (20 ms/division) ⟶

FOURIER ANALYSES

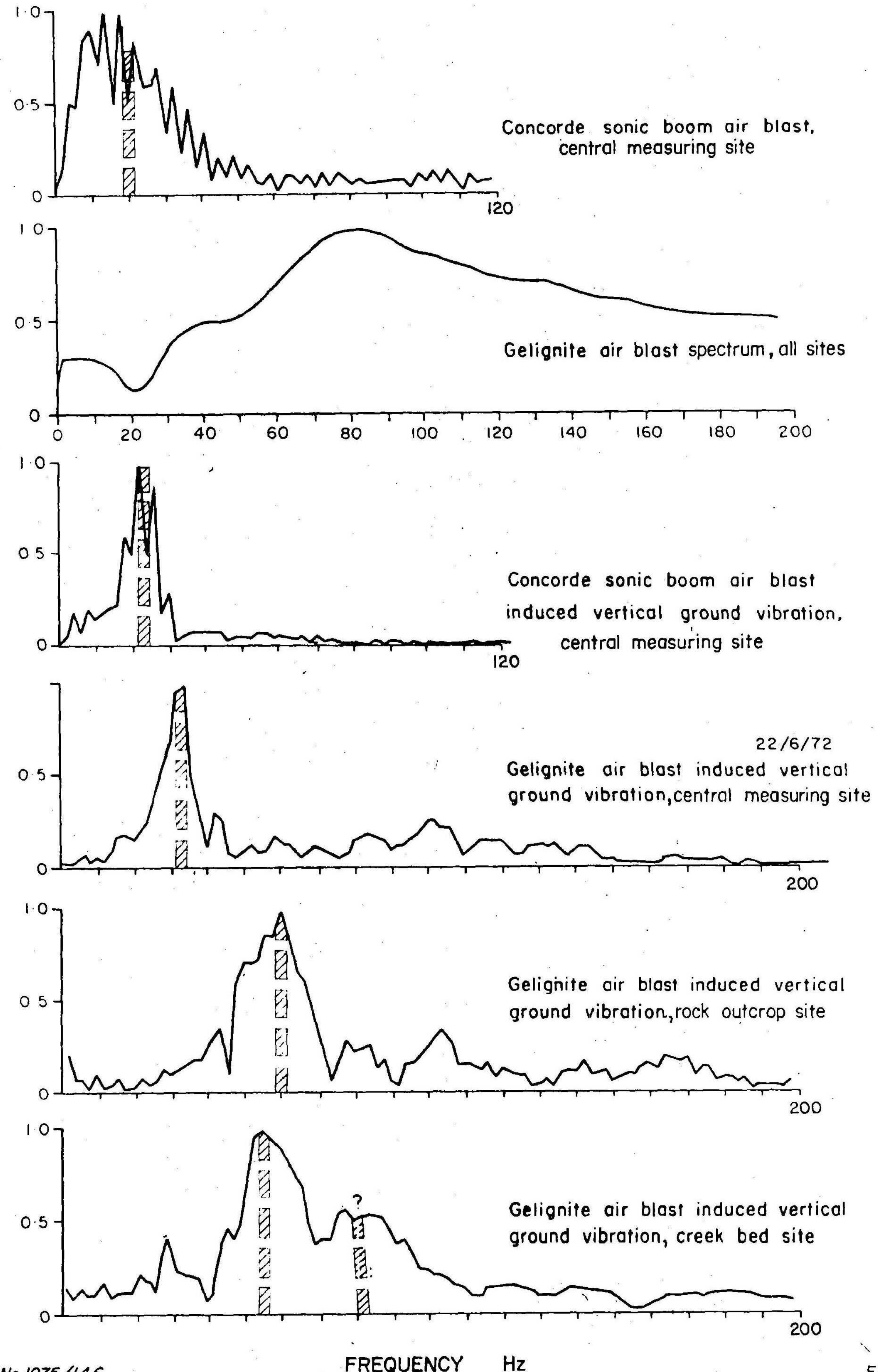
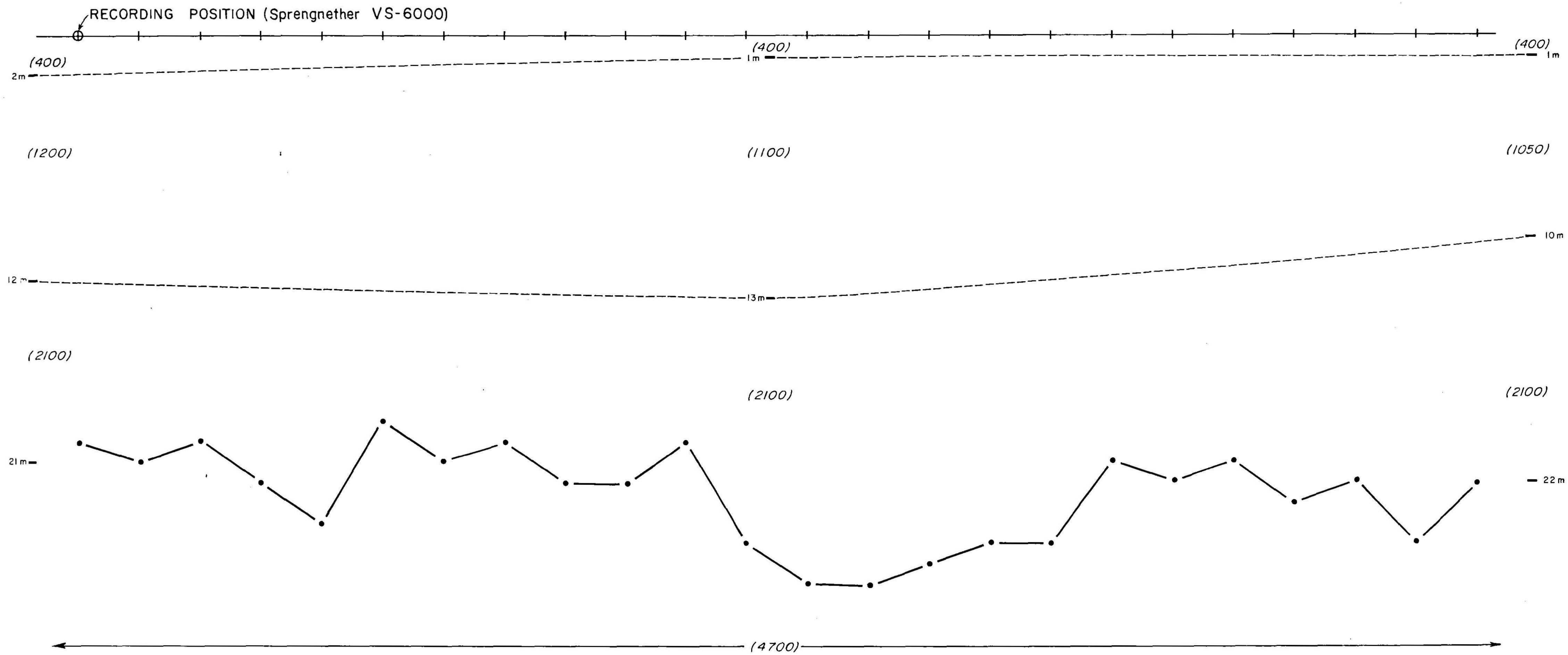


PLATE 9



SEISMIC-CROSS SECTION:
CENTRAL MEASURING SITE

HORIZONTAL AND VERTICAL SCALE

10 5 0 10 20 METRES

LEGEND

(1200) LONGITUDINAL SEISMIC VELOCITY IN m/s

2m - - - DEPTH TO FORMATION WITH DIFFERENT SEISMIC VELOCITY

BEDROCK BOUNDARY